Assessing the Carbon Content of the AESA Benchmark Sites from 1998 to 2004

Prepared for:

**AESA Soil Quality Monitoring Program,
Alberta Agriculture, Food and Rural Development
Conservation and Development Branch**

Prepared by:

**Doug Keyes, M.Sc., P.Ag.
Pro Soil Investigations Inc.**

March, 2005

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

The Alberta Environmentally Sustainable Agriculture Program (AESA) Soil Quality Resource Monitoring Program has provided a data set containing soil organic carbon (OC) values and associated characteristics. These have been used to assess both the total amount, and changes in soil OC at these sites. The program consists of 42 sites distributed throughout the province and covering the major agricultural regions. Each site is intended to represent the ecodistrict where it is located. At each site, upper, mid and lower slope positions were sampled to evaluate the influence of topography on soil. The sites have been monitored since 1998. This monitoring included yield measurements and annual analysis of surface soil. These soil test results, combined with the total soil profile data from an initial pedological investigation, provide a unique opportunity to examine soil OC under a broad range of soils, climate and management practices.

The average carbon content of the sites, integrating the seven annual sets of analyses with the initial analysis, was 16.6 kg m^{-2} (166 t ha^{-1}), but ranged from 8.3 kg m^{-2} (83 t ha^{-1}) in the Mixed Grassland ecoregion to 25.1 kg m^{-2} (251 t ha^{-1}) in the Peace Lowlands. There was no significant difference between slope positions although, for most ecoregions, there was a trend toward more OC at the lower slopes and less OC at the upper slope positions. The benchmark soils were compared to soil profiles from the Agricultural Regions of Alberta Soil Inventory Database (AGRASID) database. The difference between the benchmark values and the associated AGRASID values varied considerably, however, on average there was more OC in the surface metre of the benchmarks soils. This was primarily due to higher OC concentrations below the A horizon.

The seven years that this program has been in operation is a short time relative to the time scale of soil organic matter turnover, thus significant changes in OC were not necessarily expected. However, the results indicated a trend toward increasing OC within all ecoregions and slope positions, except for the upper slopes of the Aspen Parkland and Boreal Transition ecoregions. An averaged increase of 0.88 t ha^{-1} of soil OC was observed. This was after 12 soil profiles considered to be non-representative (because of extremely high rates of OC change) were eliminated from the total of 126 profiles (3 slope positions X 42 sites). The greatest increases appeared in the southern grassland regions and the Peace region. Although these trends were not statistically significant, there were a few significant differences in OC between years. These rates of increase are greater than would be expected based on other research studies in western Canada, or on the results of OC modeling. The reasons for the apparent changes could not be established based on the available information for these sites. Tillage and cropping practices did not appear to be a factor. There was some indication that increases in soil carbon were associated with drier weather conditions.

ACKNOWLEDGEMENTS

I would like to thank Jason Cathcart and Tom Goddard of AAFRD, Conservation and Development Branch for their help in formulating approaches to analyzing and evaluating the large quantity of data the Soil Quality Monitoring Program has amassed. I would also like to thank Jody Heinz for preparing data files, and all of the AESA staff involved in the project for their diligence and dedication in the field work to ensure the best possible data quality.

1.0 Introduction

The Alberta Soil Quality Monitoring Program was initiated to provide baseline soil information, monitor changes in soil quality, evaluate landscape effects on soil quality, and to provide data for validating simulation models (Cannon, 2002). Soil organic matter is a critical component of soil quality because it benefits plant growth by increasing the available water holding capacity, improving fertility and promoting soil aggregation. Organic matter contains approximately 56% organic carbon (OC) and is therefore a potential source or sink for atmospheric carbon dioxide. Carbon sequestration is the result of OC accumulation that occurs when decomposition rates are less than the accumulation rate; conversely soil can lose carbon if losses from decomposition exceed the amount of carbon added as plant residue.

Carbon dioxide emissions are a concern globally and soil management policies and practices that may affect soil carbon dynamics have been examined extensively in the both the USA (Eve et al. 2002) and Europe (Freibaur et al. 2004). In Canada, both the Agricultural Table and Sinks Table are examining agricultural lands in relation to greenhouse gas emissions. Soil simulation models are used to estimate changes in soil OC because they permit a rapid calculation of carbon change under various management and climate scenarios (McGill, 1996). This makes them potentially useful for predicting changes in OC content over large and diverse areas where it is not feasible to directly measure these changes because of the large number of combinations of soil and management practices. The reliability of any model depends on the variables it considers, and the extent to which it has been validated based on field measurements from the region where it is being applied. Smith et al. (1997) estimated changes in soil carbon in Alberta using the Century model. They concluded that agricultural soils in the province were loosing OC at an approximate rate of 0.07 t ha^{-1} yr^{-1}, compared to a nation-wide average loss of 0.04 t ha^{-1} yr^{-1} in 1990. The AESA Soil Quality Benchmark sites that were established across the province provide an opportunity to measure changes in soil OC over a period of years or decades. Thus, the data obtained should facilitate calibration and validation of these models.

Many factors influence soil OC dynamics including climate, topography and soil management. Soil zones, which vary in organic matter content from an average of approximately 4% in the Brown to 8% or more in the Black soil zone, are largely determined by climate. Climate affects plant productivity, and therefore residue inputs. It also affects decomposition rates, by influencing soil moisture and temperature conditions. Topography results in varying degrees of moisture redistribution within a field or landscape, which in turn also affects residue inputs and decomposition rates. At the extreme, upper slope positions are dry and eroded, and thus have relatively low productivity and low OC content. In contrast, lower slope positions, although they can be too wet for maximum economic yield, have relatively high inputs of plant residues. These areas are depositional in nature, and have a relatively slow decomposition rate owing to cooler and less well-aerated soils. Consequently these areas tend to be high in organic carbon. The AESA Soil Quality Benchmark sites span a broad range of climatic conditions. Each site consists of a lower, mid and upper slope position, with annual crop yield and soil data available for each position.

Soil and crop management influences both the rate of decomposition and the amount of residue added to the soil. Cultivation has generally resulted in a decline in soil organic matter in western Canada. As far back as 1939, measurements have been made between agricultural and native soils to determine changes due to cultivation; Brown et al. (1942) reported losses from 21% for Black soils to 29% for Gray soils. This is consistent with estimates by McGill et al. (1981) of 15% to 30% loss in organic matter for prairie soils of western Canada.

The effect of tillage on soil organic matter has been studied extensively, and reduced tillage has been found to increase the rate of carbon sequestration (Lang et al. 2003). Generally less tillage leads to slower microbial breakdown of residues because of less aeration and cooler soil temperatures. It may, however, take several years before a change in management practices influences soil OC and even longer before the soil approaches a new equilibrium concentration, though it is difficult to determine what the new OC content will be or how long it will take to reach this level (McGill et al. 1981).

Management practices that increase plant dry matter yield or otherwise increase the amount of crop residue going back into the soil can increase soil OC content. Yield can be increased, for example by improving moisture conservation in drier areas and/or by increasing rates of fertilizer application. Campbell et al. (2000) concluded that changing to perennial grasses would only increase soil OC if there were adequate moisture. Leaving more of the above ground residue (straw) on the field will increase organic matter inputs considerably and can also reduce soil organic matter loss due to erosion. Other practices that reduce the erodability of soil will also help retain organic matter, particularly on those areas of a field, such as upper slopes, that are most susceptible to erosion.

For the benchmark sites, management practices are only known for the length of the study (i.e. since 1998). This is a short time relative to the timeframe of soil organic matter turn-over, which is in the order of decades to hundreds of years. It is important to note that the Soil Quality Monitoring Program does not attempt to impose any particular management on the fields where the sites are located, but rather simply records the type of management utilized. Thus, the management practices can only be categorized based on the extent of tillage and the crop rotations employed at each site.

The purpose of this work was to calculate the total amount of OC contained in the soils at the benchmark sites, and to determine whether it has changed during the course of the study. To do this it was necessary to make several assumptions: for example, that all the soil OC is within the surface metre of soil. Further to this objective, an assessment was made to evaluate the degree to which the benchmark soils represent the soils in the area where they are located. This was to assess the extent to which changes observed at the sites can be generalized over broader areas. This report also considers the possible influences that climate/weather and management may have had on soil OC at these sites.

2.0 Methods

2.1 Soil monitoring program

The AESA Soil Quality Benchmark sites were selected within seven agricultural ecoregions of Alberta. Sites were selected to represent typical soils and typical farming practices in the province. The exact procedure used for selecting the sites is described in Cannon (2002). Table 1 lists the ecoregions and ecodistricts in the study and the labelling conventions used in this report. The sites bare the same identification number as the ecodistrict in which they are located, except for 1828 (dry land) and 2828 (irrigated) both of which are located in ecodistrict 828. For further information on these ecological zones and the basis for their delineation, refer to The National Ecological Framework for Canada (Ecological Stratification Working Group, 1995).

Table 1. Soil Quality Benchmark Sites

Ecoregion	Ecoregion Abbreviation	Number of Sites	Ecodistrict/Site Numbers
Aspen Parkland	**AP**	**9**	**727, 728, 730, 738,739,740, 743, 744, 746**
Boreal Transition	**BT**	**8**	**678, 680, 681, 684, 687, 688, 692, 703**
Fescue Grassland	**FG**	**2**	**798, 800**
Mixed Boreal	**MB**	**1**	**615**
Mixed Grassland	**MG**	**8**	**804, 806, 809, 812, 815,823, 1-828, 2-828**
Moist Mixed Grassland	**MM**	**5**	**769, 781, 786, 791, 793**
Peace Lowlands	**PL**	**9**	**586, 588, 590, 591, 592,593, 594, 595, 599 (598*-discontinued)**

At each of the benchmark sites, there were three sampling locations chosen to represent the upper, mid and lower slope positions along a transect within the field. Can-Ag Enterprises Ltd. conducted an initial, detailed pedological investigation at each location. This work was completed during 1998 and 1999, except for one site that was characterized in 2000. Soil samples were taken according to soil horizon at each location, and analyzed by Norwest Labs, Edmonton. (See Cannon, 2002 for further information on soil characterization and sampling methods.)

2.2 Calculation of soil organic carbon content

To meet the objectives of this work required that the OC data from the benchmark sites be presented on an area basis (m^2), rather than simply as a concentration (percentage). The general equation for calculating the amount of organic carbon is:

$$OC = OC\% \times Db \times T \div 10 \qquad \text{(Eq. 1)}$$

Where:

OC is the organic carbon content expressed in kg m^{-2}
OC% is the percent organic carbon, on a mass basis
Db is the soil bulk density, expressed in Mg m^{-3}
T is the thickness of the soil layer, expressed in cm

Sample Calculation using Eq. 1:

Given: 2.0% organic carbon
1.2 Mg m^{-3} bulk density
15-cm thick layer (e.g. 15 to 30 cm)

$$OC = 2.0\,\% \times 1.2 \text{ Mg m}^{-3} \times 15 \text{ cm} \div 10 = 3.6 \text{ kg m}^{-2}$$

2.2.1 Organic carbon to 100 cm

For the initial characterization, soils were sampled according to soil horizon, and therefore to variable depths. In some cases the maximum depth of sampling was less than 100 cm, whereas in others it exceeded 100 cm. In most cases the horizons were contiguous, but in some cases sections of the profile were missed, leaving gaps in the data.

To calculate the OC content on an area basis (i.e., kg m^{-2}, Eq. 1) required both the concentration (OC%) from lab analysis and the soil bulk density (Db). All of the horizons sampled were analyzed for OC but not all had a Db measurement. Bulk density was determined for most, but not all, A and B horizons and there were no density measurements made for any of the C horizons.

Where parts of the soil profile were missing from the data, an "X" horizon was assigned to span the depth from the bottom of the adjoining upper horizon to the top of the adjoining lower horizon. Density and OC% values were assigned to these "X" horizons based, in most cases, on the density and OC% of the underlying horizon. Note that averaging the horizons above and below the missing section would likely skew the results to a higher value because upper horizons typically contain considerably more OC than those beneath. There were 33 cases of missing (non-contiguous) horizons, totalling 329 cm or about 2.5 % of the total profile depths.

Organic carbon concentration needed to be estimated for three samples (horizons) that were obvious outliers. The first was site 791, lower slope, BC horizon that had a value of 1.84%, which is high relative to the overlying horizons so it was changed to 0.34%, the same as the overlying Bm horizon. Likewise, site 592, lower slope, Ahk horizon had a value of 9% which was changed to 5.4%, the same value as the overlying Ap. The third sample, site 688, upper slope, had a value considered too low for the Ap horizon (0.35%) so it was replaced with 5.27%, the value obtained for the mid-slope Ap horizon taken at the same site.

Bulk density values were assigned to horizons lacking Db measurements. For A and B horizons these values were based on the density of adjacent horizons; for the C horizons, a density of 1.60 Mg m^{-3} was assigned in most cases, although there were 22 cases where a value of 1.50 was used and three cases where 1.7 was more appropriate, based on known densities of adjacent horizons.

Standardizing the OC content to 100 cm required that profiles deeper than 100 cm were truncated, and that those shallower were extrapolated to 100 cm. The profile depth was extended by adding an X horizon (__ to 100 cm), and assigning it the same OC% and Db values as the overlying horizon. There were 7 of these profiles less than 100 cm deep (minimum depth of 80 cm) and 22 profiles that exceeded 100 cm (up to 110 or 120 cm). There were 95 profiles that needed the addition of an "X" horizon, bringing the average proportion of "X" horizons (interpolated or extrapolated) to 3.3%, or 3.3 cm per profile.

2.2.2 Organic carbon content of annual, fixed-depth samples

In addition to the initial samples that were taken, samples were also taken annually to shallower fixed depths, starting in the fall of 1998. In 1998 to 2000, samples were taken from the 0 to 15 cm depth increment; from 2001 to 2004, two increments, 0 to 15 and 15 to 30 cm, were taken each year. Note that annual sampling occurred at sites that had not yet undergone a pedological investigation as of the start of the experiment (i.e., sites were sampled in 1998, even if their pedological descriptions were not completed until 1999). Furthermore, there were no samples for the first year (1998) at sites 594, 599, 740 and 744, and site 2828 was not sampled until 2000. All samples taken were analyzed for OC%. Bulk density was determined on most of the 0 to 15 cm samples but not on the 15 to 30 cm samples.

Calculation of OC content was based on OC% and Db using Equation 1. This calculation was made for each slope position (sample locations) at each site for each year of the study. In those instances where Db values were missing, an estimate was made. For the 0 to 15 cm layer, the density value for the same location from the previous year (or other years) was used in place of the missing value. The 15 to 30 cm layer densities were estimated from the initial profile samples using horizons that included all or part of the 15 to 30 cm depth range; where more than one horizon intersected the 15 to 30 cm layer, a weighted average calculation was performed to determine the density of this layer.

2.2.3 Amalgamation of annual and initial profile results

To express total carbon to a standard depth of 100 cm for each year required amalgamating the annual data set with data from the initial profile samples. To do this it was necessary to assume that the OC content of the soil below the annual sampling depth had not changed. This is likely a valid assumption for the relatively short period of this study. Campbell et al. (2000), in studying the effects of tillage and crop rotation, found no change in OC below 15 cm despite significant changes at shallower depths.

The total profile OC for any given year was calculated by summing the OC for the annual sampling and the OC of the underlying soil, as determined from the initial pedological investigation. The overlapping of the horizon depths (from the initial samples) with the fixed depths (from the annual samples) was handled by calculating a new, weighted average value for each horizon in the profile. For near surface horizons, only results from the annual samples may have been needed, the amount of OC contributed to the new horizon value being proportional to the amount of intrusion of the fixed-depths into the horizon's depth range. For deeper soils, where the annual sample depth may have included only part of the horizon, the weighted average was calculated using the OC content and thickness of the initial horizon sample. Where the horizon did not include any of the annual sample depth, only the result for the initial, horizon sample was used. For these deeper horizons, therefore, the value stayed the same for each year.

Figure 1 illustrates the six different patterns of initial depths relative to the 15 and 30 cm depths employed at annual sampling. The form of the equation needed to calculate the profile total is the same for all profiles having the same pattern. Table 2 lists the profiles that corresponded to each pattern. Both the pattern and the total profile OC calculations were performed using Microsoft Excel™.

Once the OC content for the individual horizons were calculated, it was possible to not only determine the carbon content to a specific depth but also to extract OC (kg m^{-2}) data for any particular horizon. Organic carbon for surface horizons was extracted for comparison to total and fixed-depth OC results.

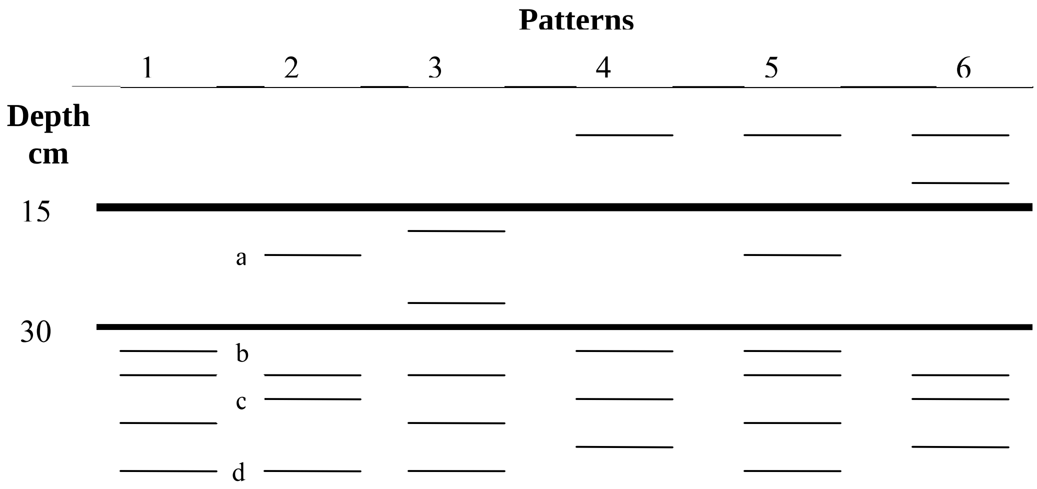


Figure 1. Calculation of OC content of soils to a depth of 100 cm based on the OC contents of the initial horizon samples and the annual fixed-depth samples. Heavy lines represent the fixed depths of 15 or 30 cm; the short vertical lines represent the horizon depths relative to these fixed depths. Each pattern involves a slightly different equation.

