Volume 2:

AESA Soil Quality Monitoring Project

Assessment of Environmental Sustainability in Alberta's Agricultural Watersheds Project

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EXECUTIVE SUMMARY

Soil quality, which can be defined as "the capacity of the soil to function", is crucial for agricultural crop, range, and woodland production and can assist in maintaining natural resources such as water, air, wildlife habitat, and biodiversity. Because soil is closely linked with crop productivity and environmental health, maintaining and/or improving soil quality in Alberta was identified as a key element in Alberta Agriculture, Food and Rural Development's Alberta Environmentally Sustainable Agriculture (AESA) Program.

In 1997, the AESA Soil Quality Monitoring Program was initiated, with the goals of assessing:

- the state of soil quality across Alberta,
- the risk of change in soil quality resulting from farm management practices, and
- how soil quality can be integrated into concepts of environmental sustainability.

To achieve these goals, the AESA Soil Quality Monitoring Program set out in 1997 to:

- monitor soils through a multi-site benchmark program,
- provide extension services and information to stakeholders,
- assess the risk associated with soil loss or deterioration on agricultural production, and
- develop the science and understanding of soil quality in an Alberta context.

To address the AESA Soil Quality Monitoring Program's goal of monitoring soils using a multi-site benchmark program, the AESA Soil Quality Benchmark Sites program was developed. This program consisted of 42 benchmark sites representing farms and soils in each of Alberta's seven main agricultural ecoregions. Soil quality indicators (e.g., bulk density, organic matter, fertility, etc.) were monitored at each site from 1998 to 2006, where data were collected at three landscape positions along a catena (upper, mid and lower landscape position), as well as at two sampling depths (0 to 15 cm and 15 to 30 cm).

Specifically, the AESA Soil Quality Benchmark Sites program was designed to:

- provide spatial and temporal baseline soil information across the province,
- evaluate landscape position effects on soil properties and quality,
- provide a dataset to test and validate simulation models,
- monitor changes in soil quality on a field landscape basis over time, and
- examine the relationship between farm management practices and soil quality, if changes in soil quality were identified.

The first phase of the report examined the data collected from 1998 to 2000 from the initial soil pedological characterization of the AESA Soil Quality Benchmark sites. In general, the results indicate that the benchmark sites included in the study were representative of agricultural sites in Alberta. As such, the results of the soil monitoring study may be extrapolated across ecoregions and throughout the entire province.

Initially, a total of 43 benchmark sites were identified and characterized, although one site was removed shortly after the program started. All remaining sites were positioned within the Boreal Plains and Prairies ecozones and were from one of Alberta's seven main agricultural ecoregions: Aspen Parkland, Boreal Transition, Fescue Grassland, Mid-Boreal Uplands, Mixed Grassland, Moist Mixed Grassland and Peace Lowland.

Ninety-five percent of the chosen benchmark sites were representative of their provincial ecodistricts, with only two profiles being darker in colour and higher in organic carbon than expected. The majority of selected sites were gently undulating loam soils on morainal parent materials in the dryland regions of Alberta. Soil texture, cation exchange capacity, calcium carbonate content, and soil pH reflected regional differences in the quaternary geology and agricultural practices employed in Alberta. For example, southern Alberta was characterized by higher pH and sandier textured soil profiles; whereas, the Peace Lowland, being derived from marine shale deposits, exhibited finer soil textures and higher cation exchanges capacities. Owing to climatic and vegetative differences, starting point organic carbon levels were significantly greater in northern Alberta compared to southern Alberta, but were found to differ based on soil horizon and landscape position. Upper landscape positions typically had lower organic carbon levels, particularly in the A horizon. Similar results were observed for total soil N, although other soil nutrients differed in relation to soil properties, landscape position and ecoregion.

The chosen benchmark sites also encompassed a range of agricultural practices and soil landscapes. Thirty-nine sites were located on dryland landscapes with the majority following some form of annual cultivation (predominantly minimum tillage), while the irrigation region of southern Alberta was represented with three sites located in the Mixed Grassland ecoregion.

The second phase of the study examined nine years of data collected at 42 AESA Soil Quality Benchmark sites. Variability in the dataset was highest for the nitrogen and sulfur related soil parameters (i.e. nitrate nitrogen, ammonium nitrogen and sulfate), likely due to their high mobility and resulting instability in agricultural systems.

In general, differences in soil quality across the province were driven by landscape position, sampling depth, year, and to a lesser extent, ecoregion. Landscape position effects were the largest driver of fluctuations in soil quality across the province and were highly dependent on ecoregion, reflecting climatic trends and/or management practices common to a given ecoregion. For parameters that were measured at two sampling depths, sampling depth was often a significant source of variation in soil quality, reflecting the effects of management, weather and different soil processes that occur at upper and lower soil depths. In many cases, the effect of year was significant on the various soil quality measures. Ecoregions also differed for some soil quality parameters (e.g., organic carbon), although soil quality fluctuations among ecoregions did not differ according to year, suggesting that ecoregions responded similarly to year-to-year variation. This indicates that differences at the ecoregion level were reflective of long-term climatic trends and other factors, such as management, rather than year-to-year variations in weather.

Provincially, only bulk density and soil test phosphorus concentration showed significant trends over time, suggesting that soil quality in Alberta stayed relatively constant under production practices used during the period of this study. Reflective of site management that includes reduced tillage and the increased use of forages in rotation, bulk density appears to have decreased over time; whereas, soil test phosphorus appears to have increased over the duration of the study, but remains below marginal soil test levels for optimum crop growth.

Farm practices from the agronomic history of the sites also remained relatively stable during the nine years that soil monitoring took place in Alberta. Preliminary analysis of the agronomic data with respect to the observed changes in soil quality appeared to indicate that farm management did play a role in some of these changes, although further analysis of the agronomic data is necessary to directly correlate farm management to changes in soil quality. However, as no major changes in agronomic practices were observed to have occurred, no drastic changes in soil quality were expected.

In conclusion, although limited in time frame with respect to changes in many soil quality parameters, the results of this study on Alberta’s agricultural land is still a good news story. In general, it appears that agricultural production using farm practices currently employed by many producers across the province has not had a negative impact on the soil resources of Alberta’s agricultural areas.

