Paper 6 (draft)

Soil Biological Activity in Recent Clearcuts in West-Central Alberta

N. A. Startsev, D. H. McNabb, and A. D. Startsev

Forest Resources,
Alberta Research Council
Bag 4000, Vegreville, Alberta, T9C 1T4

ABSTRACT

Soil biota response to changes in the soil physical environment following forest harvesting is relatively unknown in boreal forests. Soil biological activity was measured at four sites with Luvisolic soil following clearcut forest harvesting. Aerobic respiration rate and cellulose decomposition in flooded soils were measured on soil samples collected from treatment plots subjected to tree removal only and tree removal associated with three levels of skidding activity immediately after clearcut harvesting and after one and two years. More than half of variation in respiration and cellulose decomposition rates was related to soil properties. Soil respiration rate increased significantly after one year but was not affected by skidder traffic. Cellulose decomposition was highest in soil with air-filled porosity $<0.10\ m^3\ m^{-3}$, and increased significantly with skidder traffic. Air-filled porosity measured in the field at the time of harvest indicated a poorly aerated environment that becomes wetter in subsequent years. The results imply that soil had biota well adapted to poor soil aeration. The development of a fully anaerobic soil environment following forest harvesting only occurred on compacted soil after heavy precipitation, but partial anaerobiosis of these boreal forest soils was common. Although partial anaerobiosis increased decomposition rate, it is considered sufficient to adversely affect the growth of plant roots and change the availability and mobility of nutrients.

Key words: Forest harvesting, soil compaction, biological activity, respiration rate, decomposition rate, Alberta, boreal forests.

The post-harvest soil environment is an essential determinant of tree regrowth and the reestablishment of a healthy and diverse plant community. Forest harvesting primarily affects the soil environment as a consequence of tree removal and changes in soil physical properties caused by soil modification by harvesting equipment (Froehlich and McNabb 1984, Waring and Schlesinger 1985, Kimmins 1987). Depending on the amount of trees removed and the understory remaining, forest harvesting decreases transpiration, increases soil heating and its diurnal fluctuations, and leaves a large amount of slash, forest litter and dying tree roots that are easily decomposed. The greatest changes occur when the forest is harvested by clearcutting. Soil modification by forest harvesting equipment, particularly ground-based wheeled and tracked skidders, can significantly decrease soil macroporosity and increase soil strength (Greacen and Sands, 1980, Froehlich and McNabb 1984, McNabb and Boersma 1993). Decreased macroporosity reduces the exchange of soil gases with the atmosphere causing the soil environment to become more anaerobic (Bird and Chatarpaul 1987, Ruark et al. 1982).

Soil compaction can affect both the growth of roots and soil biota (Ruark et al. 1982, Dick et al. 1988). But the effect of soil compaction on soil biology varies. The removal of trees is most beneficial to soil microflora that decompose fresh organic substrate and soil humus (Swift et al. 1979, Mollis et al. 1995, Russell 1973, Trettin et al. 1996). Although fresh substrate is available, soil respiration generally decreases as a result of soil compaction (Liebig et al. 1995, Nielson and Pepper 1990). Soil respiration can be suppressed in compacted soil compaction reduces air-filled pore space cririca1 to gas diffusion (Xu et al. 1992). While respiration and decomposition rates usually increase as a function of soil temperature and availability of nutrients, there are no indications that the microorganisms responsible are the same or that they will act similarly in compacted soil. Although aerobic decomposition is a major factor in transformation of soil organic matter, but decomposition of organic matter is also accelerated in water-logged soils by an increase in activity of anaerobic microflora (Nikolaeva et al. 1984).

Most western boreal forests grow on medium- to fine-textured tills (Strong 1992) that are frequently subject to periods of water-logging after clearcut harvesting (Dubé and Plamondon 1995). Frequent water-logging has been reported to increase decomposition in other ecosystems (Nikolaeva et al. 1984, Mollis et al. 1995). If biological activity increases in boreal forest soils because of temporary water-logging, the activity may also increase following soil compaction (Adkison and Jackson. 1996, Dick et al. 1988). Our objective was to determine the effects of clearcut harvesting and soil compaction by rubber-tired skidders on soil biological activity and organic matter in the boreal forest of west-central Alberta.

MATERIALS AND METHODS

Soil Samples

The soil samples for this study were collected from four experimental sites that are part of a larger study of forest soil compaction during clearcut harvesting in west-central Alberta (Figure 1) (Startsev et al. 1995). The sites are in the Lower and Upper Boreal Cordilleran part of the Southern Alberta Uplands; the soils developed from moraine tills (Strong 1992). The forest cover was predominantly lodgepole pine (*Pinus* *contorta* Dougl. ex Loud. var. *latifolia* Engelm.) or white spruce (*Picea glauca* (Moench) Voss) with a small component of aspen (*Populus tremuloides* Michx.). Three sites were logged during the summer of 1994 and the fourth site (Pinto Creek) was logged during the summer 1995. At each site, four replicated blocks of four treatments were installed. Each block was approximately 40 m on a side, and contained three levels of skidding (3, 7, and 12 cycles), and a control (Figure 2). A skidding cycle was one empty and one loaded pass of a skidder operating in a corridor approximately 6 m wide and 40 m long. A control area 10 m wide separated the skidding corridors. The two control areas in each block were not trafficked by skidders. This block layout allowed the monitoring of seedling performance within a specific level of compaction and at the boundary between the three combinations of compacted and undisturbed soil as part of the larger study.

Soil cores for determining bulk density were collected immediately after skidding at four randomly located points within each treatment in a block. Cores were collected from approximately the 3- to 7- cm depth in rings 3 cm high and 7 cm in diameter (McNabb and Boersma 1993). Smaller cores that were 3 cm high and 5.1 cm in diameter were also collected at that same point in the most modal block for determination of soil water retention in Tempe cells (Reginato and van Bavel 1962). The small cores were sealed to maintain soil water content and stored at 4°C.