Example calculation for Pattern 2:

$$\text{New } a = OCn + [(a - 15)/15 \times OCm]$$
$$\text{New } b = [(30 - a)/15 \times OCm] + [(b-30)/(b-a) \times OCb`$$
$$\text{New } c = OCc$$
$$\text{New } d = OCd$$
$$\text{Profile } OC = \text{New } a + \text{New } b + \text{New } c + \text{New } d$$

Where:
New a is the annual estimate for the first horizon, (kg m^{-2})
OCn is the 0 to 15 cm increment organic carbon content, (kg m^{-2})
OCm is the 15 to 30 cm increment organic carbon content, (kg m^{-2})
a is the depth of the bottom of horizon a, (cm)
b is the depth to the bottom of horizon b, (cm)
OCb is the organic carbon from the initial sampling of horizon b, (kg $m\text{-}^{2}$)
etc.

Table 2. Patterns of soil horizons (ecoregion/site/slope) as described in Figure 1.

Pattern 1	Pattern 2	Pattern 3	Pattern 4	Pattern 5	Pattern 6
AP 727 L	AP 727 M	AP 738 U	AP 730 M	AP 728 U	AP 730 U
AP 728 L	AP 727 U	AP 739 U	AP 738 L	AP 743 U	BT 680 U
AP 728 M	AP 730 L	BT 681 L	AP 740 U	BT 687 U	MM 791 M
	AP 738 M	BT 681 M	AP 743 M	BT 692 M	PL 586 L
	AP 739 L	BT 681 U	AP 744 U	MG 806 L	
	AP 739 M	BT 692 L	AP 746 M	MG 806 M	
	AP 740 L	BT 703 M	BT 684 U	MG 806 U	
	AP 740 M	BT 703 U	BT 692 U	MG 809 M	
	AP 743 L	FG 798 L	MB 615 U	MG 809 U	
	AP 744 L	MB 615 L	MG 804 L	MG 815 L	
	AP 744 M	MM 786 L	MG 809 L	MG 815 M	
	AP 746 L	PL 588 L	MG 815 U	MG 2828 L	
	AP 746 U	PL 592 M	MG 1828 L	MG 2828 M	
	BT 678 L	PL 592 U	MG 1828 M	MG 2828 U	
	BT 678 M	PL 594 M	MG 1828 U	MM 769 M	
	BT 678 U		MM 769 U	MM 786 U	
	BT 680 L		MM 781 L	MM 791 U	
	BT 680 M		MM 781 M	PL 588 M	
	BT 684 L		MM 781 U	PL 590 L	
	BT 684 M		MM 791 L	PL 590 U	
	BT 687 L		MM 793 L	PL 599 M	
	BT 687 M		MM 793 M		
	BT 688 L		MM 793 U		
	BT 688 M		PL 586 M		
	BT 688 U		PL 586 U		
	BT 703 L		PL 588 U		
	FG 798 M		PL 590 M		
	FG 798 U		PL 591 L		
	FG 800 L		PL 591 U		
	FG 800 M		PL 593 L		
	FG 800 U		PL 593 M		
	MB 615 M		PL 593 U		
	MG 804 M		PL 595 L		
	MG 804 U		PL 595 U		
	MG 812 L		PL 599 L		
	MG 812 M				
	MG 812 U				
	MG 823 L				
	MG 823 M				
	MG 823 U				
	MM 769 L				
	MM 786 M				
	PL 591 M				
	PL 592 L				
	PL 594 L				
	PL 594 U				
	PL 595 M				
	PL 599 U				

L = Lower Slope
M = Mid Slope
U = Upper Slope

2.2.4 Calculation of organic carbon from the AGRASID soil profile data

Benchmark soils were classified to the soil series level as part of the initial investigation. The resulting soil names facilitated comparisons with soils selected from the Agricultural Regions of Alberta Soil Inventory Database (AGRASID) (2002) database. Within AGRASID, physical locations are associated with soil polygons, and a soil landscape model is assigned to each soil polygon. The landscape model has varying proportions of upper-slope, mid-slope, lower-slope and depressional areas; any particular soil polygon may contain from one to all of these landscape positions. In some cases, the benchmark soils were compared to the profile for the same AGRASID soil series; in other cases, they were compared to which ever soils were associated with the AGRASID polygon for the particular site location. In the latter cases, soils were matched according to landscape position, i.e. the benchmark upper slope soil compared to the AGRASID upper slope soil, etc., irrespective of soil name.

The calculation of soil OC to 100 cm for the AGRASID soils was performed according to the method described above for the benchmark soils (section 2.2.1). In nearly all cases the AGRASID profiles extended to a depth of at least 100 cm, and all soil horizons were contiguous. There was, therefore, no need to estimate values for parts of the profile.

Comparison of benchmark surface soils to AGRASID native soils was complicated by the thin upper horizons encountered for native soils. Surface soil OC for the AGRASID native soils was taken as the sum of OC for all the A horizon and any overlying organic horizon, provided the A horizon was a minimum of 5 cm deep. In a few cases, where the A horizon was shallower, the next deeper horizon was added until their depths summed to over 5 cm. This resulted in surface soil depths similar to the benchmark or the AGRASID agricultural soils, and thus facilitated comparisons of OC content of surface soils.

In making these comparisons, it was assumed that horizons were always identified in a similar manner for both the benchmark and AGRASID soils, regardless who characterized the profiles. Additionally, it was assumed that the methods used for determining OC concentrations gave equivalent results for all data compared.

2.2.5 Calculation of organic carbon across landscapes

Landscape variability is represented in this study by the upper, mid and lower slope locations at each site. Comparison of the landscape at benchmark sites to the corresponding AGRASID polygon required calculating an OC value for the site as a whole. For the benchmark sites this value was calculated using the OC content to 100 cm from the initial profile investigations; the AGRASID OC data was obtained for the soils of the associated polygon and slope position. Slope lengths (upper, mid and lower) were obtained from the AGRASID landscape model, and a total slope length was calculated by summing these three segments. Any length associated with depressional areas was ignored. The proportion of each segment (segment length / total slope length) was used to calculate weighted averages for the site using either the benchmark OC values or the AGRASID values.

Ideally, slope lengths specific to the benchmark sites (rather than those from AGRASID) would have been used to calculate the benchmark values, but this data was not available. The distances from the upper to the mid, and from the mid to lower slope sampling locations are available, and these give some indication of relative slope length, but there is no way to accurately determine the proportion of the slope represented by each sampling location based on these measurements. Simply assuming, for example, that the upper slope segment extends an equal distance up-slope as it does down-slope from the upper slope sampling location is not valid, and would have resulted in a much smaller proportions of the slope being designated mid-slope than was designated based on the landscape model.

A number of the AGRASID soil polygons did not have soils designated for all three slope positions as do the benchmark sites. Usually the upper or lower slope soil was lacking, affecting sites 595, 615, 678, 680, 681 and 684. In these instances, the mid slope soil was used in place of the upper or lower slope soils for the purpose of the calculation. There was no mid slope soil for the polygon associated with site 786 so an average of the upper and lower slope OC values was used.

2.2.6 Assessing the rate of change in OC

The rate of carbon change at each of the benchmark sites was calculated using a linear regression of carbon content over time (years). An analysis of variance was performed using Proc GLM in SAS ver. 9.1 (SAS 2004) to test the significance of OC differences between years. Differences were separated using the Tukey-Kramer pair-wise comparison, with the probability of making a Type-1 Error (α) set at 0.05.

2.2.7 Crop residue determination

Crop yields, total above-ground yield and grain yield (kg ha^{-1}), were determined every year for all slope positions at every site. A description of the harvest techniques employed at the benchmark sites can be found in Cannon (2002). The calculation of residue was based on the total above-ground yield to which root mass was added. Root mass was calculated by multiplying the above ground yield by a ratio of typical root mass to above-ground mass. Crops were classified into crop types. Each crop type has an associated ratio: annual cereal 0.6; annual oil seed, 0.3; annual legume, 0.25; annual cereal forage, 0.6; perennial forage, 2.0 and; summer fallow, 0.0 (Sauvé, 2000). The harvested portion (grain or forage) was then deducted. A further deduction was made if the farm records indicated that the straw had been baled.

2.2.8 The 2004 organic carbon data set

Although the 2004 data was included in the analysis summarized in this report, a note of caution must be indicated as to their integrity. Owing to an error made in the laboratory, OC values, although appearing reasonable based on previous years research, may not necessarily be representative of actual field values. Only through the incorporation of future years data will we know whether the values fit with the time series, although we will not, unfortunately, ever be able to indicate with 100% certainty whether the 2004 data are indeed correct.

3.0 Organic Carbon Content of Benchmark Soils

Soil organic carbon inventories are generally limited to the surface metre of soil. Jabbagy et al. (2000), however, in examining OC depth distribution, determined that on a global scale there is 56% more carbon to a depth of 3 metres than there is in the top metre. For the purpose of this study a depth of 1 metre was chosen because data were available for up to this depth. Furthermore, based on the AGRASID soils used in this study, there appeared to be very few soils in Alberta that have significant amounts of OC below 1 metre.

The amounts of OC in the top metre of soil, calculated according to the methods discussed previously, are summarized in Table 3. The first columns show the OC to 100 cm based on values from the initial profile characterization whereas the second pair of columns shows the results of amalgamating the initial and annual OC results, and averaged them across all years. The slightly higher OC content obtained when results were amalgamated should be the more accurate value because of the replication. These results demonstrate how OC tends to increase from the southern regions to more northern regions. The Peace Lowlands (PL) sites contained the most OC, at 25.1 kg m^{-2} (251 t ha^{-1}), followed by the Fescue Grasslands (FG), Aspen Parkland (AP), Mixed Boreal (MB), and Boreal Transition (BT). As expected, the Moist Mixed Grassland (MM) and the Mixed Grassland (MG) had the lowest OC levels, at 13.0 and 8.3 kg m^{-2} respectively.

Table 3. Mean OC content, by ecoregion, of soil profiles from the benchmark sites (surface 100 cm)

Ecoregion	Based on Initial Profile Characterization		Based on Initial and Annual Samples	
	kg m^{-2}	****t ha^{-1}***	***kg m^{-2}***	****t ha^{-1}***
AP (N=9)	17.1	171	19.0	190
BT (N=8)	11.7	117	14.2	142
FG (N= 2)	16.8	168	19.1	191
MB (N=1)	11.2	112	18.8	188
MG (N=8)	6.0	60	8.3	83
MM (N=5)	10.8	108	13.0	130
PL (N=9)	22.2	222	25.1	251
Mean (N=42)	14.1	141	16.6	166

*t ha^{-1} = 10 X kg m^{-2}

The average OC content for each ecoregion and slope position is shown in Figure 2. Organic carbon tended to increase moving down-slope to the lower slope position in all except the FG ecoregion, which had only two sites. This trend was not consistent across all sites however, and was not found to be statistically significant for any of the ecoregions explored in this project. Site-specific results (Figure 3) showed, for example, that site 781, within the MM ecoregion, had just over 20 kg OC m^{-2} in the top 100 cm of soil; much more than other sites within this ecoregion, but like the other sites, the OC was greater toward the lower slope position.

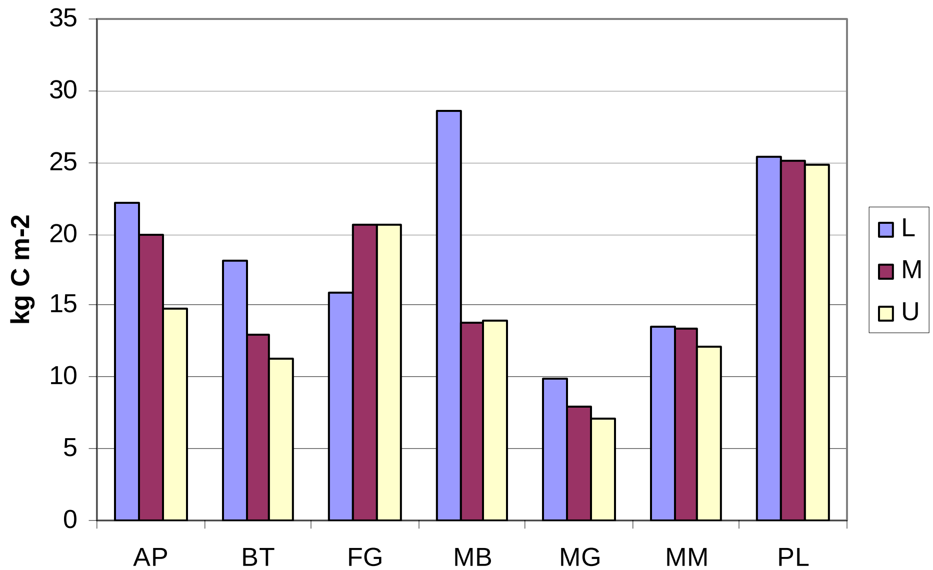


Figure 2. Average OC content by ecoregion and slope position. (L= lower slope; M=mid slope; U=upper slope); Aspen Parkland (AP) N=9; Boreal Transition (BT) N=8; Fescue Grassland (FG) N=2; Mixed Boreal (MB) N=1; Mixed Grassland (MG) N=8; Moist Mixed Grassland (MM) N=5; Peace Lowlands (PL) N=9.

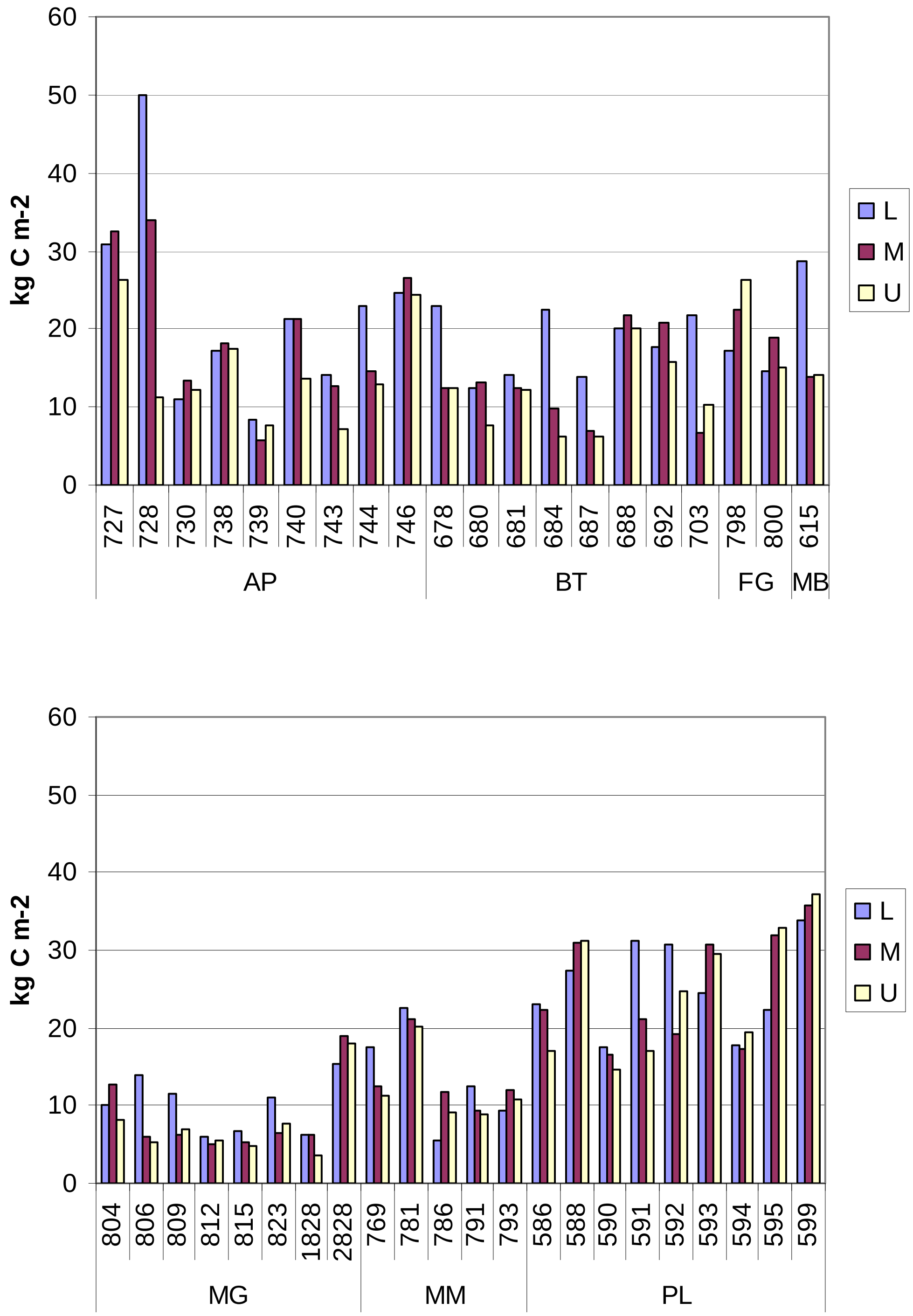


Figure 3. Organic carbon content to 100 cm by slope position for each site. (L= lower slope; M=mid slope; U=upper slope) Aspen Parkland (AP); Boreal Transition (BT); Fescue Grassland (FG); Mixed Boreal (MB); Mixed Grassland (MG); Moist Mixed Grassland (MM); Peace Lowlands (PL).