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INTRODUCTION

The concept of soil quality is often defined as “the capacity of the soil to function” (Karlen et al. 1997) although other definitions exist in the literature (Larson and Pierce 1994, Acton and Gregorich 1995). Soil supports and sustains agricultural crops, range and woodland production, and functions in water and solute flow and retention, physical stability and support, nutrient cycling, and buffering and filtering of toxic substances (Daily et al. 1997, Bolinder et al. 1999, Brejda et al. 2000a, b, Carter 2002, Wander et al. 2002). Soil is also important in maintaining natural resources such as water, air, wildlife habitat, and biodiversity (Daily et al. 1997, Karlen et al. 1997, Knoepp et al. 2000, Karlen et al. 2003, Andrews et al. 2004).

Interest in maintaining and/or improving soil quality has had a long history on the Canadian prairies (Bremer and Ellert 2004). Most notably, it began in response to the severe drought of the early 1930s, the “Dust Bowl” years, where dust storms, soil erosion and crop failure were common occurrences throughout much of the annually cropped farm area of western North America. To combat the problem in Canada, the Prairie Farm Rehabilitation Administration (PFRA) was created in 1935 to promote farm practices that minimized soil erosion and deterioration and ensured greater economic security in western Canada (Vaisey et al. 2000). Legislation in Alberta supporting these goals was put in place in 1935 (the Soil Drifting Act), and was later replaced with Canada’s only Soil Conservation Act in 1962. Furthermore, the National Soil Conservation Program (NSCP), under PFRA, was established in 1989 to address and make recommendations for specific provincial soil degradation problems across the prairie region (Vaisey et al. 2000). The Permanent Cover Program (PCP) of 1989 and 1991 provides an example of these recommendations.

Questions continue in the scientific literature relative to the measurement, reporting and interpretation of concepts surrounding soil quality (Karlen et al. 2003, Sojka and Upchurch 1999, Letey et al. 2003). To identify these differing opinions, Hall (2003) conducted a summary of the literature for the AESA Soil Quality Monitoring Program, with the intent of synthesizing the available information (to 2003) on soil quality and soil quality indices. This work and the work of Bremer and Ellert (2004) identified several key outcomes, or accountability indicators, to justify soil and/or land monitoring over time. These included crop production goals, clean water and air, low greenhouse gas emissions, safe and nutritious food and the preservation of wildlife habitat (Bremer and Ellert 2004). All of these potential outcomes of soil/land monitoring have a number of biological, chemical or physical indicators from which they can be compared over time:

- *Crop productivity.* The role of soil quality relative to crop productivity can be defined as the ability of the soil resource not to limit the production of absolute, attainable, affordable and actual yields as described in the model of Cook and Veseth (1991).
- *Water quality.* The maintenance of soil quality provides safe, high quality, water through a reduction in soil erosion (suspended solid), nutrient (chemical and organic) and health concerns (fecal coliform and/or pesticides).
- *Air quality.* Appropriate land and soil management reduces the potential for soil (and possible contaminants in the soil) to become airborne as particulate matter (dust). Thereby increasing the risk of human and animal health.

- *Greenhouse gas emissions.* Proper soil management through the use of permanent cover, reduced till and the appropriate application timing and placement of nutrients (chemical and organic) not only improves soil quality, but reduces potential losses of CO_2, N_2O and CH_4.
- *Safe, nutritious food.* A quality soil can ensure the production of foods that avoid potential contamination from heavy metals and pathogens in the soil, but that maintain high levels of healthy micronutrients, proteins and energy.
- *Wildlife habitat.* Generally there is an inverse relationship between the quality of wildlife habitat and the intensity of soil resource use. Maintaining a high quality soil, inevitably leads to the maintenance of biodiversity.

In the mid 1990s, the Government of Alberta's Ministry of Agriculture, Food and Rural Development (AAFRD, now referred to as Alberta Agriculture and Rural Development (ARD)) adopted several accountability performance indicators for natural resources, including soil quality. This was in response to increasing awareness of the environment and our use of natural resources, such as soil and water. This led to the establishment of the AESA Soil Quality Monitoring Program in 1997. At that time, maintaining and/or improving soil quality was identified as a significant research priority by Alberta industry stakeholders and as a key element to the newly created Alberta Environmentally Sustainable Agriculture (AESA) Program. The AESA Soil Quality Program followed directly from work completed under the Canada-Alberta Environmentally Sustainable Agriculture (CAESA) Soil Quality Program from 1994 to 1997, where data were collected on wind and water erosion, soil salinity, organic matter content, and land use (Wang et al. 1994). The three goals of the AESA Soil Quality Monitoring Program were to determine:

- the state of soil quality across Alberta,
- the risk of change in soil quality resulting from farm management practices, and
- how soil quality can be integrated into concepts of environmental sustainability.

The AESA Soil Quality Monitoring Program balanced its operation in the three main areas of education, training and research using four separate, but equally important components:

- *Monitoring.* The soil resource located in the agricultural regions of Alberta was monitored through a multi-site benchmark program, which included the collection of soil and crop samples. Agronomic information from each site was also collected on an annual basis.
- *Extension.* Awareness of soil quality and issues surrounding factors that could potentially change soil quality were presented and discussed across the province. Information was presented at conferences, workshops, field days and tours. Educational materials were also developed for elementary school programs.
- *Risk assessment.* Numerous projects that helped to identify, assess and mitigate risk associated with soil loss or deterioration have been done. For example, the Soil Quality Program has focused in the areas of erosion, soil quality modeling and GIS technologies to delineate high risk areas.
- *Science development.* Development of the science and understanding of soil quality has been an important component to the AESA Soil Quality Program,

and this has led to a number of successful partnerships with academics throughout Canada that furthered the concepts of soil quality.

During the 10 years that the AESA Soil Quality Monitoring Program was operational (1997 to 2007), these components generated a large number of projects and a significant amount of information that could be used by the AESA Soil Quality Monitoring Program, other government divisions and/or ministries, academic institutions and/or in a number of partnerships with private consulting companies (Appendix 1). Examples of this work include evaluation of field methods to estimate soil organic matter levels (Card 2004), evaluation of the United States Department of Agriculture (USDA) Soil Quality Test Kit (Winder et al. 2003), evaluation of soil sampling strategies (Cathcart and Huang 2005) and regional assessments of 2,4-D mineralization (Gaultier et al. 2008). It is important to note that of the four main components, soil monitoring represented the backbone of the program, and provided a significant quantity of information that could be used by the other three components to ensure their continued success.