Bulk soil samples were also collected in the late summer of 1995 and 1996 from within 0.5 m of the previous sampling locations. These samples were sealed in plastic bags and stored at 4° C for measurement of respiration. Part of these samples was air-dried for analyses of organic matter content and humic to fulvic carbon ratio.

Precipitation and soil temperature, water potential, pH and RedOx potential (ORP) were monitored in the field using Campbell Scientific Inc. dataloggers. Soil sensors were installed at two depth (5 and 10 cm) on the control and the 7-cycle treatments in one replication at each site. Data were averaged by 24 hour periods.

Soil Analysis

Soil respiration rate was measured on 20 g of the fresh bulk soil samples collected in 1995 and 1996. Soil was incubated at room temperature for 14 days (Anderson 1982). The carbon dioxide produced during incubation was absorbed by 0.25 N sodium hydroxide solution and determined by titration with 0.25 m HCL. Bulk soil samples collected in 1994 had been dried before respiration rates could be measured. Therefore, the 1994 respiration rates were measured on the small undisturbed cores rather then bulk soils. All respiration rates were converted to a gram of dry soil basis for analyses. Comparison of the respiration rate measured on bulk soil and on intact soil cores collected in 1995 at the Pinto Creek site confirmed that the differences in respiration rate between cores and bulk soil were not statistically significant. Therefore data for all years were combined for subsequent analyses.

Decomposition rate was measured on flooded soil to simulate a temporary water-logged environment. The weight loss of a polyethylene-backed absorbent paper (Benchkote®, Whatman) provided a measure of cellulose decomposition (Katayama et al. 1991). Two pre-weighed strips of paper (1 by 6 cm) were inserted vertically in a 40 g sample of bulk soil, collected in 1995 and 1996. The sample was flooded to a depth of 3 cm with deionized water and incubated for two months at room temperature. After incubation, the paper strips were removed, carefully rinsed with deionized water, and air-dried. Each paper was weighed and percentage weight loss was the measure of decomposition. ORP and pH of the soil paste were measured at the start and end of the incubation.

Soil organic matter content and the humic to fulvic carbon ratio were determined on samples collected in 1994 and 1995. Organic matter was extracted with 0.1 N NaOH (Schnitzer 1983). The extract was acidified at pH 2 with 2 N HCl and humic fraction separated. Both fractions were oven-dried at 50° C and organic carbon analyzed by wet combustion (Nelson and Sommers 1982).

Soil water retention of the small, undisturbed soil cores was determined at a water potential of −10 kPa (Reginato and van Bavel 1962). Air-filled porosity was the volume of air in the undisturbed core at −10 kPa (Xu et al. 1982).

Statistical analysis

An analysis of variance using a completely randomized design was performed for each year to test the effect of soil compaction. The repeated measures procedure with time as the repeated factor was used to test the effect of compaction on soil respiration rate (SAS Institute 1989).

RESULTS

The soils are Gray Luvisols of similar texture but varying amounts of gleying (Table 1). Trafficking by skidders with wide, rubber tires caused a significant increase in bulk density after only three cycles at three of the four sites (Table 2). Bulk density did not increase significantly after more intensive skidding which is a common consequence of trafficking forest soils (Froehlich and McNabb 1984). Skidding did not result in significant compaction at the Elk River site because the soil water potential was lower than the others (Table 1). Soils at other sites in the region were not significantly compacted when soil water potential was low (Startsev et al. 1995). Soils at low water potential are less compressible during loading because soil strength is much higher (McNabb and Boersma 1996).

Differences in air-filled porosity and soil temperature at the 5 cm depth of the control and the 7 cycle treatment were small but consistent during the growing season (Figure 3). During the winter, the soils were generally protected from freezing by the winter snowpack. Higher precipitation contributed to lower ORP in compacted soil in the summer of 1996 than in the summer of 1995 (not shown), and differences in air-filled porosity between the control and compacted soil were much smaller. ORP was consistently lower in compacted soils except for the winter months. The similarity of ORP in late winter is attributed to soil biological activity being suppressed in the cold soil.

Soil respiration rate of individual samples immediately following harvesting in 1994 was positively correlated with the soil organic matter content ($r^2 = 0.31$, $p < 0.001$, $n = 80$), and negatively correlated with bulk density ($r^2 = 0.38$, $p < 0.001$, $n = 84$). The regression of organic matter and bulk density versus respiration rate accounted for over half of the variation in respiration rate ($r^2 = 0.52$, $p < 0.0001$, $n = 80$). One year after harvesting, the soil respiration rate was significantly higher for all treatments (Figure 4). The minor decrease in respiration rates of trafficked soil relative to the control was not statistically significant but remained consistent between the first and second years after harvesting.

Decomposition of cellulose in flooded soil was related to the field air-filled porosity of the soil measured in the field immediately following skidding (Figure 5). These rates reflect the activity of the soil biota indigenous to the mature forests. Decomposition was often higher in samples when the air-filled porosity was less than 0.10 $m^3 m^{-3}$. Similar patterns in the relationship between air-filled porosity and decomposition rate were observed on compacted soils and control for the next year after harvesting (not shown). The decomposition rate was positively correlated with the soil organic matter content ($r^2 = 0.28$, $p < 0.0006$, $n= 51$), and negatively correlated with air-filled porosity at –10 kPa ($r^2 = 0.37$, $p < 0.0008$, $n = 51$). More than half of the variation in decomposition rate was explained by the combined regression of organic matter and bulk density versus decomposition ($r^2 = 0.56$, $p < 0.0001$, $n = 51$). Compaction resulted in significant increase in decomposition rate (Figure 6).