The results of this study indicated that not only does the total amount of OC differ from one ecoregion or ecodistrict to another, but so to does its depth distribution. Figure 4 illustrates the amount of OC in the surface 15 cm, the conventionally assumed depth of cultivation, versus the measured depth of the surface Ap horizon. In some areas, such as the Aspen Parkland (sites 727 and 728), the Ap is much deeper than 15 cm. In the Mixed, and Moist Mixed Grasslands, in addition to the Peace Lowlands, many sites have Ap horizons shallower than 15 cm. The results also show a tendency for shallower soils in the upper slopes, likely due to erosion and lower productivity. This trend was most apparent for the AP and BT ecoregions where the A horizon was the thickest. For example, site 728 had an Ap horizon less than 15 cm deep for the upper slope but nearly 40 cm deep for the lower slope.

The amount of OC in the surface horizon is of course related to the horizon thickness, but is also related to the carbon concentration (OC%) in the soil below 15 cm. The distribution of OC can be important from the perspective of carbon sequestration because OC nearer the surface tends to be biologically and chemically more active (Jabbagy et al. 2004).

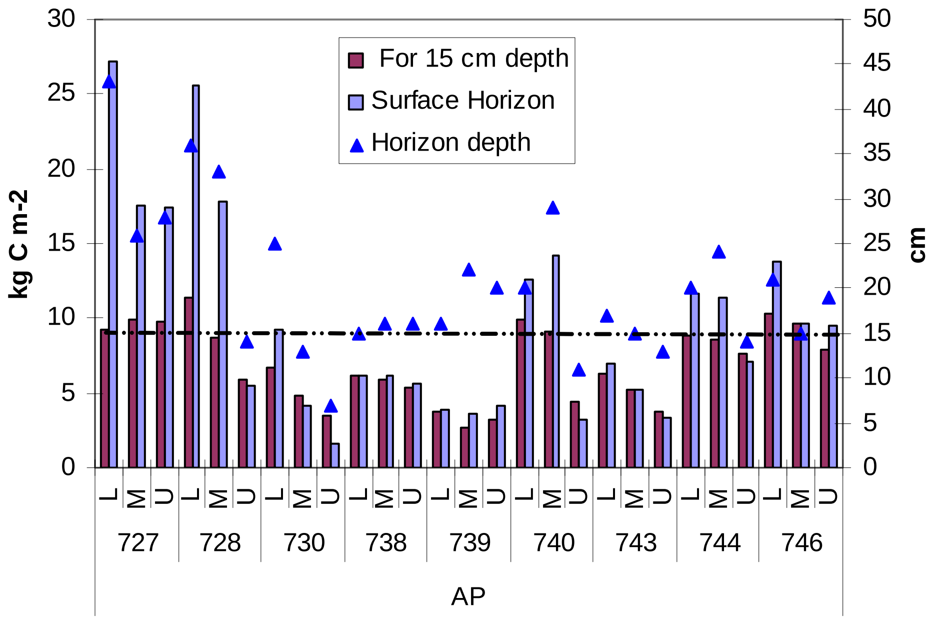
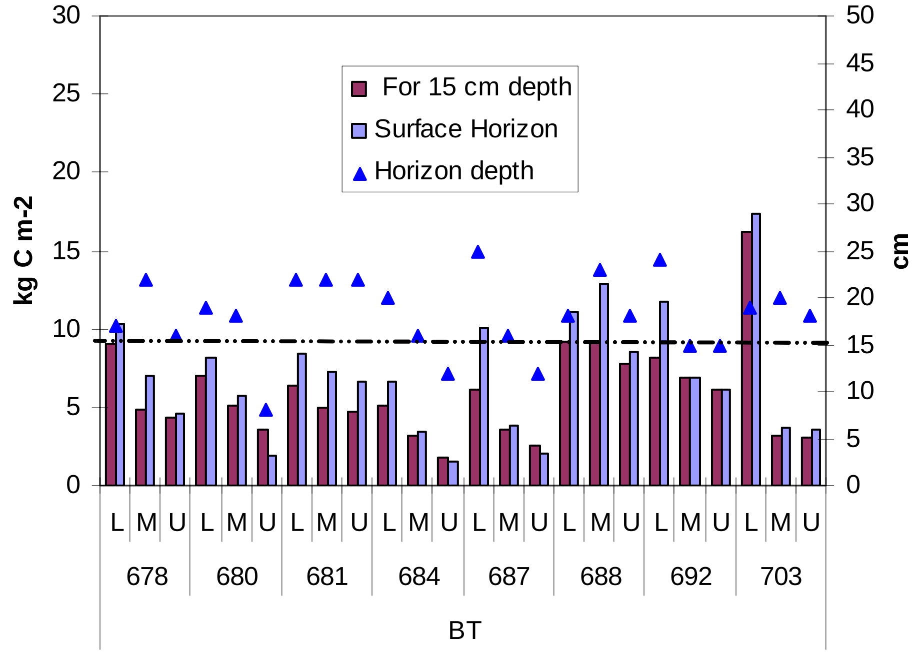


Figure 4. Organic carbon content of the surface 15 cm compared to the depth and OC content of the surface (Ap) horizon for each site, averaged over 7 years. Aspen Parkland (AP); Boreal Transition (BT); Fescue Grassland (FG); Mixed Boreal (MB); Mixed Grassland (MG); Moist Mixed Grassland (MM); Peace Lowlands (PL).



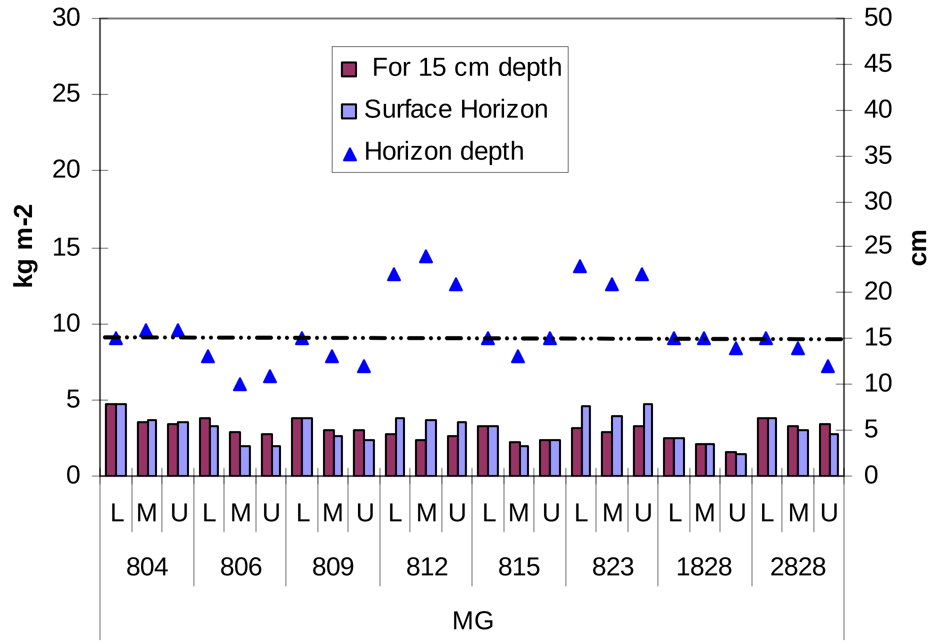
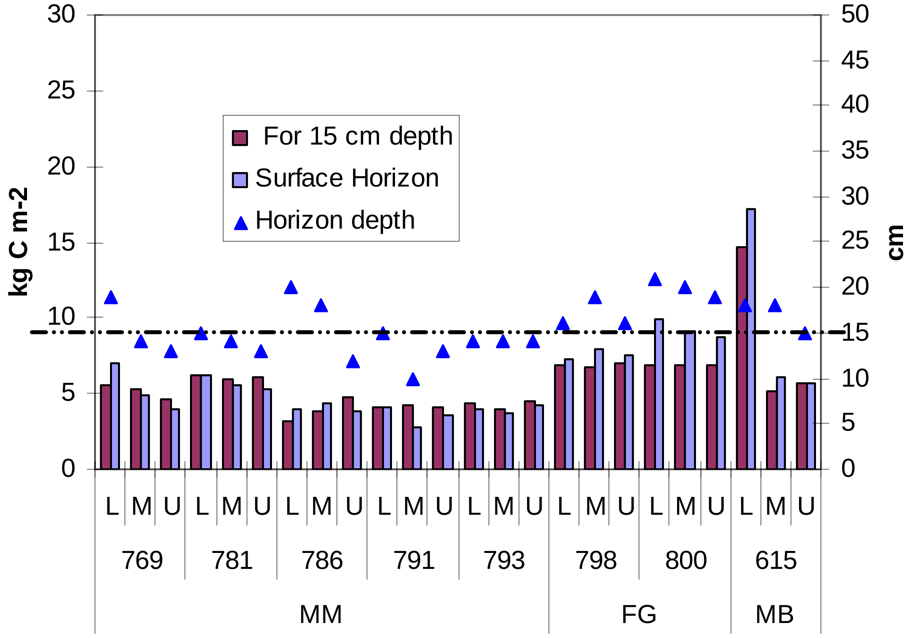


Figure 4. (continued)



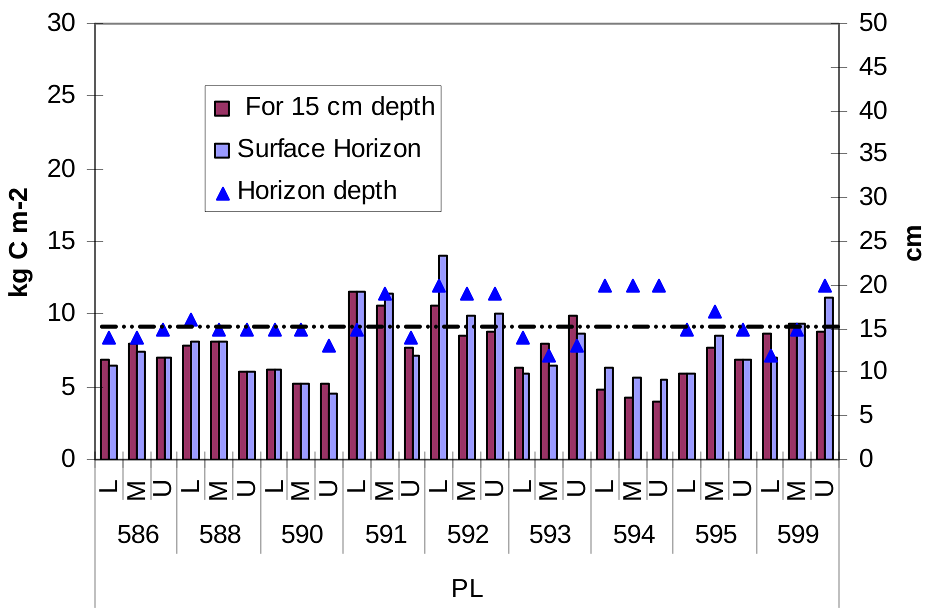


Figure 4. (continued)

4.0 Comparison of the Benchmark Sites to the AGRASID Soil Polygons

Information on the benchmark soils is of limited use beyond the fields where they are situated unless it can be demonstrated that what has occurred, or may occur, at these sites is potentially applicable to other soils in the area. In relation to OC, one way of demonstrating this is to show that the benchmark soils are pedologically similar and have similar OC content to other soils in the same area. The most comprehensive and detailed database covering all agricultural soils in Alberta is contained in the Agricultural Regions of Alberta Soil Inventory Database (AGRASID) (2002). Therefore, benchmark soils were compared to soils from AGRASID.

4.1 Soil series agreement

The soils from the benchmark sites were compared with the soil series from the AGRASID database, except for site 591 that did not have AGRASID data associated with it. There were 19 cases where the soil series name for the benchmark location matched the name of the soil, for the same landscape position, from the AGRASID polygon. These matches represent 18 sites; only site 680 had more than one slope position that matched.

It is important to note that the number of potential matches was just 58 and not the total 123 (41 sites X 3 slope positions) benchmark sampling locations. One reason for this is that there was not always a soil associated with all slope positions at a site; some AGRASID polygons did not have a soil series associated with all three slope positions. For example, a polygon may not have had a lower slope soil simply because the polygon would not normally contain a significant area considered lower-slope. Another reason for a reduced number of potential matches is that some soils in the AGRASID database were indicated as “misc. eroded” or “misc. course” whereas the benchmark site would not have been named in this way. When these cases were also eliminated as potential matches, the benchmark soil names matched the AGRASID names 33% (19/58) of the time. The successful matches were mainly (14) from the mid slope position. There were only four matches for the upper slope and just one for the lower slope position. There was better agreement for the AP ecoregion than for other regions: seven out of the nine mid slope locations had the same soil as the AGRASID soil polygon. Appendix 10.3 lists all of the soils that were compared.

4.2 Carbon content of the benchmark soils compared to AGRASID soils

Figure 5 shows a comparison of the surface soil OC content for all sites and slope positions that had an associated AGRASID soil, whereas Figure 6 shows the comparison for only those sites where the associated AGRASID soil bore the same name as the benchmark soil. The carbon content of the benchmark soils was similar in many cases to the carbon content of the AGRASID soils, regardless whether the soils were considered to belong to the same soil series, for example, sites 740 and 786. These figures also compare the depths of the Ap horizons. It is apparent from Figure 5, for example, that for site 680 (within the BT ecoregion) that the benchmark Ap horizon is much deeper (32 *versus* 23 cm) and contains more OC than the AGRASID Ap horizon. The overall correlation between the benchmark and AGRASID values was better where the soil names were an identical match (62% *versus* 53%).

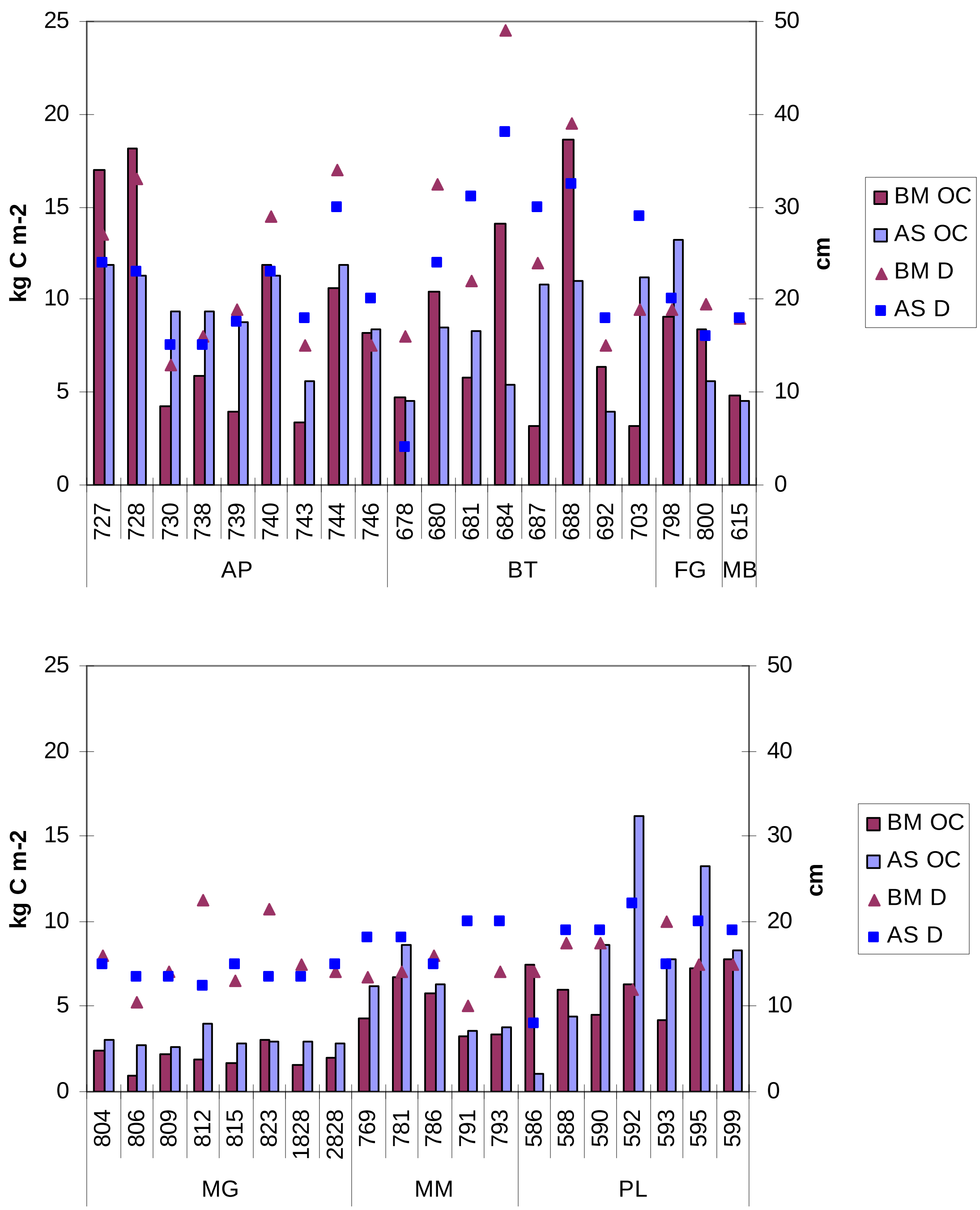


Figure 5. Comparison of OC content and depth (D) of Ap horizon between benchmark (BM) soils and AGRASID (AS) soils from the same soil polygon, averaged across all slope positions. (N = 1 to 3 slope positions per bar) Aspen Parkland (AP); Boreal Transition (BT); Fescue Grassland (FG); Mixed Boreal (MB); Mixed Grassland (MG); Moist Mixed Grassland (MM); Peace Lowlands (PL).