Developers of the AESA Soil Quality Monitoring Program (AESA Soil Quality Committee 1998) agreed that mechanistic modeling would be the key strategy/technique used in the future to assess soil quality on a provincial scale. Adoption of this strategy addressed several concerns, including limited resources to hire additional personnel to conduct sampling and to fund extensive annual soil analyses on samples collected from across all areas of the province. In order to verify modeled estimates however, a cross-validation dataset representing agricultural soil conditions across the province would be required. Once these benchmark sites were established, the annual data could be used to determine long-term temporal changes as well as verify trends predicted by soil and/or crop models. This led to a significant expansion of soil monitoring in 1997/98, with the establishment of the AESA Soil Quality Benchmark Sites program across the agricultural areas (i.e., white zone) of Alberta. This benchmark program constituted the very basis of the AESA Soil Quality Monitoring Program.

Although a number of soil benchmark programs exist worldwide (Bernes et al. 1986, Kellogg et al. 1994, Sanka and Patterson 1995, Skinner and Todd 1998, Mol et al. 2001, Sparling et al. 2004), the AESA Soil Quality Benchmark Sites were unique in that they included all agricultural regions of Alberta and that the sampling intensity was annually at three distinct landscape positions along a catena (upper, mid and lower landscape positions). This supported the suggestions of Pennock et al. (1994), who emphasized the need for landscape-scale research on soil, particularly in rain-fed agricultural systems on the Canadian prairies. These soils are often prone to significant changes in soil quality without proper management. The chosen indicators of soil quality included fertility, bulk density, organic matter and crop yield. These indicators were chosen based on those suggested by Knoepp et al. (2000) in that they were responsive to farm management, were integrative to ecological processes, and were, or could be components of existing data bases, within government and/or academia. The objectives of the AESA Soil Quality Benchmark Sites program were to conduct annual autumn soil sampling to:

- provide spatial and temporal baseline soil information across the province,
- evaluate landscape position effects on soil properties and quality,
- provide a dataset to test and validate simulation models,
- monitor changes in soil quality on a field landscape basis over time, and

- examine the relationship between farm management practices and soil quality, if changes in soil quality were identified.

The emphasis of the sampling protocol was on autumn sampling, following crop harvest, but prior to fall fertilization or soil freeze-up. Employing this protocol allowed for yearly comparisons to be made for each measured soil parameter (i.e., to assess trends over time). These comparisons would not have been possible if sampling had been conducted at different times during each year of the study. By remaining consistent in the timing of soil (and crop) sampling, soils (crops) experienced a similar length of season each year, prior to the measurement of a specific parameter. This was particularly important with highly mobile and/or seasonally variable parameters, such as nitrate or bulk density.

In addition to changes in soil parameters attributable to landscape position effects or spatial location in the province, another objective of the AESA Soil Quality Benchmark Sites program was to examine the relationship between soil properties as a result of farm management practices. Management practices are known to have significant effects on numerous parameters associated with soil quality over time (Pennock et al. 1994, Bolinder et al. 1999). Specifically, the aim was to follow any potential changes in soil quality as a response to the natural trajectory of farm agronomic practices employed by the cooperators in the study. For this reason, no specific farm practices were dictated at any of the benchmark sites. The practices employed were, however, left to the discretion of the producer and were recorded during the AESA Soil Quality Monitoring Program.

Objectives of this Report

The purpose of this report is to summarize, analyze, and interpret the soil parameter data that were collected from the 42 AESA Soil Quality Benchmark sites from 1998 to 2006. To accomplish these objectives, two phases of analysis were identified and carried out; the results of which are presented in this document.

Phase One. The first phase of the project was to examine the data that were collected from 1998 to 2000 for the initial soil pedological characterization of the AESA Soil Quality Benchmark sites (Cathcart et al. 2008). These data were collected over a three-year period, early in the study, by soil scientists employed by Can-Ag Enterprises Ltd. (now Paragon Soils, Edmonton, AB). It is important to note that annual soil sampling (as discussed in Phase Two) had occurred on approximately half of the Benchmark Sites program prior to the completion of the data collection period of Phase one (i.e., annual data were collected prior to the completion of site characterization in 1999 or 2000).

Specifically, phase one of this report provides:

- a detailed description of the AESA Soil Quality Benchmark site selection procedures and the various monitoring processes employed at each site, and

- an analysis to determine how representative the selected AESA Soil Quality Benchmark sites were of the ecoregions from which they were selected.

To answer the second objective of phase one, data collected from each site and the ecoregion from which the site was located, were compared with the accepted descriptions from publications such as the *Agricultural Region of Alberta Soil Inventory Database* (AGRASID, 1:100,000 scale) (Brierley et al. 1998), *The Canadian System of Soil Classification. 2nd ed.* (Agriculture Canada Expert Committee on Soil Survey 1987) and *The National Ecological Framework for Canada* (Ecological Stratification Working Group 1995). Furthermore, comparisons also involved expert opinion at the time.

Phase Two. The objectives of the second phase of the analysis were twofold. The first was to explore and analyze the data to answer two main questions (where appropriate):

- What are the mean parameter values for year of sampling, ecoregion, landscape position and sampling depth?
- What are the significant differences between temporal (year) and spatial (ecoregion, landscape position and depth) effects and their interactions for measured soil parameters?

To answer these questions, it was necessary to (a) determine the most appropriate analytical design for the annually collected data based on a brief literature search, (b) clearly outline the required SAS programming using PROC MIXED (SAS Institute 2002), and (c) conduct the analysis of variance to explore and identify whether certain main effects and/or their second order interactions were significant.

The second component of phase two involved a regression analysis to identify trends (and their level of significance) in soil parameters over time (i.e., year of sampling). This was done with the goal of answering the following two questions:

- Within a given ecoregion and within the province as a whole (using the entire, combined data set), what are the overall trends (i.e., slope of the line) in soil parameters, and are these significant (i.e., slope $\neq 0$)?
- When comparing the observed trends in soil parameters, when significant slopes existed, were there differences among ecoregions?

Similar to the above analysis of variance, this component also required that the data be explored, and an appropriate statistical design using regression analysis (separated by landscape position and sampling depth) be constructed using the PROC REG procedure in SAS.