The high ORP of flooded samples indicate that the soil is inherently aerobic two years after harvest (Table 3). This is confirmed by the in situ measurement of ORP in the field, although the air-filled porosity is less than the 0.10 $m^3 m^{-3}$ which is considered a minimum for soil gas exchange (Xu et al. 1992) (Figure 3). Two months of flooding caused a significant decrease in ORP, a larger decrease occurred in the second year (Table 3). However, ORP seldom dropped below 200 mv, which is regarded as a completely anaerobic environment (Orlov, 1985).

Soil pH at the beginning of the cellulose decomposition test increased from the first to the second year following harvesting (Figure 7). The interaction of time and number of skidding cycles was significant.

Organic carbon content immediately after clearcutting was about 0.015 m m^{-3} in the upper horizon, and the average C/N ratio was approximately 19 (Table 1) but both parameters were highly variable within each site. No significant change was found in the organic matter content over two years. Because of high variability of organic matter content in forest soils more samples may be needed to determine if any significant changes take place over time (McNabb et al., 1985). However, the humic/fulvic carbon ratio decreased significantly as the intensity of skidding traffic increased. The decrease was greatest at the three sites where the increase in bulk density was significant (Figure 8). The time and treatment interaction was significant, indicating that the effect of compaction on humus state was becoming more pronounced during the second year.

DISCUSSION

Most medium- to fine-textured Luvisolic soils in the western boreal forests of Alberta have developed from glacial tills and lacrustine sediments that are weakly aggregated and have subsoils that are relatively dense (Strong 1992, McNabb 1994). As a result, drainage is often restricted as evident from the presence of mottles near the surface or gleying (Table 1). The organic matter content of these soils is also low, but a relatively high C/N ratio suggests that some accumulation of soil organic matter may be occurring in mature forests (Table 1). A dense canopy and thick forest floor in mature forests can insulate the soil and lower summer soil temperatures thereby slowing decomposition

(Bird and Chatarpaul 1988, Dyrness et al. 1988). Removal of the forest by clearcut harvesting reduces the thermal insulation and decreases transpiration, which increases soil wetness. As a result, soil biological activity increases as evident from soil respiration increasing in the two years following harvesting (Figure 4). However, the combination of poor drainage and reduced transpiration occasionally causes the soil environment to become anaerobic following heavy precipitation (Figure 3). But the soil biota at these sites have apparently adapted to low soil aeration and periodic anaerobiosis, even in the mature forest, because the respiration rate of soil collected at the time of harvest was highest at low air-filled porosity when (Figure 4). The negative slope of the regression between respiration and air-filled porosity of individual samples also indicates a microsite response to differences in soil drainage and wetness.

Although a well-aerated soil is commonly considered a necessary prerequisite for decomposition (Dick et al. 1988), relatively high decomposition rates can also occur in temporarily waterlogged soils (Nikolaeva et al. 1984, Mollis et al. 1995). Our results indicate that poor aeration does not inhibit decomposition of organic matter in these boreal forest soils. The higher rates of decomposition at an air-filled porosity less than 0.10 m^3m^{-3} (Figure 5) indicate that some microbial groups can proliferate in these poorly aerated soils, while the growth of vascular plants is likely to be suppressed (Russell 1973, Ruark et al. 1982, Froehlich and McNabb 1984).

At the time of harvesting, respiration of individual soil samples tended to be lower in soil of higher bulk density and lower air-filled porosity. Low air-filled porosity reduces gas diffusion (Xu et al. 1992), which can increase CO_2 and decrease O_2 concentrations in soil, and suppress soil respiration (MacFadyen 1973). However, soil compaction caused only a minor decrease in soil respiration in the two years following harvesting (Figure 4). Soil compaction typically causes a significant reduction in the larger pore sizes (Froehlich and McNabb 1984), but differences in air-filled porosity of the control and compacted soil in the field were generally small, although ORP in compacted soil was much lower (Figure 3). Soil compaction did cause a significant increase in decomposition at the highest level of skidding traffic (Figure 6), and is attributed to anaerobic decomposers. Soil compaction enhances anaerobic decomposition because anaerobic biota was present in soil under the mature forest and the low ORP following harvesting allowed this population of organisms to expand.

A decrease in soil organic matter as a result of increased decomposition was not observed, although the decrease in the humic/fulvic carbon ratio indicates changes are occurring in soil carbon (Figure 8). The significant decrease in humic/fulvic ratio with increasing levels of compaction is attributed to increased decomposition of in situ soil organic matter rather than inputs from surface debris for several reasons. Little mixing of the forest floor with the surface soil was observed in this study. If the input of carbon compounds from surface materials had been high because of increased decomposition, the ratio in the control soil should have also decreased with time. Furthermore, compaction reduces hydraulic conductivity (Froehlich and McNabb 1984), which would also reduce the likelihood that organic compounds were leached from the surface soil into the mineral soil. The accelerated decomposition of soil organic matter in compacted soil may lead to a decrease in soil organic matter content, but the variability of soil organic matter makes the detection of these changes more difficult (McNabb et al. 1986).

Increased soil respiration, which consumes soil oxygen (Figure 4), and reduced air-filled porosity because of soil compaction and reduced transpiration, which slows gas diffusion, results in the ORP dropping below 200mv and short-term anaerobiosis (Figure 3). Low ORP accelerates denitrification (Swift et al. 1979) and increases the potential for nitrogen to be lost. Reduced aeration is contributing to the increase in soil pH (Figure 7), particularly in compacted soil (Orlov 1985). The release of cations at advanced stages of decomposition, and the gradual replacement of symbiotic fungi with bacterial microflora can also cause increase in soil pH (Swift et al. 1979). The increase in soil pH also decreases the solubility of phosphorus, but more importantly, the formation of iron-phosphorus compounds in an anaerobic environment (Sah and Mikkelson 1986) greatly reduces the potential for phosphorus to be leached from these soils.