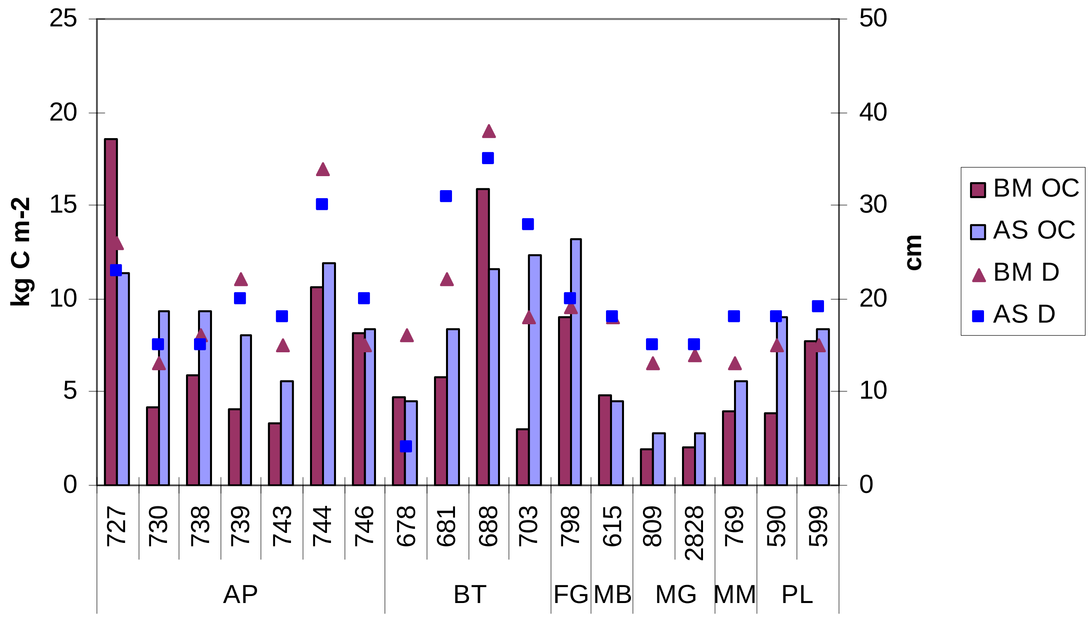


Figure 6. Comparison of OC content and depth (D) of Ap horizon between benchmark (BM) soils and AGRASID (AS) soils belonging to the same soil series. (N=1) Aspen Parkland (AP); Boreal Transition (BT); Fescue Grassland (FG); Mixed Boreal (MB); Mixed Grassland (MG); Moist Mixed Grassland (MM); Peace Lowlands (PL).

4.3 Landscape-level comparison of the benchmark sites and AGRASID polygons

Topography is an important factor in differential soil development across the landscape and soils can vary considerably within the space of a farm field. Normally the entire field is managed the same, without regard for these differences. It would be beneficial therefore to be able to evaluate soils at a field scale, rather than on an individual sample-point basis. With regard to OC sequestration, it is ultimately the effect of the total landscape that is important. Furthermore, combining the data from sample locations allowed for a comparison of the benchmark sites to the AGRASID polygons. This may be a more valid comparison because it puts greater emphasis on the more dominant, usually mid slope, soils.

This comparison shows that although the benchmark sites had a greater mean OC content than the AGRASID transects (13.8 *vs* 12.3 kg m^{-2}), there were approximately an equal number of sites for which the benchmark value was higher than the predicted AGRASID value as there were sites where it was lower (Figure 7): seven sites contained more than 150% of the AGRASID value (793, 586, 727, 588, 728 and 2828) and six sites contained less than 67% of the AGRASID value (739, 812, 687, 1828, 703 and 815). This shows that although some benchmark sites may not have been representative of the general area in terms of OC content, there was little inherent bias. This suggests that there should be no bias in measuring changes in soil OC at the benchmark sites, either now or in the future. Discrepancies between the two values do not show preference for any particular ecoregion. Overall the correlation in OC content between the benchmark sites and the associated AGRASID polygons was 60%; higher than the 53% calculated based on the individual soils.

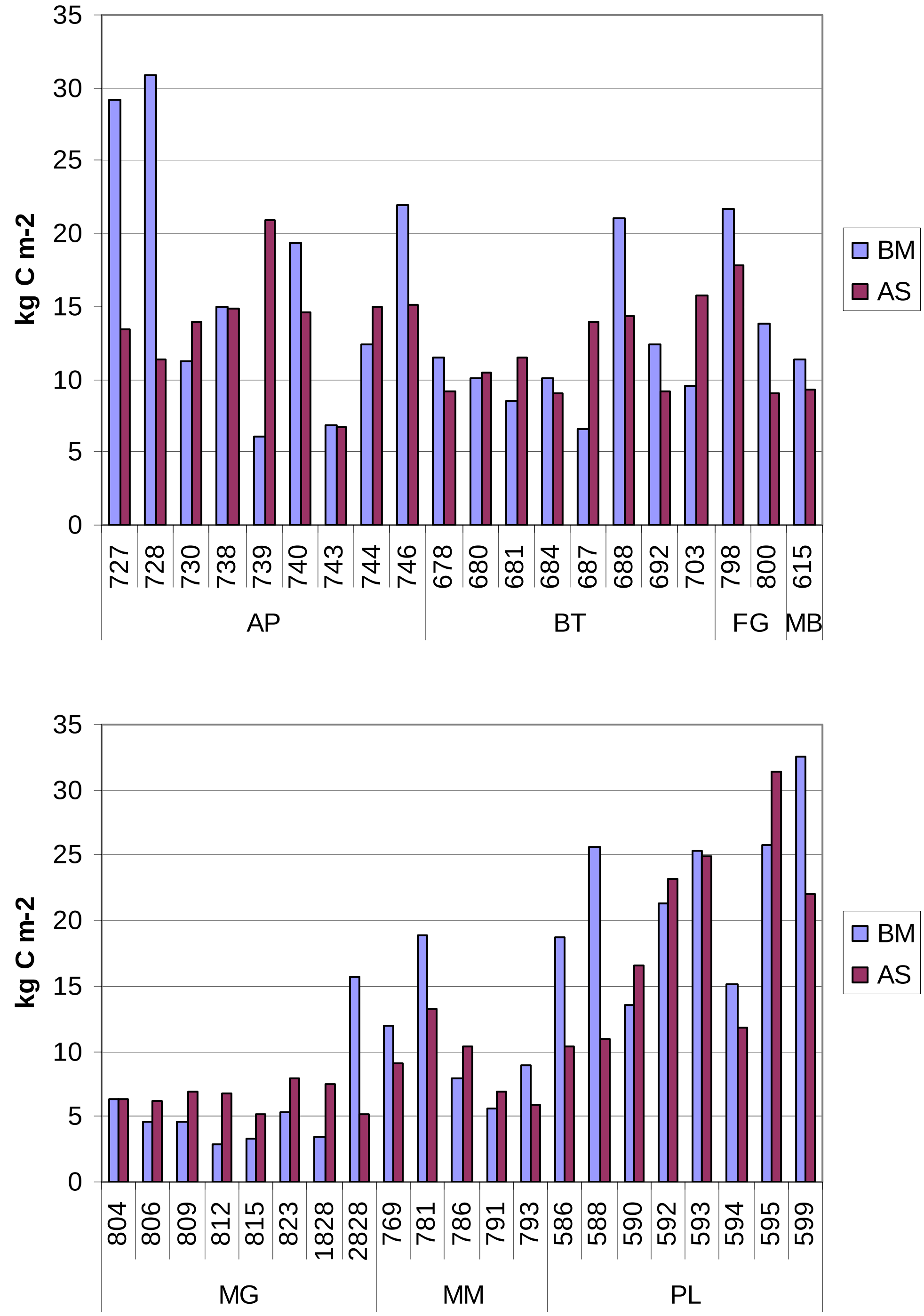


Figure 7. Comparison of the landscape average OC content between the benchmark (BM) sites and the AGRASID (AS) soil polygons. Aspen Parkland (AP); Boreal Transition (BT); Fescue Grassland (FG); Mixed Boreal (MB); Mixed Grassland (MG); Moist Mixed Grassland (MM); Peace Lowlands (PL).

5.0 Changes in Organic Carbon at the Benchmark Sites

Organic carbon appears to have increased overall at the benchmark sites. This section deals with the rate of change, where it has occurred and what factors may have been responsible for the change.

5.1 Rate of organic carbon change

There was considerable variation from one site to another in the calculated rate of OC change; the rate even varied considerably from one slope position to another at some sites. For some locations, the magnitude of the change calculated was outside of a plausible range and therefore the value should be disregarded. These values are likely a result of sampling and/or analytical error associated with the collection and analysis of the soil. A difference of 0.5 cm in sample depth from one year to another, for example, equates to 1 t ha^{-1} of OC, assuming a typical cultivated soil having an OC content of 2% and a bulk density of 1 Mg/m^3. Likewise, a difference in the measured OC concentration of 5%, for example from 2% to 2.1%, for a 15 cm layer of soil would result in an apparent change of approximately 1.5 t ha^{-1}. There was no replication to diminish these types of errors: each year there was only one sample taken per location. Rates of OC change, calculated by regression analysis, should become more reliable as more years are added to the database.

Assuming there is no deposition due to erosion, the amount of potential increase in OC is limited by the amount of residue added to the soil. Voroney et al. (1981) reported 1.2 t ha^{-1} yr^{-1} of OC in crop residue is added to grassland soils under continuous cropping. In this study there were approximately two to ten tonnes of crop residue added per year, with the grassland regions being at the lower end of this range. Campbell et al. (2000) estimated that crop residue contains approximately 45% carbon. Using this value, the most OC that might have been added to sites in the moister regions would have been 4 t ha^{-1} yr^{-1}. This does not consider losses due to decomposition which would further reduce the potential OC increase.

The extent to which soils may lose OC is perhaps less limited than their potential for gain. The greatest losses would be expected at sites where crop residue contributions are small and/or, rates of soil organic matter decomposition are high. Decomposition rates are limited by the amount of decomposable residue and are likely to only marginally exceed the rate of residue accumulation. Erosion has the potential to dramatically reduce soil organic matter; however losses are limited if fields are well managed. A considerable amount of soil must be lost to affect the total OC content. For example, to reduce the OC of a soil (assuming a Db of 1.2 Mg m^{-3} and 2% OC) by 4 t ha^{-1}, there would need to be nearly 2 cm of soil removed from the profile. It is unlikely any of the sites in this study would have experienced this much erosion.

Assuming a 20% error in the OC measurement, the greatest plausible change in OC might be plus or minus 5 t ha^{-1} yr^{-1}. Anything outside of this range could not possibly represent actual changes; and in fact, even 2 or 3 t ha^{-1} added or removed per year is unlikely. However, for the purpose of this study profiles within plus or minus 5.0 t ha^{-1} yr^{-1} are included, assuming that errors inherent in the measurements were responsible for most of the variability within this range.

Table 4 lists the average OC increase rates for different levels of data acceptance. When the range is set to within 5.0 t ha^{-1} yr^{-1}, 10 percent of locations (such as one which had 15 t ha^{-1} yr^{-1}) are eliminated and the mean OC increase is reduced from 1.13 to 0.88 t ha^{-1} yr^{-1}. This value is toward the upper end of the range expected for well managed fields where conservation practices such as reduced tillage are employed. When the limit is narrowed further to plus or minus 2.5 t ha^{-1} yr^{-1}, the number of sites eliminated increases to one third, mostly by dropping sites with a positive change in OC content (see Table 5). Thus, the mean is reduced to just 0.39 t ha^{-1} yr^{-1} ; a value typical of fields under conservation management.

Assuming that there is greater potential for large losses than there is for large gains in OC, the limits of data acceptance for this study may be altered accordingly. By rejecting those locations with increases exceeding 2.5 t ha^{-1} yr^{-1} but only rejecting locations with decreases exceeding 5 t ha^{-1} yr^{-1}, the mean OC increase would have been 0.22 t ha^{-1} yr^{-1}: less than ought to be achieved with conservation practices but still an increase overall. As indicated in Table 4, this scenario does not add many more sites with OC losses but it does substantially reduce the overall mean increase.

Table 4. Effect of narrowing the range of accepted values on the mean rate of soil OC change - all sites

Range selected		Mean OC change	Number of Profiles
Min	**Max**	**(t ha^{-1} yr^{-1})**	**Eliminated* (%)**
none	none	1.13	0 (0%)
-5.0	5	0.88	12 (10%)
-2.5	2.5	0.39	41 (33%)
-5.0	2.5	0.22	36 (29%)

* of a total of 126 (3 slope positions X 42 sites)

There were some notable trends in OC changes by ecoregion as shown in Table 6. This table shows the average of all sites for each slope position, in addition to the average for the three slope positions and a weighted average, calculated based on the portion of slope length each profile represents. The greatest increases were measured within the Moist Mixed Grassland (MM); the least increase was in the Boreal Transition (BT) ecoregion. The rate for the Mixed Boreal (MB) ecoregion is excluded from the OC rate of change analysis because it contained only one site, and the results for two of its slope positions were rejected because they were too high (greater than 5 t ha^{-1} yr^{-1}).

Slope position appears to be a factor in the rate of OC accumulation, although it was not found to be statistically significant. Most ecoregions experienced the greatest rate of OC increase at the lower slopes, and on average the lower slopes had approximately twice the rate of the upper slopes (Table 6). This trend was not evident for all ecoregions, however. Within the Peace Lowlands (PL), for example, the trend was opposite. Sites rejected from the analysis for being too high or too low (Table 5) were not concentrated in any particular ecoregion but they did tend to be from the lower slopes.

Table 5. Profiles that were outside of the ranges listed in Table 4, site numbers in bold indicate sites with an OC increase or decrease greater than 5 t ha^{-1} yr^{-1}

Ecoregion	**Change in organic carbon (t ha^{-1} yr^{-1})**					
	<2.5 or **<5.0**			>2.5 or > **5.0**		
Slope	*Lower*	*Mid*	*Upper*	*Lower*	*Mid*	*Upper*
AP		743		727	727	**727**
				730		728
				738	738	**738**
				740		
			744	**744**		
BT	684			678		
		687		680	**680**	
			692	681		
					688	
				703		
MB				**615**	**615**	
MG				804		
				806		
				2828	2828	
MM					769	
				781	781	
				786		
PL	**592**				586	586
	594	594		588		
		599			591	591
						595

There was considerable variability in the results even after eliminating the more extreme values from the data. Figure 8 shows the rates of OC change at each site and slope position. For most of these locations there was an apparent increase in organic carbon.

The surface soil carbon (0 to 15 cm) accounted for varying proportion of the total profile OC but averaged nearly one half overall (Table 7). Accordingly, any changes that may have occurred in the surface soil would have substantially affected the total soil OC.

Figure 9 plots the OC content of the surface soil horizon and Figure 10 plots OC for the entire profile (to 100 cm) for the duration of the study, up to 2004. The changes in OC are barely discernable because they are extremely small relative to the total OC. Both sets of figures (Figure 9 and Figure 10) are based on the same OC data and, therefore, show similar trends. The profile OC however includes changes that may have occurred in the 15 to 30 cm depth range whereas the surface data in most cases includes only some, or none, of this soil. The influence of the 15 to 30 cm depth is also limited because it was not sampled at the beginning of the study (1998 to 2000). These figures are discussed further in section 5.3.