MATERIALS AND METHODS

Benchmark Site Selection

Forty-three of the 100 ecodistricts located in Alberta's agricultural area were chosen as monitoring sites. Ecodistricts represent areas characterized by distinctive assemblages of abiotic and biotic characteristics including, but not limited to, soils, climate, and land use (Ecological Stratification Working Group 1995). Ecodistricts are distributed geographically across the province and are further stratified based on major land use and landscape patterns (Figure 1).

Stratification of sites in accordance with the Canadian National Ecostratification Network (Ecological Stratification Working Group 1995) allowed for use of other relevant databases and to provide a basis for comparison with other initiatives across Canada. Soil, climate, and landscape information for each of the chosen ecodistricts was obtained using the *Agricultural Region of Alberta Soil Inventory Database* (AGRASID, 1:100,000 scale) (Brierley et al. 1998) and *The National Ecological Framework for Canada* (Ecological Stratification Working Group 1995). Characteristic surface landforms, soil textures and soil types were identified for each ecodistrict and used in the site selection process.

The selected sites occurred only on cultivated land (including domestic forage in rotation) and each is representative of the soil-landscape pattern and agricultural land-use found in the ecodistrict in which it is located. Field headlands and corners, pipeline right-of-ways, watercourses, and areas of heavy weed infestation were avoided during site selection. Selection of the benchmark sites was further confined based on the need to maintain long-term site security and to minimize interference in the producer's field operations during the growing season.

In addition to the legal location, benchmark sites were located in each field site using a real-time differential global positioning system (DGPS using geostationary satellite corrections – OmniStar) to permit annual repositioning. Two brands of the same class of receivers were used: Trimble AgGPS®132 (Cansel Survey Equipment, Edmonton, AB) and Satloc SLXg (Yorkton Aircraft Hangar 2, Yorkton, SK). Both receivers used a real-time geostationary differential correction service (OmniStar, Houston, TX) so that the quality of corrections would be consistent regardless of where in the province the equipment was being used.

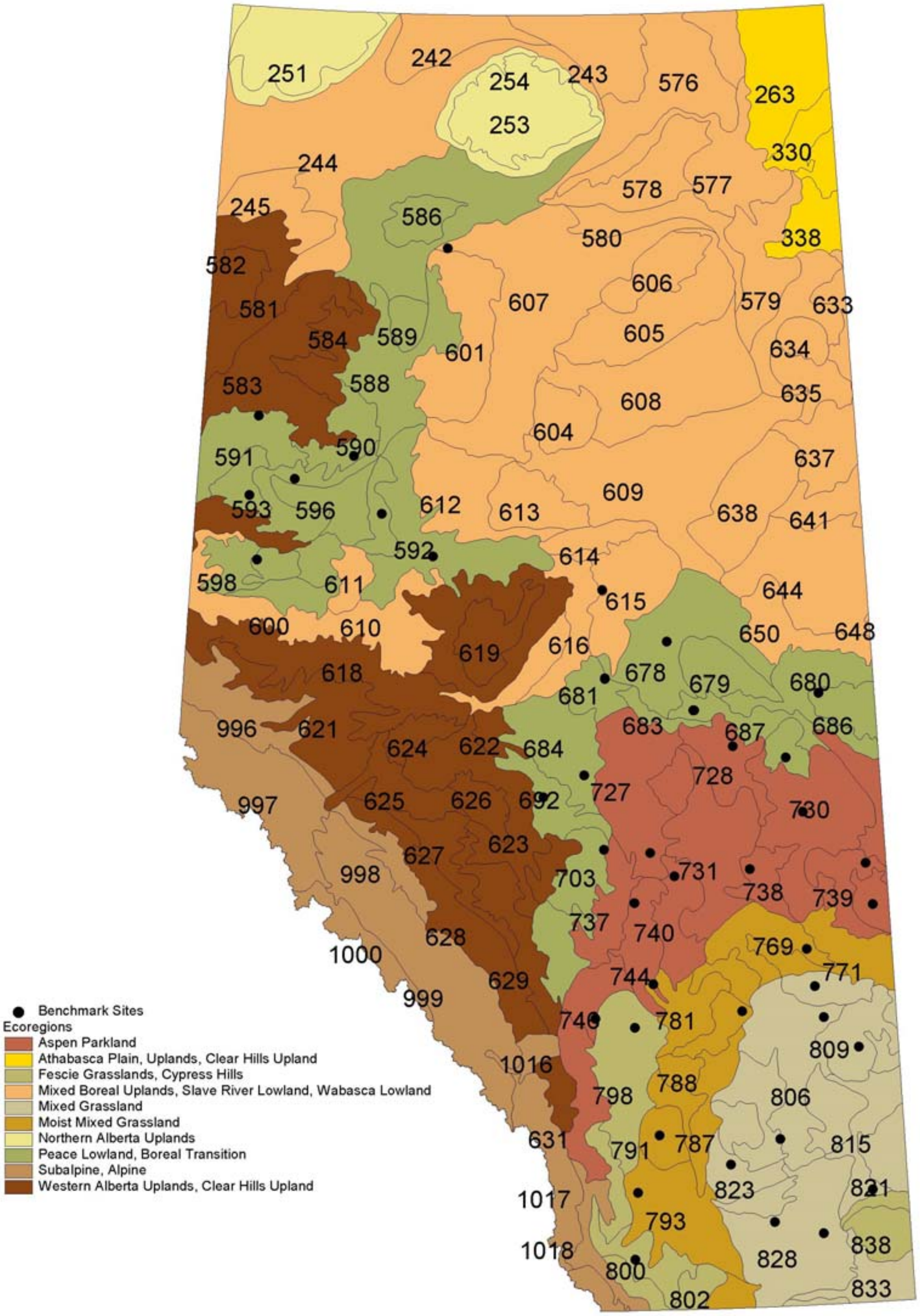

Figure 1. Location of the AESA Soil Quality Benchmark sites within ecozones, ecoregions and ecodistricts (numbered) of Alberta, Canada.
Note that only 9 sites are indicated in the Peace Lowland, as site 598 was removed from the program in 2002.