CONCLUSIONS

The carbon/nitrogen and humic/fulvic ratios of these soils are typical of mature boreal forests that are slowly accumulating carbon because low soil temperatures limit decomposition. These soils also have a soil biota that is partially adapted to reduced soil aeration. Clearcut forest harvesting and soil compaction by skidders changes the soil environment and accelerates aerobic and anaerobic decomposition relative to the input of soil carbon. Higher soil temperatures following harvesting probably accounts for the increase in aerobic decomposition. A combination of increased soil wetness following harvesting and reduced air-filled porosity with increasing levels of soil compaction cause anaerobic decomposition to increase. While these soils are only occasionally fully anaerobic, the partial anaerobiosis is probably sufficient to adversely affect the growth of plants, and the availability and mobility of nutrients such as nitrogen and phosphorus. Whether these soils are aerobic or anaerobic depends on the dynamic balance among soil organic matter, air-filled porosity, soil wetness, soil temperature, and the amount of precipitation versus transpiration. Periodic and annual increases in either soil temperature or precipitation will cause these soils to become more anaerobic. Whether increased decomposition will ultimately lead to a decrease in soil organic matter relative to the effects that other types of natural disturbances have on decomposition is uncertain. Obviously, the reestablishment of a vegetation cover and decompaction of these soils will slow the anaerobic decomposition process and improve the soil environment for the growth of trees and other vegetation.

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Table 1. Soil characteristics at four west-central Alberta sites

Site	Soil	pH (1:1)	Water content $m^3 m^{-3}$	Water potential kPa	Texture	Organic carbon $m^3 m^{-3}$	C/N ratio
Robb	Orthic/Gleyed Gray Luvisol	5.9	0.26	-10.0	Loam	0.0131	19.6
Lynx Creek	Orthic Gray Luvisol	5.5	0.32	-4.5	Loam	0.0177	19.3
Elk River	Brunisolic Gray Luvisol	5.5	0.23	-50.0	Sandy Loam	0.0132	17.5
Pinto Creek	Orthic/Gleyed Gray Luvisol	5.0	0.34	-2.5	Loam	0.0169	20.1

Table 2. Effects of skidder traffic on soil bulk density at an average depth of 5 cm

	Bulk density			
	Control	3 cycles	7 cycles	12 cycles
Site		Mg m^{-3}		
Robb	1.13a[z]	1.30b	1.31b	1.28b
Lynx Creek	1.19a	1.27b	1.39b	1.37b
Elk River-CAT	1.16a	1.16a	1.21a	1.14a
Pinto Creek	1.09a	1.30b	1.30b	1.31b

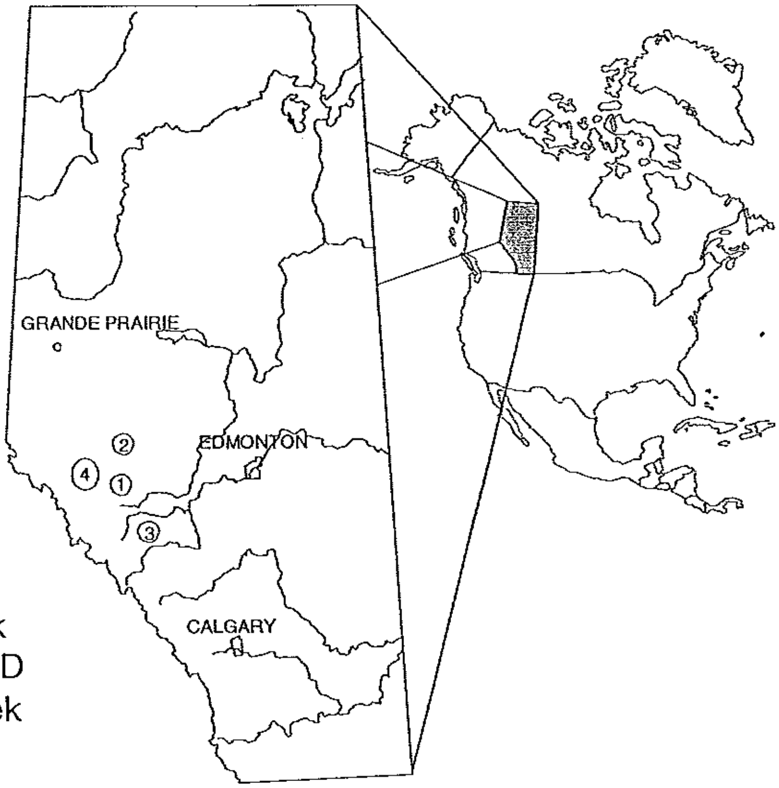
[z] – Different letters indicate significant difference between treatments at $P < 0.05$.