Table 6. Mean increases in soil OC for each ecoregion (based on individual values within + / - 5 t ha^{-1} yr^{-1})

Ecoregion	Slope Position			Mean (All slopes)	Weighted Mean*
	Lower	Mid	Upper		
	------------------------------		t ha^{-1} yr^{-1}	--------------------------------	
AP (N=9)	2.17	0.59	-0.70	0.68	0.45
BT (N=8)	0.64	0.89	-0.18	0.44	0.40
FG (N=2)	0.65	1.05	0.77	0.82	0.93
MG (N=8)	1.48	0.50	1.07	1.01	0.86
MM (N=5)	1.80	1.79	0.56	1.38	1.49
PL (N=9)	0.19	1.26	1.51	1.01	0.85
Mean of All Ecoregions	1.186	0.94	0.54	0.88	0.76

*Averaged based on proportion of each site estimated to occupy each slope positions

Table 7. Portion of profile OC within the surface 15 cm of soil for each ecoregion with more than 2 sites, and overall (averaged over 7 years)

Ecoregion	Slope Position	Min.	Mean	Max.
AP (N=9)	Lower	22%	49%	133%
	Mid	11%	41%	78%
	Upper	19%	45%	90%
BT (N=8)	Lower	28%	69%	214%
	Mid	14%	41%	84%
	Upper	10%	44%	76%
MG (N=8)	Lower	19%	42%	68%
	Mid	15%	46%	71%
	Upper	18%	52%	78%
MM (N=5)	Lower	26%	44%	96%
	Mid	26%	44%	105%
	Upper	27%	47%	78%
PL (N=9)	Lower	14%	32%	51%
	Mid	21%	34%	53%
	Upper	18%	33%	51%
Overall mean		10%	44%	214%

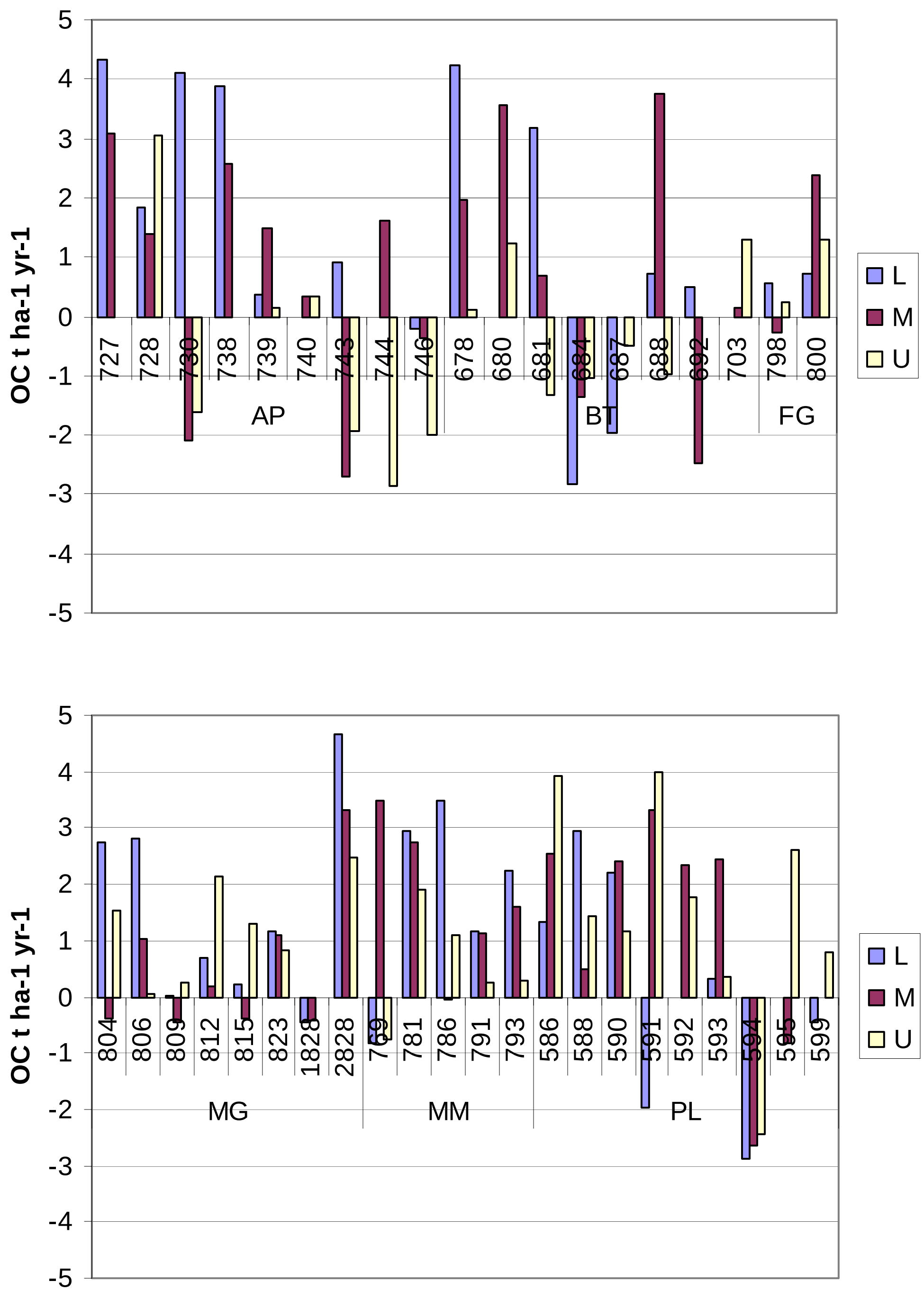
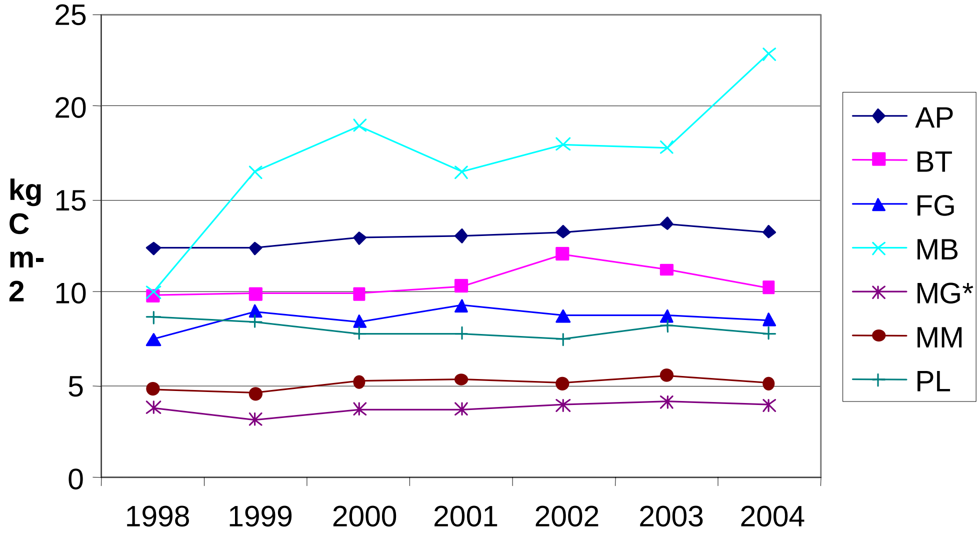


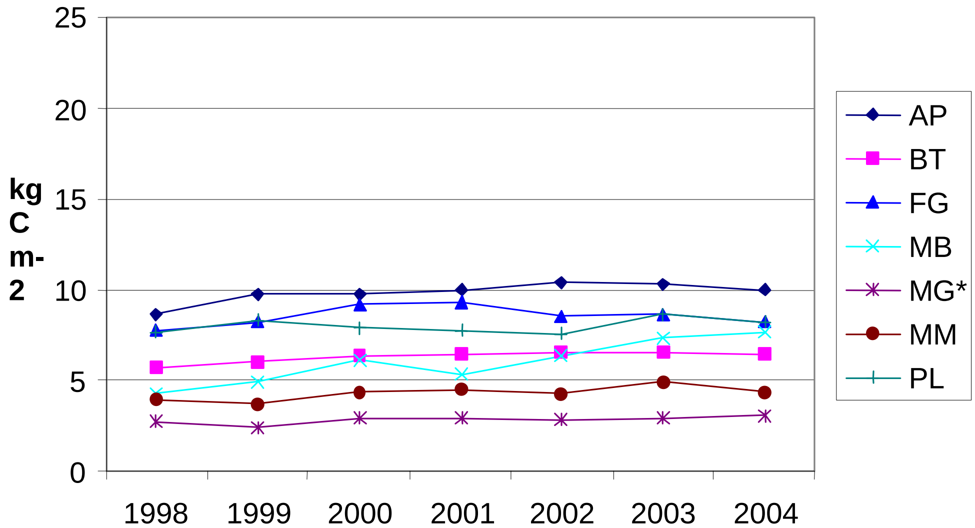
Figure 8. Rate of OC change at each site and slope position based on regression analysis. (L= lower slope; M=mid slope; U=upper slope). Aspen Parkland (AP); Boreal Transition (BT); Fescue Grassland (FG); Mixed Boreal (MB); Mixed Grassland (MG); Moist Mixed Grassland (MM); Peace Lowlands (PL).

a) Surface Soil Lower Slope



MG	a	ab	ab	ab	b	b	b

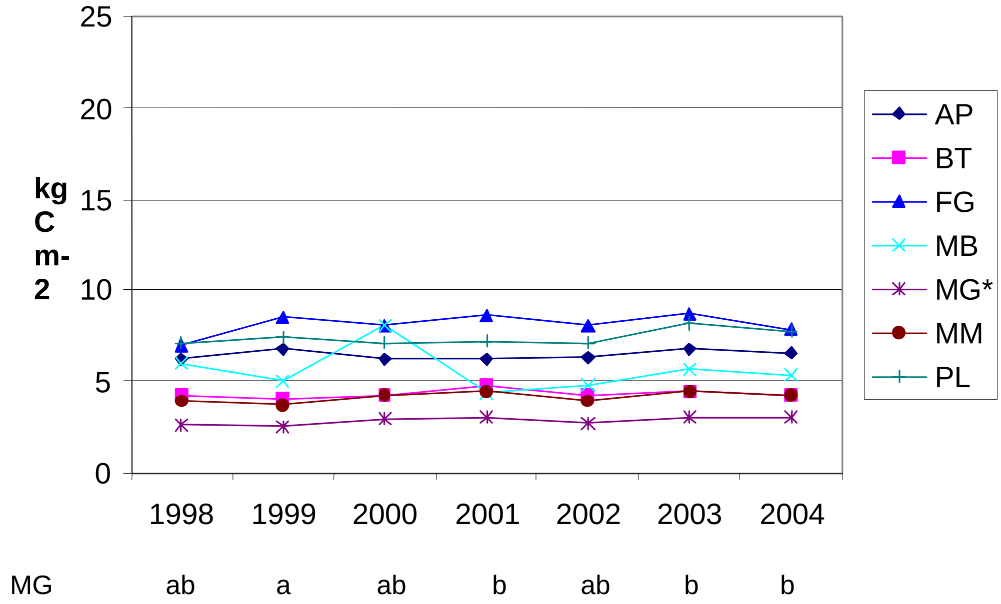
b) Surface Soil Mid Slope



MG	ab	a	ab	b	ab	ab	b

Figure 9. Trends in surface (Ap horizon) OC over 7 years for: a) lower, b) mid, c) upper, and d) all slope positions. Aspen Parkland (AP) N=9; Boreal Transition (BT) N=8; Fescue Grassland (FG) N=2; Mixed Boreal (MB) N=1; Mixed Grassland (MG) N=8; Moist Mixed Grassland (MM) N=5; Peace Lowlands (PL) N=9 (* indicates ecoregions with significant ($\alpha = 0.05$) differences among years). Years with the same letters below are not significantly different for the ecoregion indicated.

c) Surface Soil Upper Slope



d) Surface Soil Summary (average of upper, mid and lower slopes)

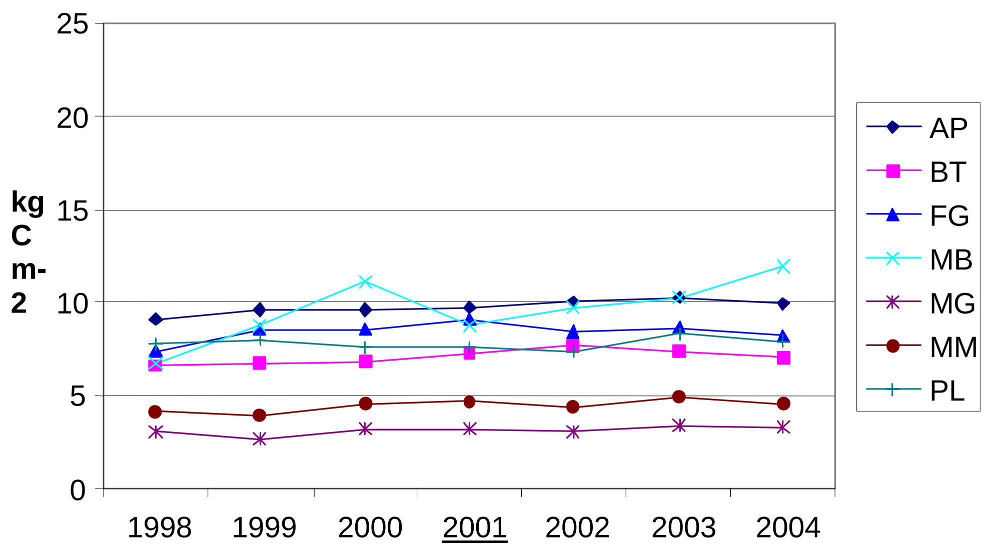
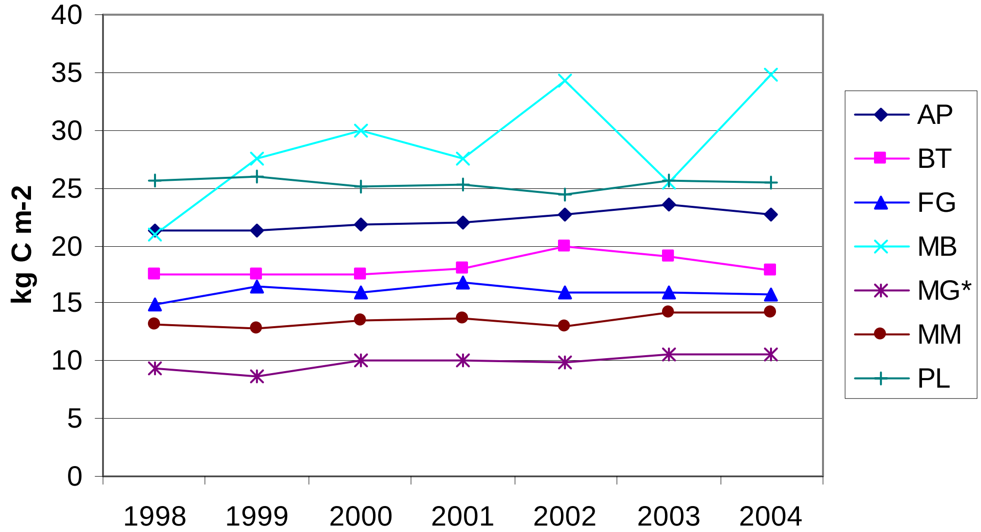


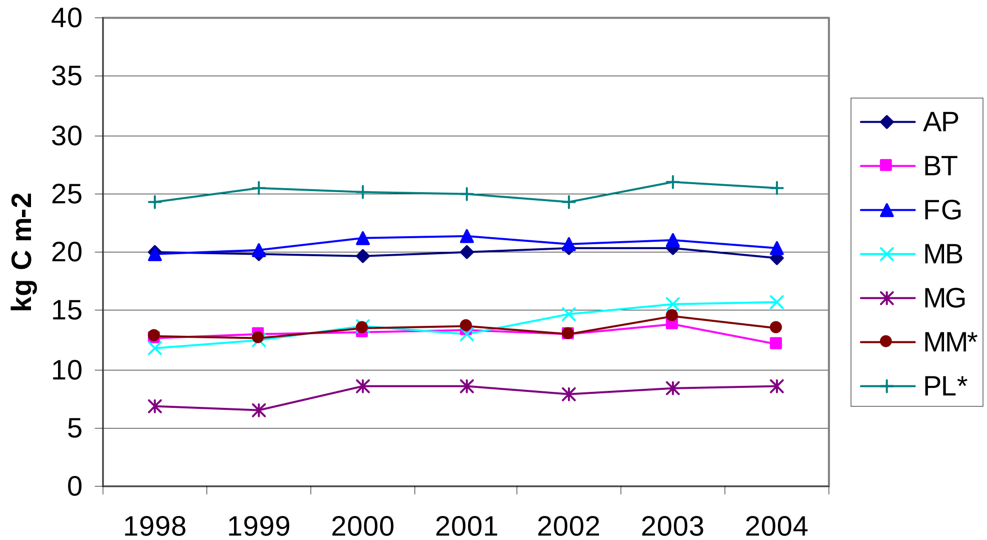
Figure 9. (Continued)

a) Total Profile Lower Slope



	1998	1999	2000	2001	2002	2003	2004
MG	ab	a	ab	b	ab	b	b

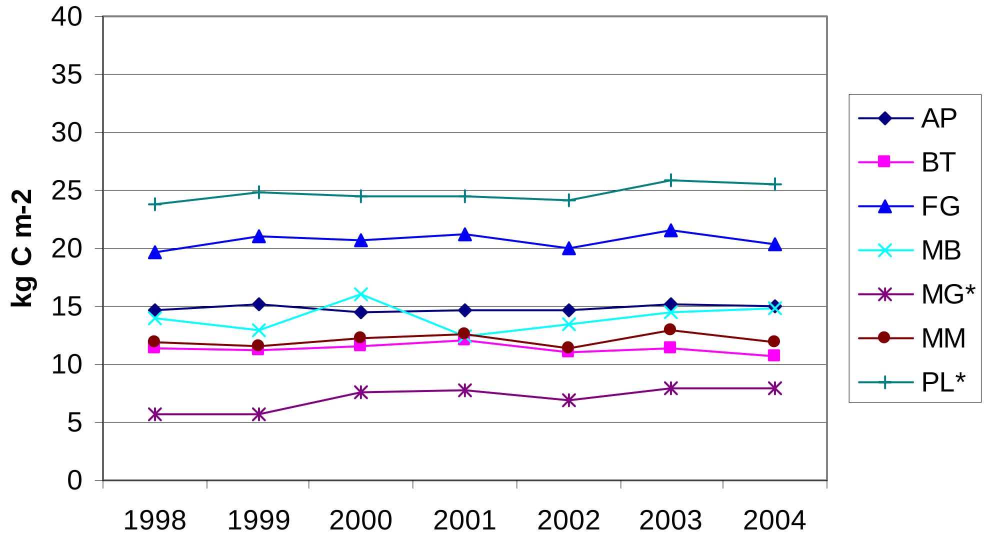
b) Total Profile Mid Slope



	1998	1999	2000	2001	2002	2003	2004
MM	a	a	ab	ab	ab	b	ab
PL	ab	ab	ab	ab	a	b	ab

Figure 10. Trends in total profile soil OC over 7 years for: a) lower, b) mid, c) upper, and d) all slope positions. Aspen Parkland (AP) N=9; Boreal Transition (BT) N=8; Fescue Grassland (FG) N=2; Mixed Boreal (MB) N=1; Mixed Grassland (MG) N=8; Moist Mixed Grassland (MM) N=5; Peace Lowlands (PL) N=9 (* indicates ecoregions with significant ($\alpha = 0.05$) differences among years). Years with the same letters below are not significantly different for the ecoregion indicated.

c) Total Profile Upper Slope



	1998	1999	2000	2001	2002	2003	2004
MG	a	a	ab	ab	a	b	b
PL	ab	ab	ab	ab	a	b	ab

d) Summary Total Profile (average of upper, mid and lower slopes)

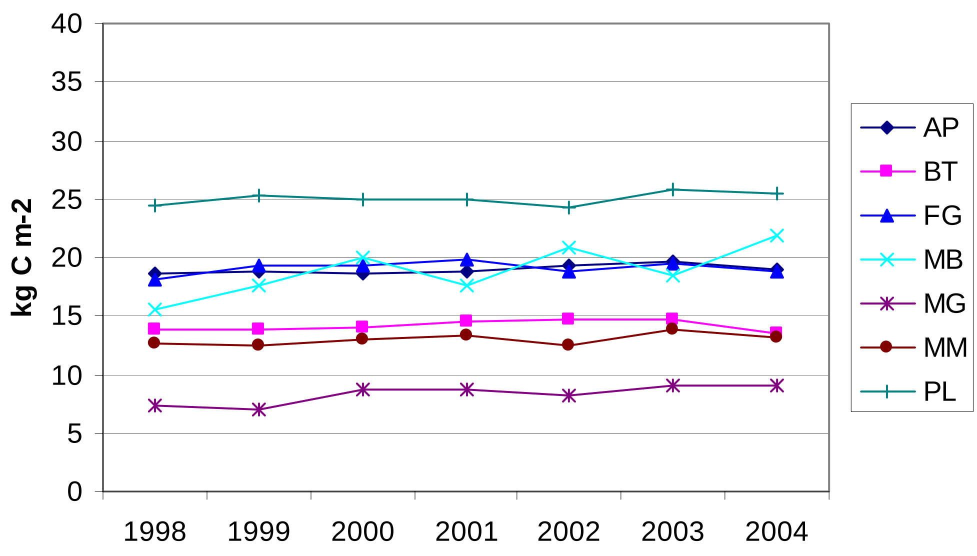


Figure 10. (Continued)

5.2 Effect of management on soil organic carbon changes

The factors that influence organic carbon accumulation and/or decomposition (temperature, moisture, nutrients etc.) are well known (Jenkinson, 1988). Quantifying these effects in the field where the exact soil conditions are not always known is a challenge however. This study was designed primarily to measure changes over time rather than as an experiment on the effect of different management practices. However, sites were classified according to management and an attempt was made to correlate management practices and weather conditions to changes in organic carbon.