Field Soil Inspection and Site Description

Each benchmark site consisted of three sample locations at an upper, mid and lower landscape position along a catena. Soil scientists with Can-Ag Enterprises Ltd. (now Paragon Soils, Edmonton, AB) completed site characterization, profile descriptions and sampling for each of the landscape positions within the benchmark site. This was done to ensure that each site could be compared to provincial data and that it was representative of the ecodistrict within which it was located. The soil pit and pedological studies were done in late fall, after harvest when the soils were relatively dry, and not frozen. A total of 20 initial soil inspections were completed between 22 September and 6 October 1998. Twenty-two more inspections were conducted between 30 September and 23 November 1999, and one last field site was inspected on 2 November 2000. One benchmark site (site 598, located in the Peace Lowland) withdrew from the program in 2002, resulting in a program consisting of 42 sites.

Soil profiles were sampled to a depth of 100 cm and classified according to *The Canadian System of Soil Classification, 3rd Edition* (Soil Classification Working Group 1998). At each site, a drop sheet with a 30 cm diameter hole was placed on the ground to prevent admixing with surrounding surface soil. The soil pit was dug through this hole and excavated soil from each of the principal horizons was placed separately on the drop sheet. After site characterization, classification and horizon sampling, the soil was replaced, by principal horizon, and no soil was left on the surface.

Pedon descriptions of the soil pit included parent geological material, soil horizons and thickness, colour, texture, structure, consistence, and vegetation rooting characteristics. Landscape descriptions, including the landscape position, drainage, stoniness, transect aspect, present erosion, and moisture regime of the site were also recorded (Leskiw et al. 2000).

Soil samples from each of the principal horizons (A, B, BC and/or C) were collected and delivered to the laboratory (Norwest Labs Ltd., Edmonton, AB) for analyses. Analyses to characterize each site included: particle size analysis by hydrometer (Gee and Bauder 1986); cation exchange capacity (CEC); pH in $CaCl_2$ and H_2O; extractable NH_4-N, NO_3-N, soil test phosphorus, K and SO_4-S (McKeague 1978); total nitrogen (Dumas method, FP-528, LECO Corporation, St. Joseph, MI); organic carbon (McKeague 1978); and calcium carbonate ($CaCO_3$) (Goh et al. 1993). Bulk density samples (7.5 cm diameter and 7.6 cm depth) were taken in duplicate for the topsoil (sampled at a depth between 3 to 15 cm), and for the subsoil (sampled at a depth between 20 cm to 50 cm) (McKeague 1978). On completion of sampling, photographs of each soil pit were taken and aerial photos obtained for each site from Alberta Sustainable Resource Development’s Air Photo Services (Edmonton, AB)

Annual Field Sampling and Laboratory Analyses

Four ARD regional conservation teams and the same analytical laboratory carried out the annual soil and crop analyses from 1998 to 2006. This was done to ensure that the same protocols were used on a yearly basis in the field and lab. Annual training and refresher courses on sampling procedures were also conducted, and the same sampling equipment was supplied to each of the four teams to further ensure consistency among regions.

The specific soil and crop parameters selected were based on common soil and crop analyses performed for Alberta producers, literature review, and on the database requirements of current soil/crop models under development by ARD. Sampling of soil was conducted only in the fall to ensure that comparisons among years could be made. If soil sampling had been conducted at differing times each year (e.g., spring of 1999 and fall of 2000), it would not be possible to fulfill the goals of the AESA Soil Quality Benchmark Sites program.

Soil Sampling. Soil samples were taken each fall after harvest, but before freeze-up and prior to fall fertilization or tillage. From each of the three landscape positions, ten soil cores were taken within 2 m of the centre marker from the 0 to 15 cm and 15 to 30 cm depth using either a core sampler (STAR soil sampler, Star Quality Samplers, Edmonton, AB) or dutch auger (Commercial Solutions Inc., Edmonton, AB). A composite sample of approximately 2 kg was sent to the laboratory within 24 hours of sampling. The remaining soil not used by the laboratory was placed in 500 mL glass jars and archived in a heated facility for future analyses, if warranted.

Once at the lab, the soil samples were air-dried at 45 ºC for 4 to 6 hours and ground to pass a 10-mesh sieve (<2 mm diameter). Annual soil samples were analyzed for fertility (extractable N, P, K, and S), pH in water and $CaCl_2$, electrical conductivity (EC), sodium adsorption ratio (SAR, if EC >4), mineralizable N and light fraction carbon (LFC) using the appropriate methodologies as described in McKeague (1978), Campbell et al. (1997) and Gregorich and Ellert (1993). Additional information, including specific measurement units, is in Table 1.

In addition to the chemical analyses, topsoil bulk density for each of the three landscape positions was done *in situ*, starting 1 to 2 cm below the soil surface, using a 7.5 cm diameter (7.6 cm in depth) Tube Density Sampler (Model E129-5450, ELE International Soiltest Product Division, Loveland, CO). The samples were then oven dried at 105ºC for 24 hours and the bulk density determined according to the methodology outlined by McKeague (1978).

Table 1. Summary of measured soil parameters and unit of measurement.

Parameter	Unit	Comments
Soil fertility:		
Nitrate N (NO_3-N)	mg kg^{-1}	- available, 2 depths[z]
Ammonium N (NH_4-N)	mg kg^{-1}	- available, 2 depths
Hot KCl Extractable N (KCl - NH_4-N)	mg kg^{-1}	- hot KCl extractable, includes tightly bound NH_4, 2 depths
Soil Test Phosphorus (STP)	mg kg^{-1}	- available, 2 depths
Potassium (K)	mg kg^{-1}	- available, 2 depths
Sulfate S (SO_4-S)	mg kg^{-1}	- available, 2 depths
Chemical/Physical:		
pHw	---	- 1:2 soil:water, 2 depths
pHc	---	- 1:2 soil: $CaCl_2$ solution, 2 depths
Electrical Conductivity (EC)	dSm^{-1}	- @ 25°C, saturate paste extract, 2 depths
Bulk Density (BD)	Mg m^{-3}	- 2 depths
Biologically derived:		
Organic Matter (OM)	%	- by weight, loss on ignition, 2 depths
OM	kg m^{-2}	- kg m^{-2} = OM x BD x 1.5
Organic Carbon (OC)	kg m^{-2}	- kg m^{-2} = (OM/1.724) x BD x 1.5. Assumes OM = 58% OC
Light Fraction Organic Matter (LF)	mg g^{-1}	- 0 to 15 cm only
Light Fraction Carbon (LFC)	%	- 0 to 15 cm only
Light Fraction Nitrogen (LFN)	%	- 0 to 15 cm only
LFC_{mass}	mg g^{-1}	- mg C g^{-1} = mg LF g^{-1}_{soil} x (LFC/100), 0 to 15 cm only
LFN_{mass}	mg g^{-1}	- mg N g^{-1} = mg LF g^{-1}_{soil} x (LFN/100), 0 to 15 cm only

[z] The two depths sampled were 0 to 15 cm and 15 to 30 cm.