Table 3. ORP in soil before and after incubation under flooded conditions

	ORP			
	Initial 1995	After incubation 1995	Initial 1996	After incubation 1996
Treatment		------------------------------ mv	-------------------------	
Control	712.2	487.7	652.5	330.8
3 cycles	709.6	490.7	647.8	346.8
7 cycles	700.5	483.3	631.5	338.2
12 cycles	719.7	485.2	642.2	336.8

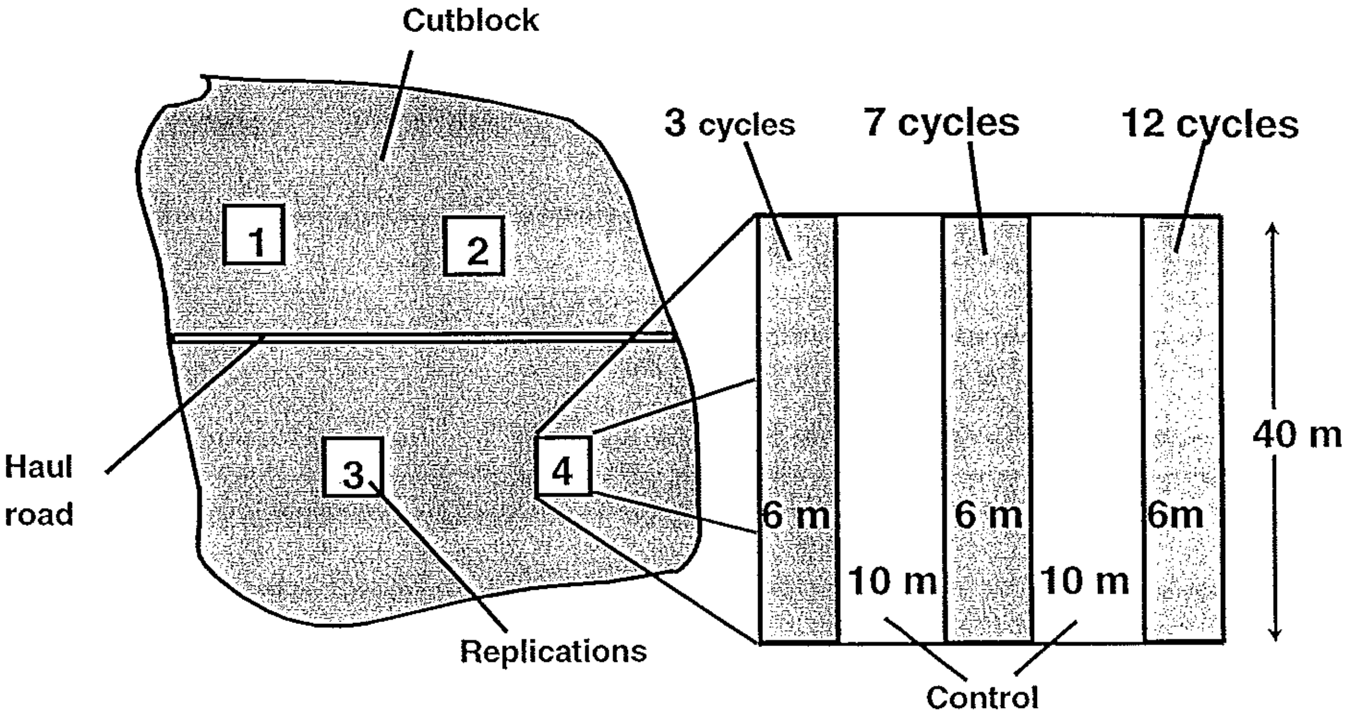
List of Figures

Alberta



Research sites:

1 - Robb
2 - Lynx Creek
3 - Elk River-JD
4 - Pinto Creek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Haul road
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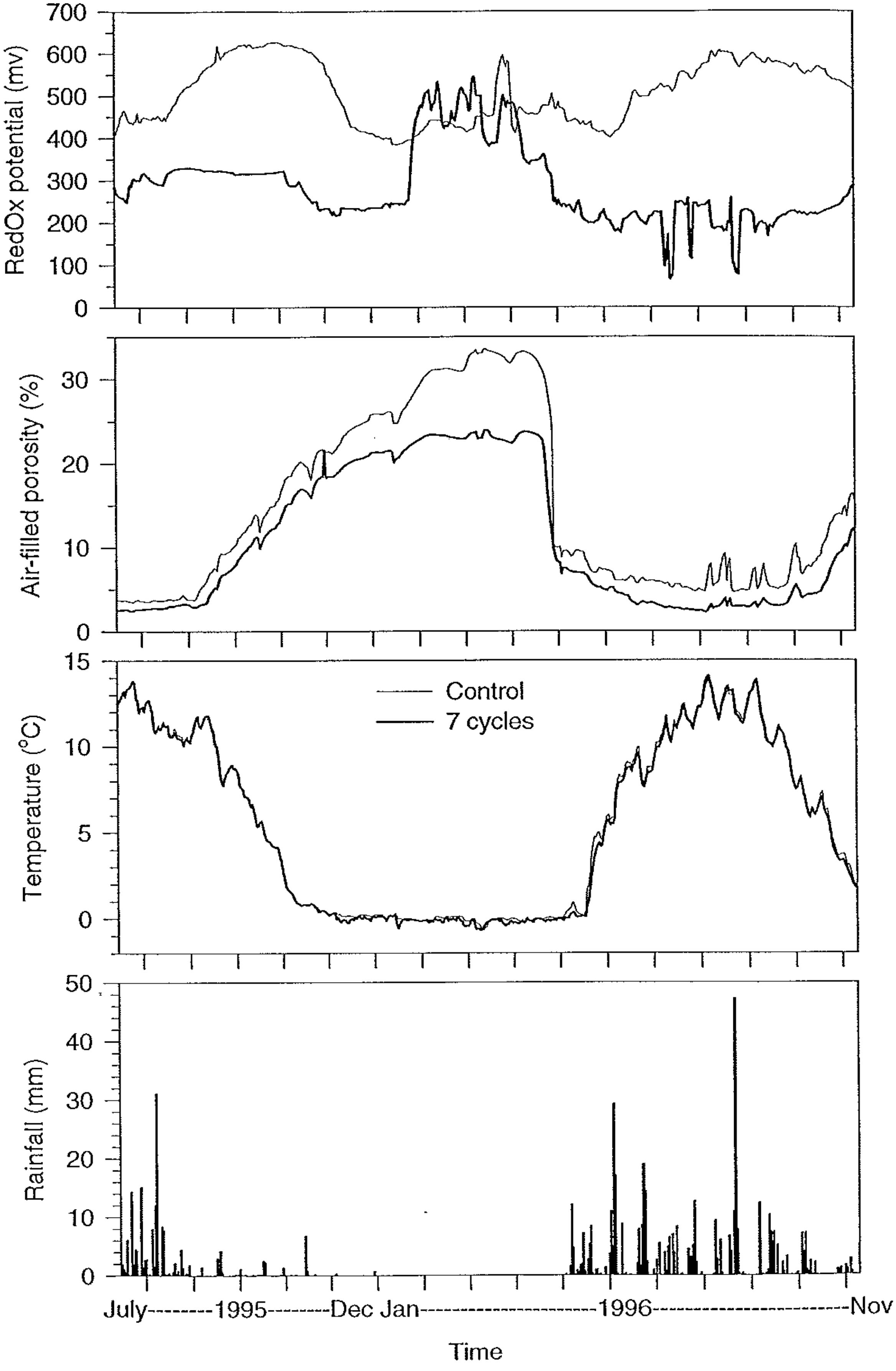
