Temporal trends in soil physical properties at a soil quality benchmark site in British Columbia, Canada

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Abstract

In 1990, a national soil quality monitoring program was started to address concerns that the quality of Canada's agricultural soils was declining. To determine the existence and extent of any decline, a network of 22 benchmark sites was established across Canada to represent the country's ten provinces and the main landforms in the most important agricultural regions. This paper reports the results of ten years of monitoring at the site in British Columbia, Canada's westernmost province. The British Columbia site (49°9'17" N latitude 121°53'46" W longitude), established in 1991, is located in the eastern part of the Lower Fraser Valley, approximately 100 km east of the city of Vancouver. It lies within the Lower Mainland Ecoregion and is located on poorly drained, medium textured fluvial soils belonging to the Pelly soil series and is classified as an Orthic Humic Gleysol (Umbric Gleysol). Degradation of the soil by compaction is a major concern on these lowland soils. The terrain is level to very gently sloping. The site is part of an ongoing dairy operation, consisting of silage corn grown in rotation with forage/pasture and peas. Sampling points were established at 25 m intervals on a square grid with eight north-south transects and ten points on each transect. Soil samples were collected in 1991, 1996 and 2001 as follows: at all 80 grid points for the Ap horizon, at 40 grid points for the BCg horizon, and at 10 grid points for the Cg horizon. Bulk density (BD) was determined at the same grid points at two depths (20 and 50 cm). Forty grid points were sampled annually from 1992 to 1998 and again in 2001 for saturated hydraulic conductivity (Ksat) at depths of 25 and 40 cm and for penetrometer resistance (PR) at four depths (10, 20, 30 and 40 cm). Also, Ksat at 60 cm and PR at 50 and 60 cm depths were measured at 10 grid points. Between 1991 and 1996 BD increased in the A horizons by 8% but decreased by 5.5% between 1996 and 2001. Bulk density at 50 cm remained unchanged. Ksat measured at 25 cm declined significantly between 1992 and 2001. Increases in BD and PR and decreases in Ksat for the A horizon indicated soil degradation by compaction. This compaction may be root limiting. However the decrease in BD between 1996 and 2001 and in PR between 1998 and 2001 indicated that management practices have alleviated some of this compaction.

Keywords: temporal change, soil quality, soil monitoring, soil physical properties, soil compaction, soil degradation

Introduction

In 1990, a national soil quality monitoring program was started to address concerns that the quality of Canada's agricultural soils was declining. Wang *et al*. (1994) summarized the world situation regarding benchmark systems for monitoring soil quality change. Baseline data sets, with which to evaluate soil quality changes were generally not available for many regions. To determine the existence and extent of any decline in soil quality, a network of 22 benchmark sites was established across Canada to represent the country's ten provinces and the main landforms in the most important agricultural regions. Seven criterias were developed to guide the selection of benchmark sites, with the objective of representing the main landforms in Canada's most important agricultural regions (Wang *et al*., 1994, 1995). Some soil properties were measured annually, while others were determined every five years. This network of sites would enable direct comparison of changes over time to a series of soil parameters and in relation to prevailing agricultural land use and management practices across Canada (Wang *et al*., 1994, 1995). The baseline data sets for soil quality would also provide reference data for validation of predictive models of various soil degradation processes (Wang *et al*., 1994) used for national assessments of the risks of soil degradation in Canadian agriculture (McRae *et al*., 2000).

The objective of this study was to report on the differences in physical soil properties over a ten years study period at a soil quality benchmark site in British Columbia, Canada. These physical properties are indicators of soil degradation by compaction. Differences in the chemical properties measured over the first five year period are reported elsewhere (Kenney *et al*., in review).

Materials and Methods

Site selection, location and description

The British Columbia site (49°9'17" N latitude 121°53'46" W longitude), established in 1991, is located in the eastern part of the Lower Fraser Valley, approximately 100 km east of the city of Vancouver. In keeping with the national objectives to represent important agricultural systems and site selection criteria, this site was chosen to: 1) represent the Lower Fraser Valley. The Lower Fraser Valley hosts some of the most productive farmland in Canada. 2) represent lowland soils (medium textured fluvial soils on level to very gently sloping terrain); 3) represent the dairy industry with corn (silage and table corn)-forage (hay and silage)/pasture rotation under conventional tillage of the 123 agricultural commodities for which statistics are reported, dairy products are by far the most economically important (B.C. Ministry Agriculture, Fisheries and Food, 1993). 4) occupy five hectares of a larger field (the monitored section is managed no differently than the rest of the field); 5) show potential for change in soil quality due to soil compaction; and 6) be close to a representative Environment Canada climatic station (Kenney *et al*., 1998).