Plant Sampling. Although the results are not discussed in this report, crop biomass and/or yield samples were also sampled as close to the time of crop maturity as possible. At each of the sampling positions along the catena, three plant harvest clips were taken. Plants were clipped at ground level, leaving minimal stubble, and were then ground and sent for feed analyses.

Agronomic Practices. Although not specifically analyzed in this report, the cooperators at each site provided annual agronomic information about their operation including (a) crop rotations and crop cultivar (crop seeded, method, and rate), (b) fertilizer applications (type, method, and rate), (c) tillage systems (method and frequency), (d) herbicide applications (type, method, and rate), (e) harvest methods and (f) an indication of general crop yields from the surrounding areas. This information remains in the ARD database. It is also important to note that since the start of the study in 1998, agronomic practices were not kept consistent at each site, but varied in accordance with the general farming practices on a yearly basis. However, each benchmark site was chosen to be representative of practices used in the ecodistrict within which each benchmark was located.

Climate Data. As part of the agronomic information collected for each site, temperature and rainfall data from meteorological stations close to each benchmark site were recorded in the Benchmark Sites database, although cooperators were also asked to document any abnormal climatic events such as early (late) frost and/or hail throughout the duration of the study. These data are maintained within the ARD database.

Statistical Design

Phase One: Pedological Characterization. The distributions of benchmark soil parameters from the initial pedological investigation were tested for normality using the D'Agostino-Pearson K^2 test (D'Agostino et al. 1990). The omnibus χ^2 test was used for detecting deviation from normality caused by skewness and/or kurtosis, and is applicable over a broad range of non-normal distributions. Computation of the K^2 statistic was accomplished using a SAS macro provided by D'Agostino et al. (1990). Soil properties not conforming to normality were log-transformed and retested. A decision as to whether to use the log-transformed data was then made depending on the degree of improvement achieved through the transformation.

Soil parameter means, medians, standard deviations, and their coefficients of variation (CV) were calculated using PROC UNIVARIATE in SAS (SAS Institute 2002). Comparisons between region and landscape position were made using PROC GLM, and means comparisons were identified by the Tukey method. The Mid-Boreal Uplands (MB) site was excluded from the ANOVA, as it was the lone site in that region and therefore not statistically representative of the surrounding area. For all tests, the probability of making a Type-1 error was assessed according to $\alpha=0.05$. PROC GLM procedures were used to determine if any significant differences in soil parameters existed due to ecoregion and/or landscape position.

Phase Two: Provincial and Ecoregion Analyses of Variance. Following the analysis of the initial pedological data, one of the main objectives of this study was to develop an experimental design that clearly outlined the statistical methods and procedures that could be used to analyze the annually collected data. Previous analyses of these data had consisted mostly of descriptive statistics performed on portions of the dataset (Keyes 2005, Leskiw and Sansom 2001, Penney 2004) and analyses of variance (ANOVA) performed using the PROC GLM procedure in SAS (Leskiw and Sansom 2001). However, these analyses yielded only limited insight into the true dynamics of soil quality over the entire monitoring period from 1998 to 2006. Descriptive statistics fail to account for interactions between fixed factors such as year, ecoregion, sampling depth, and position within topography, as well as variations in random factors such as sampling site and crop type, which are ecoregion or site-specific, respectively. In general, mixed models (models containing fixed and random effects) are more appropriately analyzed in SAS using the PROC MIXED procedure, rather than the PROC GLM procedure. This is because, although most tests of hypotheses in analyses of variance can be computed correctly with PROC GLM with optional specifications such as the TEST statement, standard errors from LSMEANS and ESTIMATE statements in PROC GLM are not computed correctly (Littell et al. 1998). A further advantage of using PROC MIXED over PROC GLM is that PROC MIXED uses a likelihood-based estimation method for missing data, while PROC GLM uses a method of moments that require the entire dataset (Wolfinger and Chang 1998). As a result, all available data can be used in the PROC MIXED analyses without ignoring subjects with missing data, hence making the PROC MIXED procedure the most appropriate for unbalanced datasets such as the dataset derived from the AESA Soil Quality Benchmark Sites.

Experimental Design - The experiment was a multi-level incomplete block design consisting of nine years of sampling (1998 to 2006) representing the blocks, and seven ecoregions representing the main plot factor. Although samples were taken in time, the data were not analyzed by repeated measures analyses due to the fact that the crop types did not remain fixed but varied for each sampling year. Sampling took place at different farm sites (SITE) within each ecoregion (ECO), thus is nested within ecoregion (SITE(ECO)) as it cannot be considered separately in the statistical model. The main-plot (SITE(ECO)) was split into sub-plots consisting of three positions of sampling within the topography (POS: upper, mid, and lower landscape position) and crop applied by factorial combination to the sub-plot. However, since crop types varied from site to site, the crop effect (CROP) was considered nested within site and ecoregion (CROP(SITE*ECO)). Within each sampling position, samples were taken from two depths (DEPTH: 0 to 15 cm and 15 to 30 cm), representing the final split in the design.

Response variables measured using the above experimental design include electrical conductivity (EC), ammonium N (NH_4-N), nitrate N (NO_3-N), soil pH in water and $CaCl_2$ (pHw and pHc), soil test phosphorus (STP), potassium (K), and sulfate S (SO_4-S) concentrations.

Other response variables, such as bulk density (BD), light fraction (LF), light fraction carbon and nitrogen mass (LFCmass and LFNmass), hot KCl extractable ammonium N (KCl - NH_4-N) and organic carbon (OC) were only measured at one depth (0 to 15 cm), thus the final split (i.e., DEPTH) in the above design was excluded.