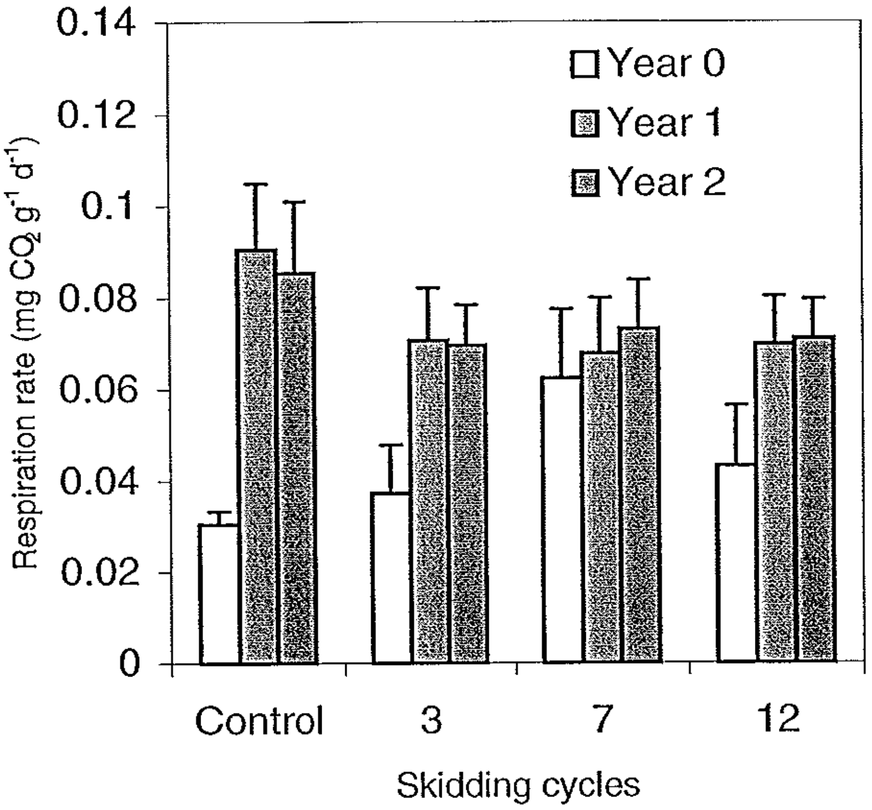
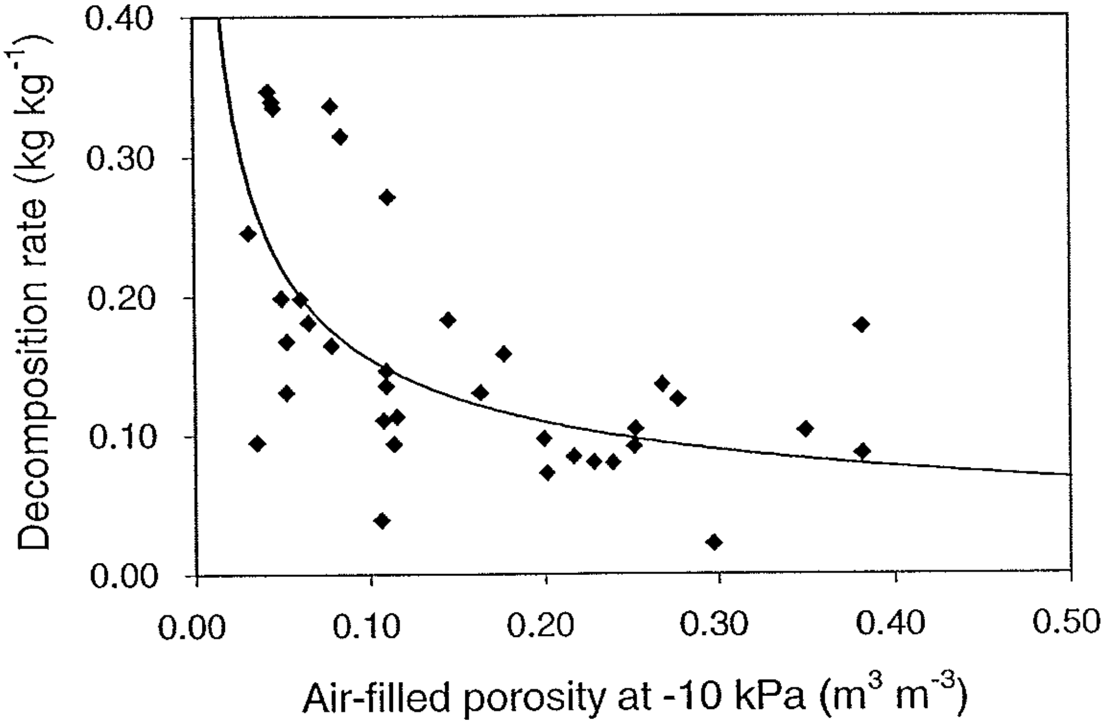
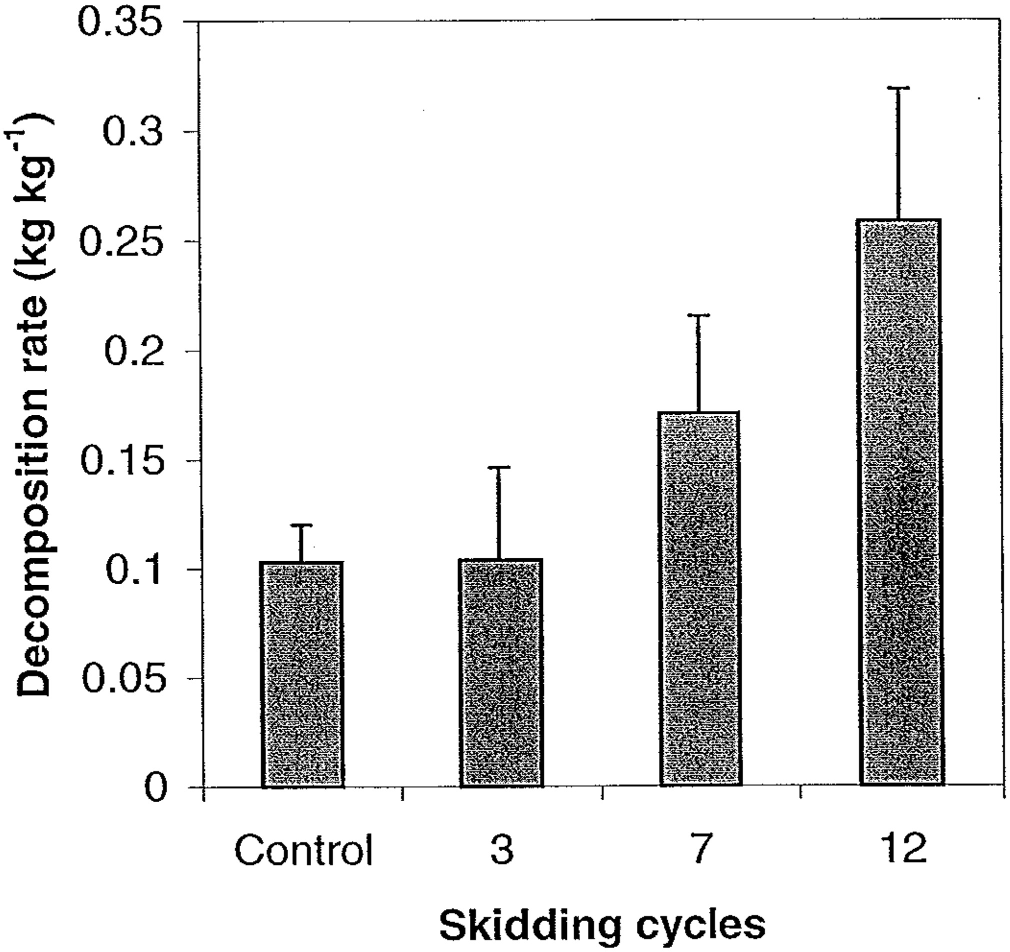
2
3
4
Replications
3 cycles
7 cycles
12 cycles
6 m
6 m
6m
10 m
10 m
40 m
Control