Information on management practices included the general type of tillage and seeding equipment used, crop residue management (removed or retained), and the crop rotations at each site (see Appendix 10.5). Crop yield (grain yield and total above-ground yield) have been determined for each location. Fields where the benchmark sites are located have been cropped primarily to annual cereals and canola. Some sites, specifically in the southern regions of the province, have had summer-fallow in their rotations. Three sites, located in the MG ecoregion, were under irrigation during the study period.

The most common management at the sites involved annual crops and what might be considered "normal" tillage. Although reported as "tilled", these sites have not likely experience cultivation to the same extent as they would have under conventional tillage practices used in the past. Only one site was reported as "zero till", and one site (703) has been under continual perennial forages throughout the duration of this study to date. Various forms of reduced tillage have been reported for the remaining sites. The only notable trend is a greater frequency of reduced tillage reported for the Peace Lowlands. Currently, there are not enough benchmark sites with zero tillage, or otherwise well-defined tillage practices, to assess the exact effect on soil OC.

Organic carbon accumulation depends on residue inputs; therefore, those sites with higher inputs might be expected to show a more positive change relative to other sites in the same area. There did not appear to be any such relationship between the quantity of residue and the observed OC increases, however. Figure 11 fails to illustrate any trends in the data, either in aggregate or on an ecoregion basis. A possible explanation may be that the study has not gone on long enough to identify these differences or, alternatively, higher decomposition rates are preventing these potential increases in organic carbon.

Figure 12 shows the average amount of crop residue input per year for each site. Inputs did not vary by ecoregion; there was as much difference from site to site within an ecoregion as there was between ecoregions, except for the Mixed Grassland. This ecoregion had relatively less crop residue input; except for the irrigated sites (812, 823 and 2828). These sites had estimated residue inputs comparable to the highest values for other ecoregions. Figure 13 plots the average crop residue inputs for each ecoregion of this study on a year-to-year basis. Fluctuations in yield were experienced in all ecoregions. In the AP ecoregion, for example, yields increased each year up until 2000, they then fell for the following two years, and then increased again in 2003. These data are discussed further, in relation to precipitation (section 5.3). (The crop residue input data are contained in Appendix 10.6.)

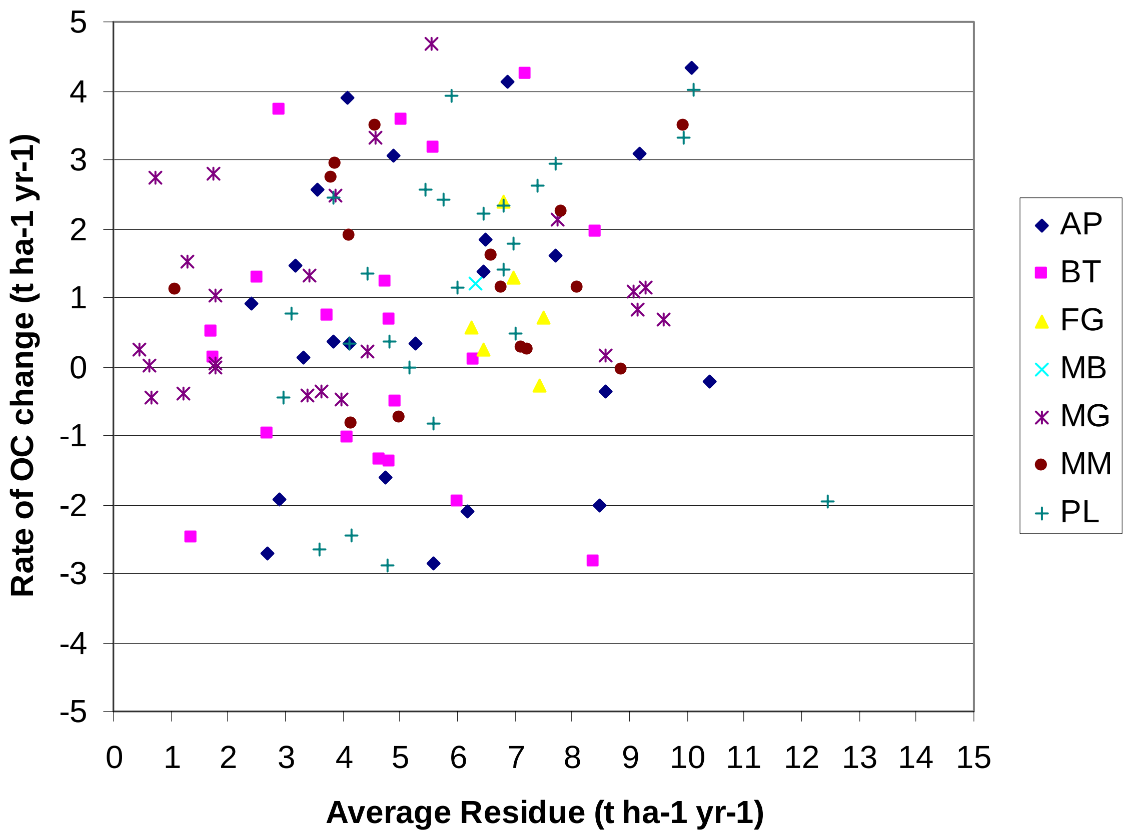


Figure 11. Relationship between the average rate of OC change and annual residue inputs. Aspen Parkland (AP) N=9; Boreal Transition (BT) N=8; Fescue Grassland (FG) N=2; Mixed Boreal (MB) N=1; Mixed Grassland (MG) N=8; Moist Mixed Grassland (MM) N=5; Peace Lowlands (PL) N=9.

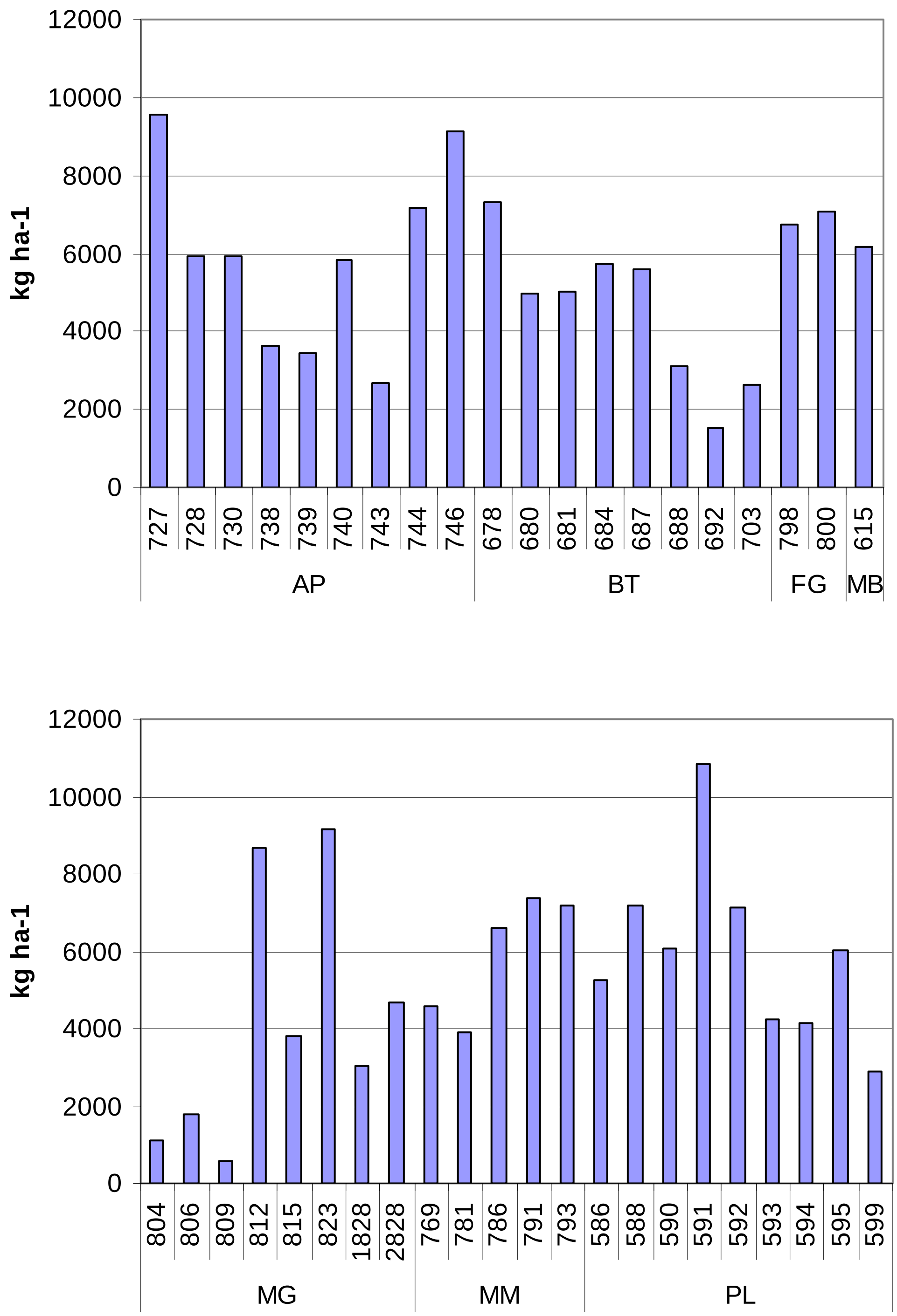


Figure 12. Crop residue inputs for each site, averaged across all years and slope positions (N=21 for each site). Aspen Parkland (AP); Boreal Transition (BT); Fescue Grassland (FG); Mixed Boreal (MB); Mixed Grassland (MG); Moist Mixed Grassland (MM); Peace Lowlands (PL).

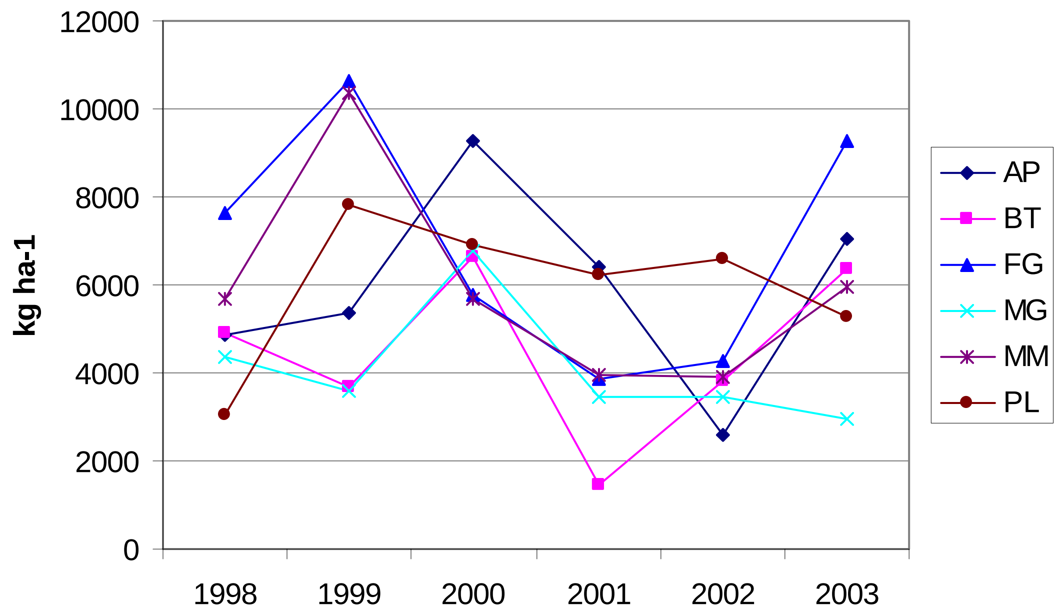


Figure 13. Average annual rate of crop residue inputs by ecoregion over six years. Aspen Parkland (AP) N=9; Boreal Transition (BT) N=8; Fescue Grassland (FG) N=2; Mixed Boreal (MB) N=1; Mixed Grassland (MG) N=8; Moist Mixed Grassland (MM) N=5; Peace Lowlands (PL) N=9

5.3 Effect of climate and weather on soil organic carbon changes

The past several years, spanning this study, have been relatively dry. Growing season precipitation has been below normal over much of the province as indicated by provincial growing season precipitation maps (see Appendix 10.7). Drier conditions result in lower crop yields and hence less crop residue returned to the soil. Furthermore, decomposition is inhibited, owing to a lack of moisture necessary for microbial action. Although weather data specific to each site was not available for this report, growing season precipitation on a regional basis was gleaned from the maps in Appendix 10.7 and used to interpret trends in soil OC content and crop residue inputs. Even within the same ecoregion, however, there may have been significantly different weather patterns. This could affect soil OC dynamics at different sites, as well as how the results for OC changes might be interpreted.

The following trends are apparent when changes in growing season precipitation patterns are compared to the crop residue data (Figure 13), and to changes in OC (Figure 10):

1) There was slightly more precipitation in 1999 than in 1998, however, the agricultural areas of northern Alberta, including the PL ecoregion, still had below normal precipitation. Crop residue inputs increased for all ecoregions except the MG and BT. Organic carbon increased for FG and PL but did not change for other ecoregions.

2) In 2000, precipitation increased to normal for most of northern Alberta, but changed from above to below normal in the southern ecoregions (MM, MG and FG). These changes were associated with increased crop residue and an increase in OC for the MG ecoregion. There was less crop residue produced at the MM sites, although OC did increase.

3) From 2000 to 2001 conditions were even drier in the south. Precipitation was much below normal in the MG, and below normal precipitation extended north into the AP ecoregion. Yields, and consequently residue inputs, declined in all ecoregions but OC content increased slightly in most ecoregions.

4) There was a reversal in the precipitation pattern between 2001 and 2002. The northern part of the province became much drier while the southern areas received above normal rainfall. There was a large decrease in residue and a slight increase in OC for the AP ecoregion. In contrast, there was, on average, an increase in both crop residue and OC content for sites in the BT ecoregion.

5) Moving into 2003, drought eased in the north, but returned to the southern areas of the province. Yields increased sharply in all but the MG and PL ecoregions. Organic carbon increased slightly in all but the BT ecoregion.

6) In 2004, above normal precipitation occurred in parts of the southern regions and in the Peace region. Yield data was not yet available for the 2004 crop year, and soil OC results indicated no particular change, or a slight decline, across all ecoregions.

These results suggest that changes in OC are not closely linked to yield and/or crop residue inputs for the growing season prior to soil sampling. Changes in OC do, however, appear to be related to growing season precipitation. Generally in those years and regions for which drier conditions prevailed there was an increase in OC content. These results suggest year-to-year changes in precipitation cause a change in OC primarily by controlling decomposition rates. Precipitation would obviously influence residue inputs as well, but this affect may be more subtle and may only be manifested over a longer time.

6.0 Potential for Carbon Sequestration at the Benchmark Sites

The apparent changes in organic carbon discussed above represent removals or additions to atmospheric carbon dioxide. Although there is considerable variability, and hence statistically insignificant year to year differences in most cases, it does appear that there has been carbon sequestered by soils at the benchmark sites.