The climate of the Lower Fraser Valley is dominated by maritime air masses and the passage of high and low pressure systems moving eastwards from the Pacific Ocean. Characteristically, this region has warm, rainy winters and relatively cool, dry summers. Temperatures are relatively uniform throughout the lowlands and have an annual average of about 10°C (Luttmerding, 1981). The Environment Canada climatic station at Chilliwack, B.C. is located approximately 3 km northwest from the site.

The soil consists of medium textured fluvial deposits with poor drainage. There may be occasional sand lenses at depth. Generally, the soil is stone free, but may contain the occasional pebble. The soil is classified according to the Canadian System of Soil Classification as an Orthic Humic Gleysol (Umbric Gleysol Soil Classification Working Group, 1998) belonging to the Pelly soil series (Luttmerding, 1981). The landscape is level to nearly level (slopes 0.5-1%).

The principal soil quality concern was soil compaction which is a major degradation problem on these lowland soils (DeVries, 1983). The principal soil physical properties determined were bulk density (BD), penetrometer resistance (PR), and saturated hydraulic conductivity (Ksat).

Site management

The benchmark site is part of a commercial dairy operation with conventional farming practices. Silage corn is grown in rotation with forage/pasture. A cash crop of peas is included in the rotation. Details of the farm management practices and crop sequence were described earlier (Kenney *et al*., 1998) and are hereby summarized. In 1991 the site was converted from pasture/forage rotation to silage corn. In 1992 the site was in "Jubilee processing (sweet table) corn". In the spring of 1993, a forage crop consisting of "Barlano perennial ryegrass" established. From 1994 until 1997 the site remained in forage and pasture. In 1998 one half of the site was in forage/pasture and the other half was seeded to silage corn. During 1999 the site was seeded to silage corn. In 2000 and 2001 peas were planted and fall- rye as a winter cover crop. In 2001, 25% of the site was planted to silage corn.

Field methods

An area, 200 m east-west by 250 m north-south, (5 ha) was selected for monitoring. Initial sampling for baseline characterization occurred in October 1991 after a crop of silage corn had been removed.

Sampling points were established at 25 m intervals on a square grid with eight north-south transects and ten points on each transect. Soil samples were collected in 1991, 1996 and 2001 as follows: At each of the 80 grid point locations, a loose bulk sample of Ap horizon (Ap1 and Ap2 horizons combined) was collected. In addition, loose samples of the BCg horizon (50-60 cm) were collected at every fourth grid point (20 samples in total) along with a parent material sample at every eighth grid point (Cg horizon at 90-110 cm for 10 samples in total). Bulk density samples were taken using a hand-held core sampler (with cores 5 cm diameter by 2 cm depth) for all of the Ap2 horizons at 20 cm depth and for the 20 subsoil (BCg) samples at 50 cm depth. Oven-dried bulk density values were determined for the core samples according to procedure 84-29-3 in Sheldrick (1984). In addition to sampling, thickness of the total Ap (Ap1 and Ap2) horizon was recorded in 1991 and again in 2001. The grid sampling was repeated in October 1996 with the Ap2 sampled from 20-30 cm and again in October 2001.

In addition to the baseline sampling (October 1991, 1996 and 2001) for selected chemical and physical properties, the benchmark site was sampled annually (starting in 1992 until 1998 and again in 2001) at 40 of the original 80 grid point locations (4 of the 8 N-S transects were selected; and 10 sites per transect sampled). In 1993 bulk density (BD) was also sampled at these grid points (40 BD at 20 cm, 10 BD at 50 cm).

Saturated hydraulic conductivity (Ksat) was measured by the Guelph Permeameter (Soil Moisture Equipment Corp. Model 2800), using a 10 cm head, at two depths (25 and 40 cm) for 40 grid points and at 60 cm for 10 of the grid point locations (per procedure 56.2.1 in Reynolds (1993). Results were expressed in m d^{-1}. Ksat measurements were performed once a year during the summer.

Resistance to penetration was measured for six depths (0-10, 10-20, 20-30, 30-40, 40-50, and 50-60 cm) using a Centre-Cone Penetrometer (Star Quality Samplers, 1990). Measurements were made at 40 grid points for the upper four depths and at 10 points for the lower two depths. The result for each sampling point and depth was the average of five readings expressed in MPa. Small soil samples, one from each depth at each sampling point, were collected in moisture tins for gravimetric determination of soil moisture. These measurements were done twice a year: once in early summer and again in the fall.