Data Analysis - Analyses of variance for the entire province were performed using the PROC MIXED procedure in SAS (SAS Institute 2002). The number of sampling sites in each ecoregion ranged from two to nine, except in the Mid-Boreal Uplands (MB), where only one sampling site was established (Cathcart et al. 2008). Because one sampling site is not representative of an entire ecoregion, the data from the MB was removed from the analysis, thereby reducing the number of ecoregions included in the study to six.

Following the ANOVA at the provincial level, it became evident that the effects of DEPTH and associated interactions were significant for a number of variables measured at two depths. For many of the variables, particularly those related to soil fertility, it made sense to look at treatment effects and least squares means on a depth basis. Thus, another series of ANOVA’s were performed at each DEPTH, for variables measured at two depths.

As sites in this study were chosen to represent agricultural land-use in their respective ecoregions, the authors expected some differences to exist among sites. One difference that existed among sites in the Mixed Grassland ecoregion was the use of irrigation. Three of the eight sites in the Mixed Grassland were irrigated, while all other sites in the entire study were not. The authors wished to include these three sites in the analysis, in order to retain an accurate representation of agricultural management within that ecoregion, but also wished to investigate how the inclusion of those sites might affect the outcome of the various statistical analyses. Thus, the provincial ANOVA was conducted with and without the three irrigated sites from the Mixed Grassland.

In order to compare the results found here with the work of Penney (2004), coefficients of variation were computed using the PROC GLM procedure in SAS.

Statistical Model for the Provincial Analyses - Treatment effects are usually considered fixed if the treatments in the experiments are the only ones to which inferences will be made (Littell et al. 1996). Considering that one of the primary objectives of the AESA program was to investigate long-term changes in the soil quality in Alberta's agricultural areas as a result of soil use type and agricultural management practices, year of sampling (YEAR) was treated as a fixed effect. Ecoregions in this study were specific to Alberta, thus ecoregion effect (ECO) was considered a fixed factor, as a result of which any inferences made in this study with regards to the ecoregions will be specific to only Alberta. The interaction of YEAR and ECO was also treated as a fixed effect. Site nested within ecoregion (SITE(ECO)) was considered a random effect, as sites were chosen to represent a sample of the entire ecoregion. Crop nested within site and ecoregion (CROP(SITE*ECO)) was treated as a random factor also, since crop type varies among years and sites, and more importantly, because crops grown in the sampling years were a representation of agricultural crops and land use systems in Alberta.

At the sub-plot level POS and two-way interactions between POS, YEAR and ECO were considered fixed effects, while at the sub-sub plot level, DEPTH and two-way interactions between DEPTH, POS, YEAR and ECO were considered as fixed effects. Higher order interaction effects (e.g., three-way interactions) were not included in the statistical model due to lack of importance and explainability.

The sources of error for a design such as this are similar to that reported by Milliken (2003) for multi-level designs. On the whole-plot level, SITE(ECO), YEAR*SITE(ECO), CROP(SITE*ECO), and YEAR* CROP(SITE*ECO) represented the whole plot error while on the sub-plot level, the error term was represented by interactions between POS, YEAR, SITE(ECO) and CROP(SITE*ECO). The sub-sub plot error was represented by the residual error effect. Sample data structuring and SAS code for this analysis are in Appendix 2.

Regression Analysis - Regression analysis examines the relationship between a dependent variable, to a set of independent variables and can serve as a useful tool in exploratory analyses of the soil quality data derived from this program, such as in determining the general trend over time of the various soil properties monitored, and the statistical significance of such trends. Linear regression fits a simple linear mathematical model to the data and determines the best-fit values of the parameters of the model, such as the slope and the intercept (Motulsky and Christopoulus 2003). Slope and intercept values obtained from the linear regression models may also be useful in verifying and improving existing soil quality-related simulation models. In a regression model, the R^2 value is a fraction between 0 and 1 and measures the extent to which the linear model fits the data points and the outcome, where an R^2 value of 1 indicates a perfect linear relationship between two variables (Motulsky and Christopoulus 2003). The most common method for fitting a regression line is the method of least-squares, which calculates the best-fitting line for the observed data by minimizing the sum of the squares of the vertical deviations from each data point to the line.

Linear regression analyses were performed using ecoregion × year least-squares means for the entire province and for individual ecoregions, using the PROC REG procedure of SAS (SAS Institute 2002). These analyses tested the null hypothesis that the slope (i.e., regression coefficient) of the regression line ($y = mx + b$) is equal to zero. Where y is the value of the response variable, m is the slope estimate, x is the value of the independent variable (YEAR), and b is the estimate for the intercept. When significant regression coefficients were detected, further analyses were conducted to compare the regression coefficients between individual ecoregions. These analyses were performed using the SAS code outlined in Appendix 3.

Where soil parameters were measured at two sampling depths, regression analyses were performed independently for each depth. A further exploration was conducted to determine whether there were differences in the regression based on landscape position.

As in the ANOVA, two analyses were conducted for the Mixed Grassland, due to the presence of irrigated and non-irrigated sites in that ecoregion.

Correlation Analysis - In order to identify relationships among soil quality parameters, correlation analysis was performed using the PROC CORR procedure in SAS. For this cursory analysis, Pearson's coefficients of correlation were computed using the least-squares means from each ecoregion, averaged over depth and landscape position. This analysis was performed using the SAS code outlined in Appendix 4.

RESULTS AND DISCUSSION

In the following discussion, analyses conducted on the entire data set are referred to as "provincial level" analyses. The reasoning behind this nomenclature is that the analyses were conducted on data collected from all (i.e., n=41, MB excluded) benchmark sites located in six ecoregions in the agricultural area of Alberta (Figure 1). This differs from references to the smaller ecoregion level analyses (e.g., the Aspen Parkland), where only data collected from sites located within any given ecoregion (i.e., n=2 to 9, depending on ecoregion (Table 2)) are discussed. As the initial 1997 design of the program was to ensure that sites adhered to the *National Ecological Framework for Canada* (Ecological Stratification Working Group 1995), there is a level of comfort in extrapolating results from the AESA Soil Quality Benchmark Sites to larger areas of the province, and to the prairie regions of western Canada (Goddard 2008, personal communication, Policy Secretariat, ARD, Edmonton, Alberta).