These gains may represent a re-building of soil organic matter toward pre-cultivation levels. Some of the organic matter that was lost through cultivation can presumably be replaced through the use of improved crop and soil management practices. The potential for carbon sequestration by agricultural soils in the prairie region of Canada has been suggested by some authors (Campbell et al. 2000, Laing et al. 2003, Voroney et al. 1981) while others have concluded that carbon is being lost from these soils (Smith et. al. 1997). In many cases the prediction of carbon sequestration is contingent upon a change in management, such as reducing the amount of tillage. In this study there was no attempt to change management at the benchmark sites, and management had not changed dramatically since the beginning of the study, yet there has apparently been an increase in soil OC.

The reason for the increase is not clear, therefore it is not known if the trends will continue. However, if the trends were to continue, and to become statistically significant, they would indicate a potential for carbon sequestration by typical agricultural fields in Alberta.

6.1 Comparison of the benchmark soils to the native soil profiles

Assuming the carbon content of native soils is near an equilibrium state, where decomposition essentially balances residue additions, these soils may represent an upper limit of carbon content for a particular region. Thus, the difference in OC content between an agricultural soil and its native counterpart may represent a potential carbon sequestration capacity. All of the benchmark soils are agricultural, therefore other sources of soils data were sought in order to make such a comparison. Soils from AGRASID were used because this database has both native and agricultural soil profiles.

The results shown in Table 8 indicated that the benchmark soils from the southern prairies (FG, MM and MG ecoregions), as expected, had less OC in the surface horizon than did the AGRASID native soils. This was not the case for other ecoregions, however. Furthermore, for the soils compared in this study, there was often little difference in surface-soil OC content between the AGRASID agricultural soil and its equivalent native soil, see for example the Angus Ridge or Elnora soil in Figure 14. Generally the native soils had higher OC contents than did the agricultural soils but this varied depending on the particular soil series.

When the soils are compared based on the entire profile (Figure 15), it is apparent that, for most sites, the benchmark soils contained more OC than either the native or agricultural

AGRASID soil. For the AP and BT ecoregions, approximately half the benchmark soils had more OC than the AGRASID soils (native or agricultural), and the average OC contents were similar. For the remaining ecoregions, most of the benchmark soils had more OC than the AGRASID soils, and the average OC content was considerably more (Table 8). This indicates that the benchmark sites have relatively more OC in the subsoil. It is not clear why this is the case but it could have be the result of differences in sampling and/or analytical methods.

These results are inconsistent with the notion that cultivation leads to a depletion of soil organic matter (McGill et al. 1981). The reason for this is not known but may be related to biases in selecting representative soil profiles. The more productive soils within a region tend to be used for agriculture, and it is likely that this bias exists even within the same soil series. Thus, because higher productivity is related to higher soil OC, the AGRASID agricultural soils would tend to have more OC than the native soils. Similarly, the criteria used to select the benchmark sites (Cannon 2000) would have likely resulted in choosing fields more productive than the average for the area. Regardless of the reasons, the results suggest that this approach of using soil survey (AGRASID) data to compare agricultural soils to native soils has limited potential. Furthermore, the large unexplained differences in OC content found between the benchmark and AGRASID soil in many cases probably makes this comparison invalid.

Table 8. Comparison of the OC content between benchmark (BM) sites and the same AGRASID, agricultural (AS-A) and native (AS-N) soils for the A horizon and the entire profile to 100cm

Ecoregion		**AS-A**	**BM**	**AS-N**
		-------------	kg m^{-2}	-------------
AP	"A" horizon	9.3	11.5	10.6
	Profile	14.9	21.5	15.5
BT	"A" horizon	6.6	7.1	5.6
	Profile	12.7	14.9	13.3
MG	"A" horizon	3.0	3.1	2.7
	Profile	5.4	8.2	5.1
MM	"A" horizon	5.7	4.4	5.9
	Profile	9.6	12.3	10.1
PL	"A" horizon	5.1	6.5	5.5
	Profile	12.0	23.2	13.1
Overall: "A" horizon		6.3	7.1	6.5
Overall: Profile		11.2	15.8	11.9

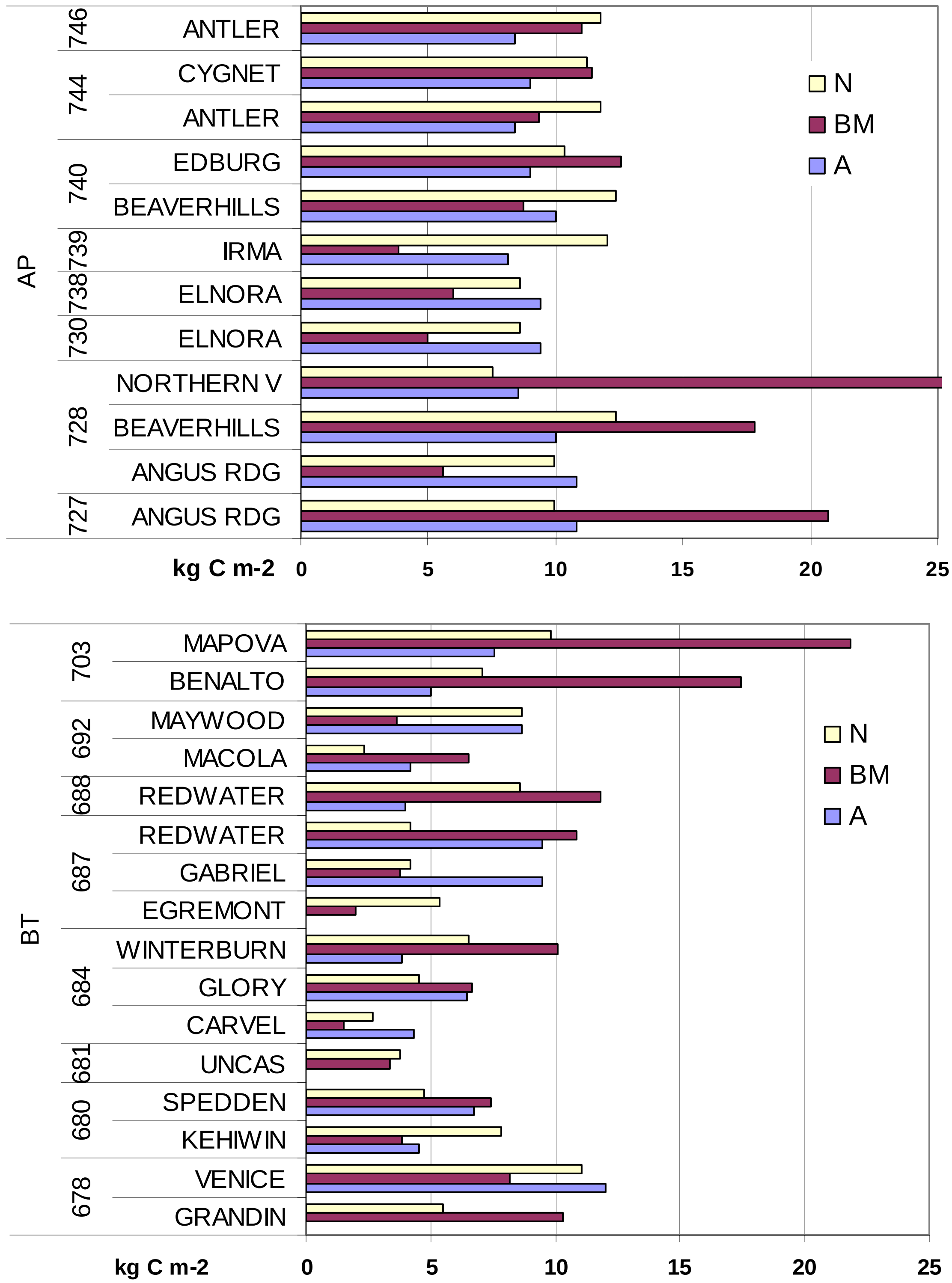
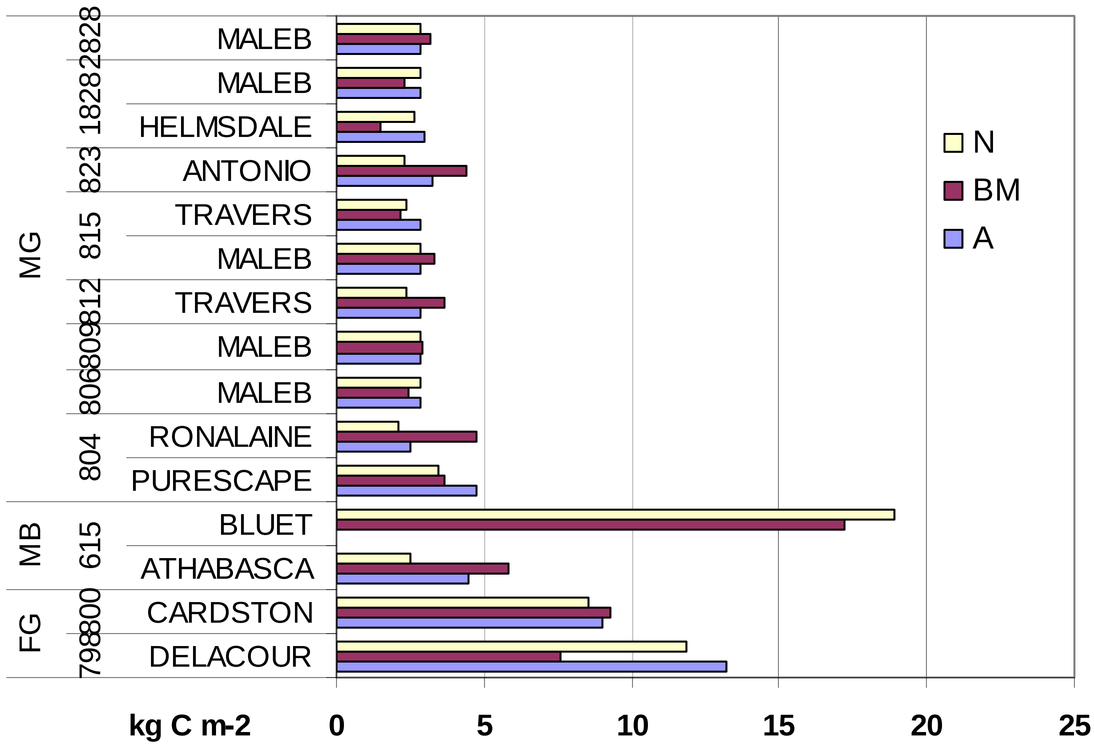


Figure 14. Comparisons of surface (A horizon) OC content of soils at each site: benchmark soil (BM) *versus* AGRASID natural (N) or agricultural (A) soils. Aspen Parkland (AP); Boreal Transition (BT); Fescue Grassland (FG); Mixed Boreal (MB); Mixed Grassland (MG); Moist Mixed Grassland (MM); Peace Lowlands (PL).



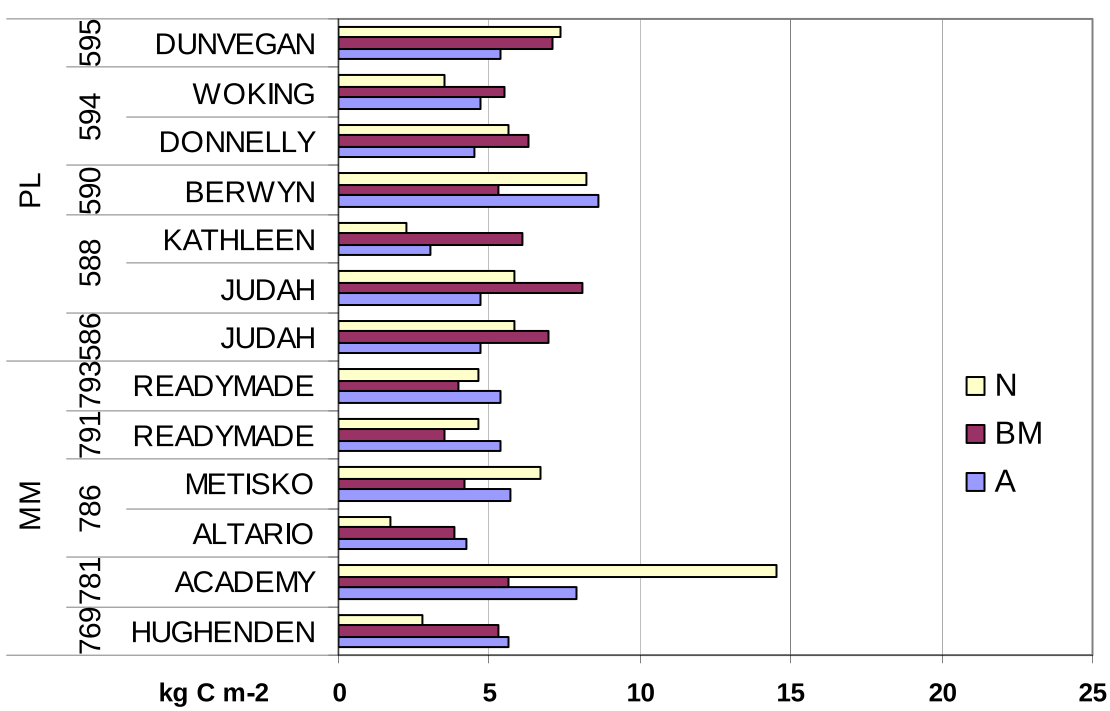
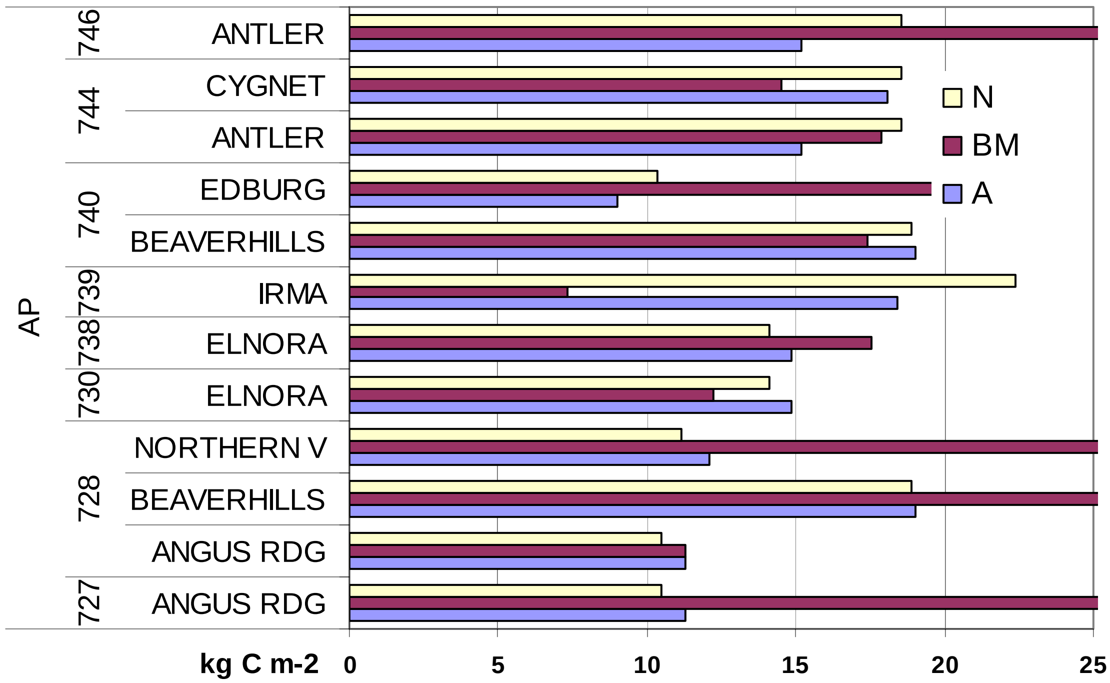


Figure 14. (Continued)



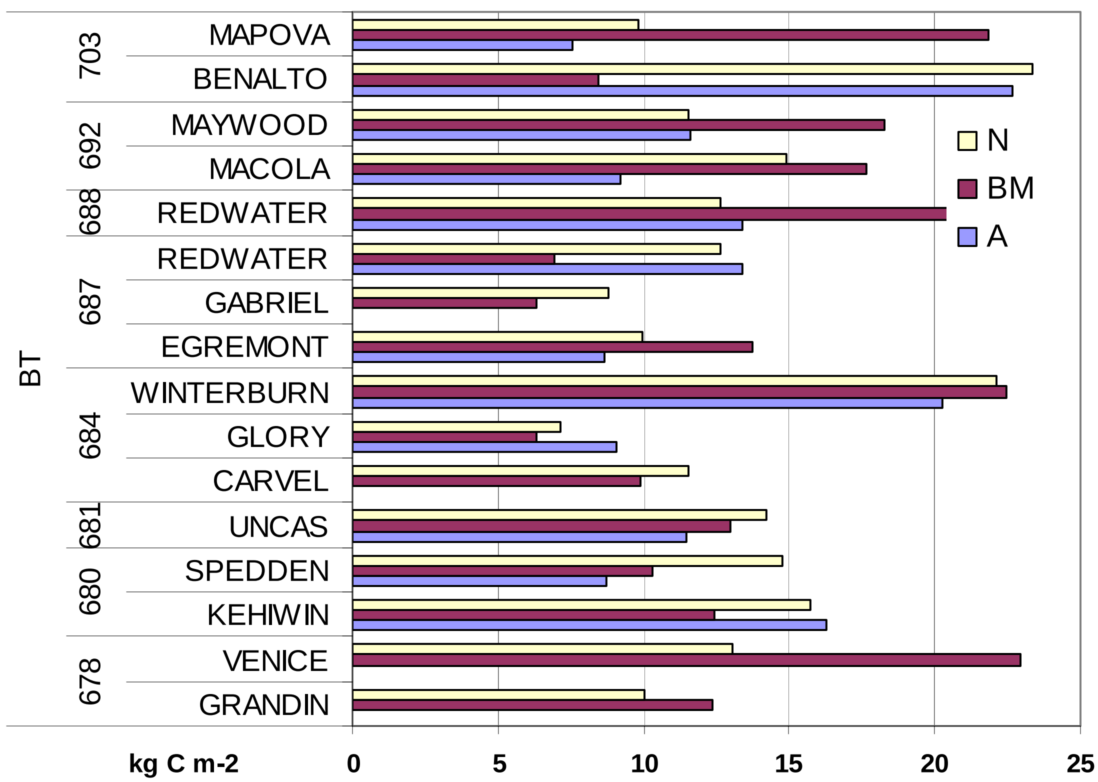


Figure 15. Comparisons of total profile OC content of soils at each site: benchmark soil (BM) *versus* AGRASID natural (N) or agricultural (A) soils. Aspen Parkland (AP); Boreal Transition (BT); Fescue Grassland (FG); Mixed Boreal (MB); Mixed Grassland (MG); Moist Mixed Grassland (MM); Peace Lowlands (PL).