For sampling yields 20 sampling points were selected by stratified random means. At the selected sites, for forage grass a 0.25 m^2 grid was placed on the ground and all the grass inside the grid was cut using a hand held sickle, at approximately the same height as the forage harvester would cut the plants. Samples were collected into perforated plastic or cotton bags. Fresh weights were obtained prior to drying in the forage dryer set at 60^{o}C. After 96 hours the samples were removed and the dry matter weight obtained. In August 1993,May and July of 1994-98 the grass was sampled just prior to harvesting by the producer. In 1998, the corn was sampled at 10 sample points. Each sample site had one metre length of corn stalks removed and total fresh weight obtained. For each sample site, all the stalks were then chipped, mixed and two subsamples taken to determine dry weight. For years when it was not feasible to sample the crop yield, farm gate yields were obtained.

Statistical methods

For the variable thickness of Ap horizon a paired t-Test was performed for the two years of data (1991 and 2001).

Saturated hydraulic conductivity (Ksat) data were transformed to logarithms to stabilize the variance. Prior to the ANOVA, the Ksat data were trimmed by deleting the 10% largest and 10% smallest values in each year at 25 cm depth and the 5% largest and 5% smallest values at 40 and 60 cm depths, to eliminate outliers (Mosteller and Tukey, 1977).

To test for year effects, a one way analysis of variance was used for each of the other variables. The Fisher's Least-Significant-Difference (LSD) pairwise comparison test was used to determine which means differed from one another. SYSTAT was used for the statistical analysis (Wilkinson, 1997) and significance level was $P< 0.05$.

Penetrometer resistance is influenced by soil moisture. Fawcett (1978) found that there was a linear relationship between the logarithm of available water and the force required for cone penetration. This linear relationship between soil moisture and penetrometer resistance was demonstrated to occur at the benchmark site. To adjust for the effect of soil moisture, the logarithm of the soil moisture content was used as a covariate in analyzing of penetrometer data.

Means of the transformed variables were back-transformed for presentation. Means reported for penetrometer resistance have been adjusted to constant soil moisture.

Results and Discussion

There was a significant increase in the thickness of the Ap horizons between 1991 and 2001 (Table 1). This likely reflects the incorporation of manures into the A horizons and the deep ploughing that occurred periodically at the site as part of the crop rotation cycle.

Table 1 Changes in selected physical properties of soil (1991-2001) at a soil quality benchmark site in British Columbia, Canada.

Depth			20 cm		50 cm	
Variable	Total Thickness Ap Horizons (cm)		Bulk Density ($Mg\ m^{-3}$)		Bulk Density ($Mg\ m^{-3}$)	
Year	Mean	SE	Mean	SE	Mean	SE
1991	34.49 a^{-z}	0.37	1259 a	12	1422 a	17
1993			1241 a	17	1411 a	25
1996			1358 b	12	1427 a	17
2001	36.6 b	0.37	1290 a	12	1401 a	17

-z Means within the same column followed by the same letter are not significantly different at $P < 0.05$ using Fisher's LSD pairwise comparison test.

There were significant changes in the bulk density (BD) of the Ap2 horizon at 20 cm during the study period (Table 1). Between 1993 and 1996 there was a significant increase (9%) in BD. The 1993 sampling occurred prior to grazing. During the period between the 1993 and 1996 sampling, the site was used for rotational grazing after the first yearly cut of grass silage. Bezkorowajnyj *et al*. (1993) report that mature cattle can exert a static ground pressure of 170 kPa on the hoof-bearing area, whereas, Scholefield *et al*. (1985) measured the maximum vertical pressure from a walking dairy cow of 530 kg to be 300 kPa. Most researchers report the increases in BD resulting from grazing to be greatest in the surface 10 cm (Scholefield *et al*., 1985; Ferrero, 1991 and Mapfumo *et al*., 1999).

In 2001, there was a significant reduction in BD at 20 cm (Table 1). During the period from 1999 to 2001 the site ceased to be used for grazing. Prior to planting peas in 2000 and 2001 there had been subsoiling to a depth of 40 cm at the site. The field was also ploughed to depth of 18 cm. Manure and crop residues were observed to be incorporated into the soil to depths of 30-35 cm. The soil management practices have significantly reduced the bulk density in the Ap2 horizon at 20 cm.