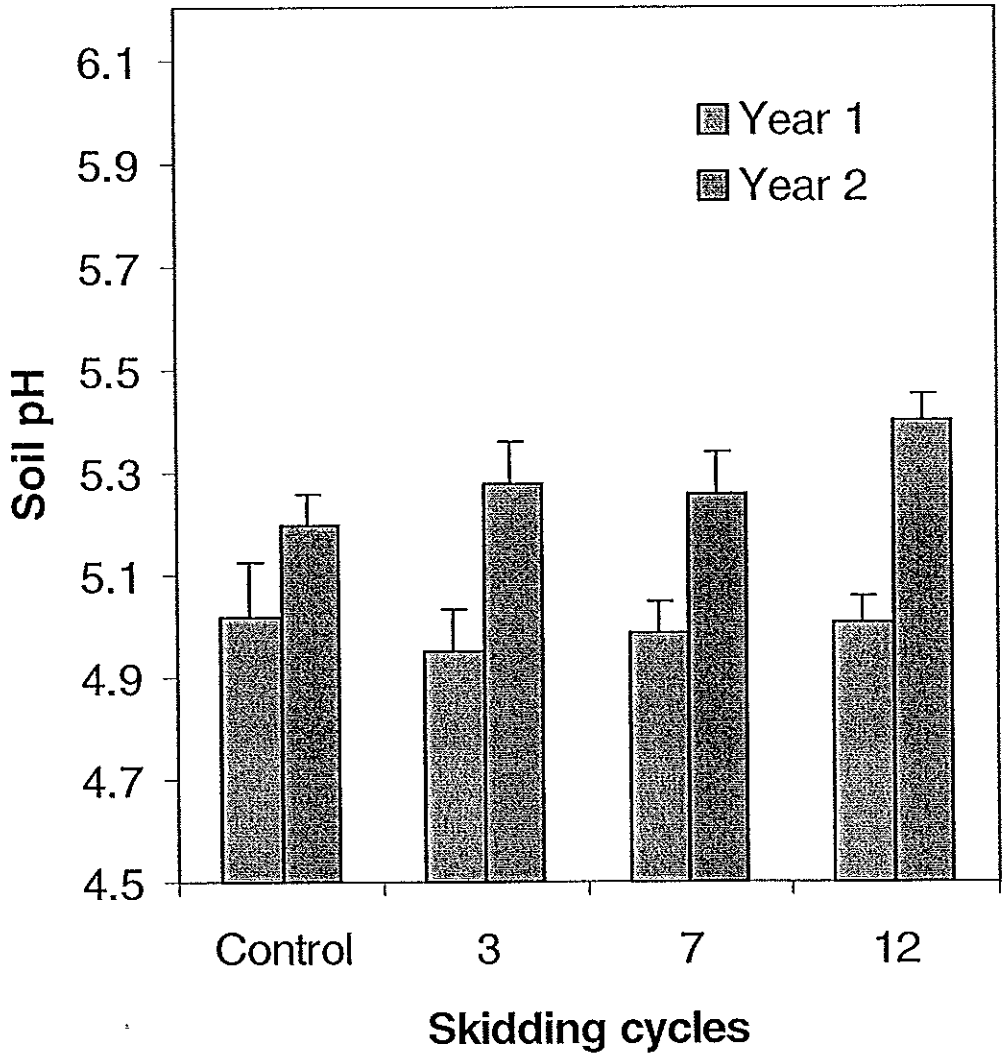


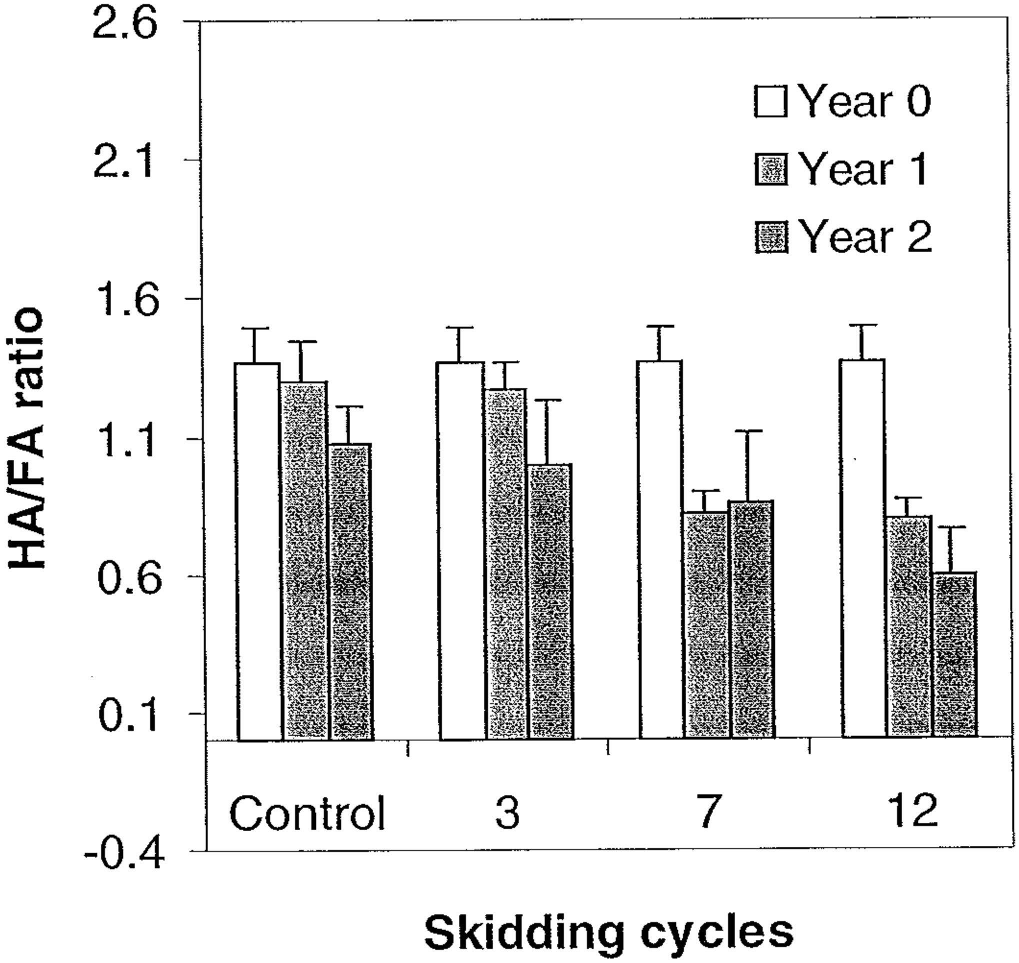
700
600
500
400
300
200
100
0
RedOx potential (mv)
30
20
10
0
Air-filled porosity (%)
15
10
5
0
Temperature (°C)
Control
7 cycles
50
40
30
20
10
0
Rainfall (mm)
July--------1995--------Dec Jan-----------------------1996-------------------------Nov
Time


0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Respiration rate (mg CO_2 g^{-1} d^{-1})
□ Year 0
▨ Year 1
▨ Year 2
Control
3
7
12
Skidding cycles


0.40
0.30
0.20
0.10
0.00
Decomposition rate (kg kg^{-1})
0.00
0.10
0.20
0.30
0.40
0.50
Air-filled porosity at -10 kPa (m^3 m^{-3})


0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Decomposition rate (kg kg-1)
Control
3
7
12
Skidding cycles


6.1
5.9
5.7
5.5
5.3
5.1
4.9
4.7
4.5
Soil pH
Year 1
Year 2
Control
3
7
12
Skidding cycles


2.6
2.1
1.6
1.1
0.6
0.1
-0.4
HA/FA ratio
Year 0
Year 1
Year 2
Control
3
7
12
Skidding cycles