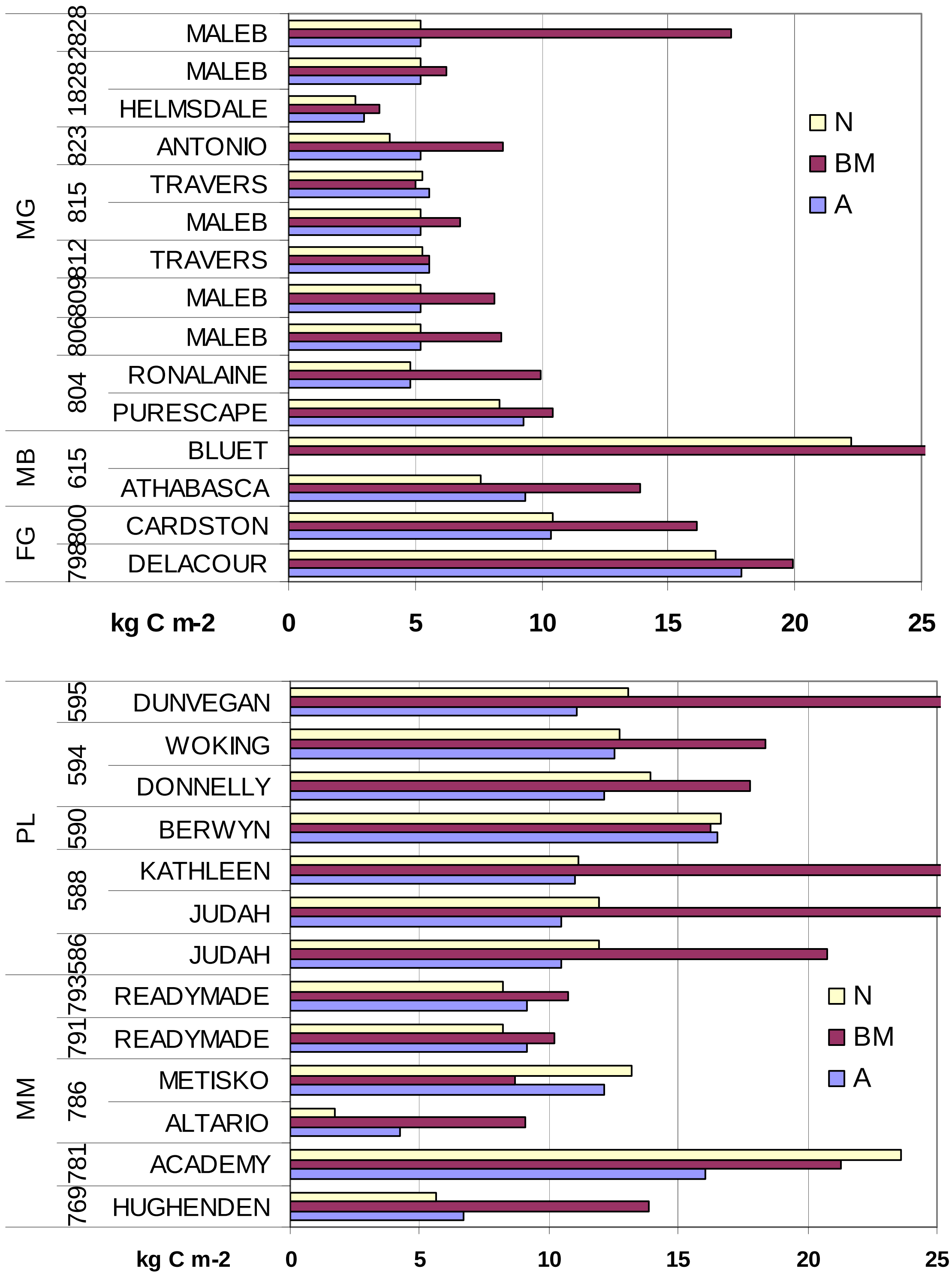


Figure 15. (Continued)

6.2 Comparison of observed to predicted changes in organic carbon

There are many models that may be used to predict OC changes based on a variety of factors associated with crops, soil or climate (McGill, 1996). Some models are more specific to a particular region. The intent was not to model carbon dynamics at the benchmark sites, but rather to look at the results of modeling done by others that may be applicable to Alberta, and to determine how well these results match observations from the present study.

The Sinks Table and the Agriculture Table have used estimates for western Canada developed by McConkey (1999). These factors are based on an empirical model that predicts a rate of soil OC gain for either adopting zero-tillage, reducing fallow or switching to forages. For each management change, there may be a different factor applied for the Black, Dark Brown or Brown soil zones. The factors for zero tillage management were applied to the benchmark sites and then compared to the annual changes calculated for each site and slope position. The factor for Brown soils was applied to the MG sites, the factor for Dark Brown was applied to the MM sites, and the factor for Black was applied to all remaining sites. Although some of these soils may not be Black Chernozens, they do occur in moister areas, so the Black soil factor was judged to be most applicable in these cases.

Table 9 compares the frequency of sites where OC was increasing faster than would have been expected. (Appendix 10.8 contains the actual rates.) Overall, 69% of the sites increased more than would have been predicted based on McConkey's factors. The observed rates from this study were higher than the predicted rates for all regions, but particularly for those in the Brown and Dark Brown soil zones. The highest frequencies, nearly all sites, were in the MG and MM ecoregions where the predicted rates of increase are lower: 0.10 and 0.20 t ha^{-1} yr^{-1} respectively, compared to a predicted rate of 0.37 t ha^{-1} yr^{-1} for the remaining ecoregions. The frequencies were similar regardless of slope position. Thus, it appears that for most sites McConley's predictions are conservative, and are considerably lower than the overall average of 0.88 t ha^{-1} yr^{-1} determined for this study.

Table 9. Frequency of benchmark profiles exceeding the rate of OC increase predicted by McConkey (1999) for zero tillage management (excluding individual profiles outside of the + / - 5 t ha^{-1} yr^{-1} range)

Ecoregion	Slope Position			Total	
(N per slope)	Lower	Mid	Upper	(all slopes)	
AP (N=9)	5	6	4	15	56%
BT (N=8)	5	3	4	12	50%
FG (N=2)	2	0	1	3	50%
MG (N=8)	7	7	8	22	92%
MM (N=5)	5	5	5	15	100%
PL (N=9)	6	5	7	18	67%
All Sites (N=41)	30	26	29	85	69%

Sauvé (2000) predicted OC changes for several ecodistricts in Alberta, for various crop types (cereals, oilseeds and forage) and for fallow. She used a simple model that takes into account regional climate and crop residue inputs (calculated based on typical yields). The predicted value for the cereal cropping scenario was selected for the purpose of this exercise. (The predicted values for each ecoregion are listed in Appendix 10.8.) The frequencies of sites with an observed OC change greater than that predicted by this model are indicated in Table 10. The value used for these purposes was the average across all slope positions at each site. Ecodistrict 615 was omitted because it did not have predicted values available.

This model yields predictions of potential OC change similar to those of McConkey (1999) but are more site-specific. Carbon sequestration rates, on average, were predicted to be 0.42 t ha^{-1} yr^{-1} for conventional tillage (CT) and 0.55 t ha^{-1} yr^{-1} or zero tillage (ZT): considerably lower than the 0.88 t ha^{-1} yr^{-1} average calculated for this study. Compared to results from the benchmark sites, it appears that the model underestimated the OC change in all, except possibly the AP and FG, ecoregions.

Table 10. Frequency of sites exceeding the rate of OC increase predicted by Sauvé (2000) for conventional (CT) and zero tillage (ZT) management (excluding individual profiles outside of + / - 5 t ha^{-1} yr^{-1} range)

Ecoregion	Number of sites	Exceed ZT		Exceed CT	
AP	9	4	44%	5	56%
BT	8	5	63%	5	63%
FG	2	1	50%	1	50%
MG	8	6	75%	6	75%
MM	5	5	100%	5	100%
PL	9	6	67%	6	67%
Total	41	27	66%	28	68%

The results of this study, although highly variable, indicate that the rates of OC accumulation may have been higher than would have been predicted by others, based either on long-term field experiments or modeling of OC dynamics. This suggests that carbon sequestration will likely continue but perhaps not as rapidly as observed up to this point of the study.

7.0 Recommended Improvements to the Monitoring Program

The following recommendations are made to assist in improving and strengthening the AESA Soil Quality Monitoring Program by providing additional information and/or improving the quality of the existing database:

1. Use the information provided in this report, along with any additional information required, to validate a computer simulation model, such as Century, so that it might be used to predict the effects of management or climate change on soil OC within the agricultural regions of Alberta.

2. Given the apparent importance of weather on soil OC, it may be beneficial to obtain precipitation data for each site.

3. Consider comparing the benchmark OC results to the organic matter data set from Norwest labs. This would provide an indication of the extent to which benchmark sites represent typical agricultural fields. Although the sampling and analytical accuracy of this data is not to the same standard as the benchmark data, it is extensive in the area that it encompasses.

4. Annually evaluate and record, perhaps with photographs, the residue cover at each site. Comparing this information with the tillage techniques subsequently reported by the producers would assist in developing a standardized index of soil disturbance that could then be compared against the OC database. This should help in assessing the effects of tillage between sites or regions, and may explain changes occurring at any particular site.

5. Investigate the sampling and analysis of the sub-soil horizons, C horizons in particular, because there appears to be more OC in the subsoil of the benchmark soils than found for similar AGRASID soils. Although the data was not examined in detail, Table 8 and cursory examination of the horizon data in Appendix 10.4 suggests a discrepancy in C horizon results between the two datasets.

6. To enable a better comparison to the AGRASID soil polygons at a landscape level, there should be a measurement or estimate made of the lengths of the upper, mid and lower slopes at each site.

7. Look in more detail at the records for those sites that had unusually high or low rates of OC change to determine the reason for these large changes.

8. Some of the differences in OC among sites may be related to soil conditions such as pH, salinity or soil texture. It may be beneficial to identify those soils that have inherent limitations to crop growth and/or to microbial decomposition.

9. For the 13 sites for which there were large differences between the OC content of the benchmark and the AGRASID landscape, there should be a re-evaluation to

determine if these sites are truly representative of the area, and whether the AGRASID soil polygons have been appropriately assigned.

10. Increase the number of sites in the MB and FG ecoregions to a minimum of three sites to ensure that these ecoregions are adequately represented, and to strengthen the statistical analysis of any future studies.

11. The apparent changes that have occurred over the relatively short span of this study would not likely have been from the stable organic components but rather the lighter fractions consisting of less decomposed organic material. Therefore it would be interesting to investigate the data for light fraction OC that has been collected as part of the monitoring program.

12. The changes reported here for the total soil profile utilize the data from the initial samples of sub-soil horizons. Although changes in OC may not be expected below 30 cm, another set of samples to a depth of one metre should be considered for the future. They may confirm that there are no changes occurring at these depths, but they would also improve the overall accuracy of the profile OC values. Sampling to one metre should be done on a regular basis; perhaps once every 10 years.

13. Continue monitoring the sites as in the past, adhering to the same basic sampling and collection protocols used previously.

8.0 Conclusions

There are no definitive conclusions regarding OC that can be drawn from the study thus far. The average carbon content of the sites was 16.6 kg m^{-2} (166 t ha^{-1}), but ranged from 8.3 kg m^{-2} (83 t ha^{-1}) in the Mixed Grassland ecoregion to 25.1 kg m^{-2} (251 t ha^{-1}) in the Peace Lowlands. Slope position appears to affect OC distribution but it is not as simple as might be expected: lower slopes did not consistently contain more carbon. The benchmark soils at most sites were similar in OC content to the AGRASID soils of the areas where they are located. However, there were many cases where the OC content was quite different from that of the AGRASID soils even when the same soil series were compared. These differences may be due to the site being non-representative of the area, or perhaps to the AGRASID polygon not being appropriate for the site. These discrepancies need to be further evaluated before extrapolating observations for a benchmark site to the surrounding area.

There were indications that soil OC increased for most of the ecoregions studied. These increases were greater than would have been predicted based on field experimentation and OC modeling work completed by others. It is important to note, however, that these changes are not statistically significant, and what they may be attributed to is not fully known. The increases in OC may be related to management or weather, but further study will be required to determine the exact cause, and to see if the rate of increase is sustained in the future.

9.0 References

AGRASID. 2002. Agricultural Regions of Alberta Soil Inventory Database, Version 3.0. Alberta Agriculture Food and Rural Development Publications.

Brown, A.L., Wyatt, F.A. and Newton, J.D. 1942. Effects of cultivation and cropping on the chemical composition of some western Canada prairie soils. Scientific Agriculture 23: 229-232.

Campbell, C. .A., Zentner, R. P., Selles, F., Biederbeck, V.O., McConkey, B. G., Blomert, B. and Jefferson, P. G. 2000. Quantifying short-term effects of crop rotation on soils organic carbon in southwestern Saskatchewan. Can. J. Soil Sci. 80: 193-202

Cannon, K. 2002. Alberta Benchmark Site Selection and Sampling Protocols. AESA Soil Quality Resource Monitoring Program. September, 2002.

Ecological Stratification Working Group. 1995. A National Ecological Framework for Canada. Agriculture and Agrifood, Research Branch, Centre for Land and Biological Recourses Research and Environment Canada, State of the Environment Directorate, Ecozone Analysis Branch, Ottawa/Hull.

Eve, M.D., Sperow, M., Howerton, K., Paustain, K and Follett, R.F. 2002. Predicted impact of management changes on soil carbon storage for each cropland region of the conterminous United States. Journal of Soil and Water Conservation. J/A 2002.

Freibauer, A., Rounsevell, M. D. A., Smith, P. and Verhagen, J. 2004. Carbon sequestration in the agricultural soils of Europe. Geoderma 122: 1-23.

Jenkinson, D.S. 1988. Soil organic matter and its dynamics. Pages 564-607 *in* A. Wild ed. Russell's Soil Conditions and Plant Growth. 11th Edition. Longman Scientific and Technical Essex.

Jabbagy, E.G. and Jackson, R.B. 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecological Applications 10: 423-436.

Liang, B. C., McConkey, B. G., Schoenau, J., Curtin, D., Campbell, D. A., Moulin, A. P., Lafond, G. P., Brandt, S.A. and Wang, W. 2003. Effect of tillage and crop rotations on the light fraction organic carbon and carbon mineralization in Chernozemic soils of Saskatchewan. Can. J. Soil Sci. 83: 65-72.

McConkey, B. G., Liang, B. C., and Campbell, C. A. 1999. Estimating gains of soil carbon over a 15-year period due to changes in fallow frequency, tillage system and fertilization practices for the Canadian Prairies (An Expert Opinion). Misc. Publication#379M0209. Swift Current: Semiarid Prairie Agricultural Research Centre, Agriculture and Agrifood Canada.

McGill, W.B., Campbell C. A., Dormaar, J.F., Paul, A. E., and Anderson, D. W. 1981. Soil organic matter losses. Pages 30-48 *in* Agricultural lands, our disappearing heritage. Proceedings of the 18th Annual Alberta Soil Science Workshop, Edmonton.

McGill, W. B. 1996. Review and classification of ten soil organic carbon models. Pages 111-132 *in* D.S. Powlson, P. Smith and J.U. Smith eds. Evaluation of soil organic models using existing long-term data sets. NATO ASI Series I, Volume38, Springer-Verlag, Heidelgerg.

SAS Statistical Analysis Systems. 2004. Cary, NC: Statistical Analysis Systems Institute.

Sauvé, J. L. 2000. A preliminary assessment of carbon dioxide and nitrous oxide emissions from agricultural soils in Alberta. Alberta Agriculture Food and Rural Development, AESA Soil Quality Committee.

Smith, W. N., Rochette, P., Monreal, C., Desjardins, R. L., Pattery, E. and Jaques, A. 1997. The rate of carbon change in agricultural soils in Canada at the landscape level. Can. J. Soil Sci. 77: 219-229.

Voroney, R. P., Van Veen J. A., and Paul, E. A. 1981. Organic C dynamics in grassland soils. 2. Model validation and simulation of the long-term effects of cultivation and rainfall erosion. Can. J. Soil Sci. 61:211-224.

10.0 Appendices

10.1 Total profile organic carbon by site and slope position

10.2 Organic carbon in surface 15cm of soil (1998 to 2004)

10.3 Comparisons of soils from benchmark sites to soils from the AGRASID database, assigned to the same soil polygon: A horizons only

10.4 Comparisons of organic carbon distribution within the profile to a depth of 100 cm for soils from benchmark sites and soils from the AGRASID database.

10.5 Management and cropping practices at benchmark sites

10.6 Crop residue inputs

10.7 Precipitation maps for Alberta 1998 to 2004

10.8 Predicted changes in soil organic carbon for Alberta