There was no significant change in BD of the BCg horizon at 50 cm during the study period (Table 1). Subsoils tend not to be affected by grazing pressures (Ferrero, 1991; Bezkorowajnyj *et al*., 1993).

Saturated hydraulic conductivity (Ksat) at all three depths studied showed changes from year to year (Table 2) and overall declined significantly between 1992 and 2001 for the 25 cm and 40 cm depths. The decrease in Ksat at 25 cm between 1992 and 1998 is likely linked to the increase in BD observed at 20 cm. Ksat increased at all depths in 1995 and 1996 (Table 2). During those summers the soil was dry and soil cracks were observed, sometimes extending to depths of 40 cm. Although obvious surface cracking was avoided when making measurements, it is possible that the soil was not completely saturated leading to measurement error. In spite of the decrease in bulk density, the Ksat at 25 cm continued to decline from 1998 to 2001. Ksat at 40 cm also fluctuated from year to year with the general trend to decrease. It appears that BD at 50 cm is not influencing the Ksat at 40 cm. The only significant difference observed in Ksat at 60 cm depth was the increase in years 1995 and 1996, likely due to drier soil conditions than in other years.

Table 2 Estimated saturated hydraulic conductivity -z of soil (1992-1998 and 2001) at a soil quality benchmark site in British Columbia, Canada.

Depth	25 cm	40 cm	60 cm
Year	Ksat (m d^{-1})	Ksat (m d^{-1})	Ksat (m d^{-1})
1992	0.163 a -y	0.034 a	0.010 a
1993	0.048 b	0.014 ad	0.014 a
1994	0.055 b	0.041 a	0.010 a
1995	0.197 a	0.173 b	0.074 b
1996	0.139 a	0.067 a	0.086 b
1997	0.029 b	0.010 cd	0.005 a
1998	0.055 b	0.022 acd	0.007 a
2001	0.025 b	0.007 c	0.012 a

-z Estimates back-transformed from logarithms.
-y Means within the same column followed by the same letter are not significantly different at $P < 0.05$ using Fisher's LSD pairwise comparison test.

Soil penetrometer resistance (PR) at all six depths showed changes from year to year and generally increased significantly between 1992 and 1998 (Tables 3 and 4). For most depths there was a significant decrease in PR between1998 and 2001. The period of increase in PR between 1994 and 1998 coincided with the time period that there was grazing included in the crop rotation, suggesting that compaction has occurred at all depths regardless of the season. The reduction in PR coincided with the rotation from pasture into corn and peas. The management practice of deep ploughing and subsoiling seems to have alleviated the compaction which occurred under grazing.

The data in Tables 3 and 4 seem to suggest that there is seasonal variation in the resistance. The correction for soil moisture content appears not to have been entirely effective. On most sampling dates soil moisture content was close to field capacity. In the summers of 1995 and 1996 soil moisture was on average 39% below field capacity. In order to be a useful diagnostic tool, the true relationship between water content and soil resistance for a given soil needs to be better defined.

Carter (1988) indicated that root growth begins to be reduced once the soil penetration resistance exceeds 1.5 MPa. Resistance values greater than 2 MPa are

Table 3 Estimated penetration resistance (adjusted for soil moisture) of soil in summer (1992-1998 and 2001) at a soil quality benchmark site in British Columbia, Canada.

Depth	0-10 cm	10-20 cm	20-30 cm	30-40 cm	40-50 cm	50-60 cm
Year	MPa	MPa	MPa	MPa	MPa	MPa
1992	0.76 a -z	1.10 a	1.32 a	2.08 a	1.54 a	1.38 a
1993	1.22 b	2.18 b	2.18 b	2.46 b	1.64 a	1.92 a
1994	1.70 c	2.58 c	2.77 c	3.13 c	1.16 a	1.41 a
1995	6.60 d	8.00d	6.81 d	6.79 d	5.77 b	6.90 b
1996	8.06 e	8.66 e	6.69 d	7.71 e	7.19 c	8.01 c
1997	1.30 bcf	2.11 bf	2.22 b	2.33 ab	2.88 d	2.97 d
1998	1.10 ab	2.05 bg	2.75 b	3.10 c	3.14 de	3.01 d
2001	0.52 a	0.96 a	1.08 a	1.69 g	1.98 a	1.89 a

-z Means within the same column followed by the same letter are not significantly different at $P < 0.05$ using Fisher's LSD pairwise comparison test.

Table 4 Estimated penetration resistance(adjusted for soil moisture) of soil in fall (1992-1998 and 2001) at a soil quality benchmark site in British Columbia, Canada.

Depth	0-10 cm	10-20 cm	20-30 cm	30-40 cm	40-50 cm	50-60 cm
Year	MPa	MPa	MPa	MPa	MPa	MPa
1992	1.37 a -z	1.94 a	1.94 a	2.98 a	2.30 a	2.22 a
1993	0.80 b	1.57 b	1.79 ae	2.15 b	1.37 b	1.53 b
1994	1.56 a	3.14 c	3.91 b	5.59 c	1.99 ad	2.99 c
1995	1.26 a	1.75 ab	2.25 ac	2.28 bd	1.42 b	1.93 ab
1996	1.33a	2.13 a	2.49 c	2.45 d	1.48 b	1.77 ab
1997	1.51 a	2.00 a	2.26 ac	2.35 bd	2.81 a	2.79 ac
1998	2.11 c	3.78 d	4.97 d	6.64 e	3.90 c	5.52 d
2001	0.76 b	2.04 a	2.41 c	2.54 d	2.54 a	2.29 a

-z Means within the same column followed by the same letter are not significantly different at $P < 0.05$ using Fisher's LSD pairwise comparison test.

regarded as limiting root growth (Mapfumo *et al*., 1999), although Carter (1988) considers a broader range of resistence (2.1-2.5 MPa) to be root restricting. Using the upper end of Carter's range as the threshold value, the resistance encountered by roots became limiting at 20 cm by the summer of 1994.

Comparing the yields for the first cut of forage from the newly established pasture in 1993 to the yield obtained in 1995 indicated no significant decline (Table 5). The yields obtained for the second cut in July of 1997 was significantly lower than those recorded for the previous two years. This decline in yield may be related more to the age of the stand and also the fact that the sampling for yield in 1997 occurred two weeks prior to the sampling dates in 1995 and 1996.

Table 5 Measured forage yields at B.C. benchmark site for selected years.

	Forage yield 1st cut t ha^{-1}		Forage yield 2nd cut t ha^{-1}	
Year	mean	SE	mean	SE
1993	6.8 a -z	0.29		
1995	6.2 a	0.29	2.3 a	0.13
1996			2.3 a	0.15
1997			1.8 b	0.11

-z Means within the same column followed by the same letter are not significantly different at P < 0.05 using Fisher's LSD pairwise comparison test.

Comparing the yields of corn reported for the benchmark site to those of the regional averages (Table 6) indicated similar yields. The planting dates at the benchmark site were later than those of the regional average, which likely accounted for some of the decrease in yield. Also, during the harvest period in 1991, there was a severe wind storm which resulted in crop damage at the benchmark site. The corn yields obtained at the benchmark site are consistent from year to year. Both grass and corn yields were not adversely affected by the changes in soil physical properties.

Table 6 Comparison corn yields at B.C. benchmark site and Chilliwack regional average.

	Corn yield regional average -z			Corn yield at benchmark site				
Year	Plant Date	Harvest Date	Silage Yield t ha^{-1}	Plant Date	Harvest Date	Silage Yield Reported by Farmer t ha^{-1}	Silage Yield Measured t ha^{-1}	% Benchmark Site Yield to Regional Average
1991	May 4	Oct 4	81.2	May 11	Oct 15-19	56		69
1998	May 12	Sept 9	86.8	June 2	Oct 8	56-67	68.9	79
2001	May 10	Sept 22	70.4	June 25	Oct 29	56-67		80

-z After Hunt and Bittman 1991, Hunt *et al.,* 1999, 2002

Conclusions

Measurements of bulk density, saturated hydraulic conductivity, and penetrometer resistance indicated that soil compaction has occurred in the Ap2 horizon during the time period 1991 to 1998. Bulk density measured at 20 cm had increased significantly and the saturated hydraulic conductivity measured at 25 cm had declined significantly during 1992-1998. The bulk density and penetrometer resistance decreased between 1998 and 2001. At 50 cm there was no significant change in the bulk density. The yield data suggests that compaction did not adversely affect yield. Management practices as part of the crop rotation appear to have alleviated the compaction that coincided with the grazing rotation.

Acknowledgments

The authors gratefully acknowledge the Prinse families: Mr. A. Prinse and Mr. J. Prinse for their on-going cooperation and support and thank them for putting up with the occasional inconveniences. The authors gratefully acknowledge L. van Vliet for assistance with SYSTAT and manuscript review.

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