Phase One: Pedological Characterization

Benchmark Site Location, Ecodistrict Characterization and Climate. A total of 43 benchmark sites were initially identified and characterized between 1998 and 2000. All sites were found to lie within the Boreal Plains and Prairies ecozones and were from the seven ecoregions: 10 sites were located in the Peace Lowland (PL), 1 site was located in the Mid-Boreal Uplands (MB), 8 sites were located in the Boreal Transition (BT), 9 sites were located in the Aspen Parkland (AP), 5 sites were located in the Moist Mixed Grassland (MM), 2 sites were located in the Fescue Grassland (FG), and 8 sites were located in the Mixed Grassland (MG)

(Figure 1). Ecoregions represent zones of similar abiotic/biotic environments, such as rainfall patterns and temperature regimes, soil types and natural vegetation (Ecological Stratification Working Group 1995). Specific site characteristics of each ecoregion are presented in Table 2. Note that in this table, only nine sites (N=9) are reported in the PL, resulting from one site in this ecoregion (Site 598) being removed from the AESA Soil Quality Benchmark Sites program in 2002.

Table 2. Site and soil characteristics for ecoregions with AESA Soil Quality Benchmark sites in Alberta, Canada. Mean value (and standard error) for January and July temperature, mean precipitation and growing degree days (GDD) (>5 ºC) were calculated using climatic data collected from 1961 to 1997 in Alberta.

Ecoregion [z]	Farm area	Soil Great Group	Climatic zone	Mean elevation	Mean temperature		Mean precipitation [x]	GDD [x]
					Jan.	July		
	(ha)[y]			(m)	(ºC)		(mm)	(>5 ºC)
Peace Lowland (PL) (n=9)	2,392,427 (11.4%)	Gray/Dark Gray Luvisol and Dark Gray Chernozem	Subhumid Low Boreal	536	-17.2 (0.32)	13.31 (0.058)	435 (11.9) – 517 (13.0)	1118 (21.6) – 1305 (17.9)
Mid-Boreal Uplands (MB) (n=1)	215,223 (1.0%)	Gray Luvisol, Gleysol and Brunisol	Subhumid Mid-Boreal	640	-16.4 (0.86)	15.5 (0.16)	508 (14.5)	1225 (18.9)
Boreal Transition (BT) (n=8)	3,127,493 (14.8%)	Gray Luvisol and Dark Gray Chernozem	Subhumid Low Boreal	697	15.0 (0.32)	15.92 (0.054)	428 (11.02) – 535 (13.5)	1287 (17.6) – 1384 (17.4)
Aspen Parkland (AP) (n=9)	5,457,399 (25.9%)	Black Chernozem	Transitional Grassland	775	-14.3 (0.29)	16.44 (0.059)	391 (8.3) – 478 (10.8)	1280 (16.3) – 1486 (18.5)
Moist Mixed Grassland (MM) (n=5)	2,871,283 (13.6%)	Dark Brown Chernozem and Solonetzic	Semiarid Grassland	880	-10.8 (1.49)	16.98 (0.084)	368 (8.8) – 422 (15.1)	1482 (163.8)– 1556 (18.8)
Fescue Grassland (FG) (n=2)	1,391,000 (6.6%)	Dark Brown Chernozem	Chinook Belt	1100	-9.5 (0.61)	15.6 (0.14)	427 (9.8) – 537 (19.4)	1290 (19.1) – 1362 (17.1)
Mixed Grassland (n=8)	4,012,162 (19%)	Brunisol, Brown Chernozem and Solonetzic	Semiarid Grassland	795	-12.8 (0.35)	17.86 (0.08)	314 (8.7) – 363 (15.1)	1459 (33.5) – 1774 (19.9)

[z] “n” = the number of benchmark sites located in each ecoregion.

[y] Value in parentheses represents the percentage of total farm area of Alberta (i.e., % of 21,067,489 ha). Summing the percent farm area for each ecoregion will not sum total 100%, as a result of ecoregions that are not included as part of the AESA Soil Quality Monitoring Program and areas attributed to farm sites in Alberta (approximately 8% of total farm area).

[x] Range in values over all of the ecodistricts/benchmark sites (i.e., n=) that are used in the calculation for that ecoregion.

Climatic parameters, such as growing degree days (>5ºC), January and July mean daily temperatures and annual precipitation were calculated for each of the ecoregions in which benchmark sites occur, based on the 1961 to 1997 climate normals (Table 2). The MG and MM ecoregions had the highest July temperatures and greatest number of Growing Degree Days (GDD), but also had the lowest annual precipitation. In comparison, the PL had the fewest GDD and coolest annual temperatures.

Within each ecoregion, the ecodistricts for each site were examined based on characteristics described in *The National Ecological Framework for Canada* (Ecological Stratification Working Group, 1995). Benchmark site dominant, subdominant and inclusive characteristics were compared to those described for each ecodistrict (Leskiw et al. 2000). Of the 42 selected benchmark sites, only two (site 586 and 592, Figure 1) located in the PL, did not fully conform to their respective ecoregions; each having a darker coloured A horizon than the dominant soil, resulting from higher organic matter levels. The remaining 40 sites were assessed as being typical examples of the ecoregion in which they were located.

Landscape and Soil Features of the Alberta Benchmark Sites. The AESA Soil Quality Benchmark sites encompassed a range of agricultural practices and soil landscapes. For example, sites were predominately located on dryland landscapes (39 sites) with the majority (30 sites) employing some form of annual cultivation, predominantly minimum tillage. As of 2000, nine of the selected dryland sites were identified as being forage based (Appendix 5, Note site 598 (also in forage) removed), although the exact percentage differed from year to year based on rotation. The irrigation region was represented with three sites (Sites 812, 823 and 828B, Figure 1) located in the MG ecoregion of southern Alberta.

A large number of sites (65%) were developed on morainal parent material with the rest being formed on either fluvial or lacustrine parent materials (Table 3). This is not surprising as most of Alberta is covered in glacial deposits ranging in thickness from less than 10 cm to hundreds of meters as a result of the Keewatin glaciation (Pawluk and Bayrock 1969). The majority of this material is locally derived unsorted till, and thus characteristic of the underlying bedrock material. The main lacustrine deposits in Alberta are a result of impounded glacial melt water from the last deglaciation. As a result of the local quaternary geology, the most common surface landform (19 sites) was undulating, while only one site was characterized as being hummocky (Table 3). The remaining sites (54%) were divided between level and rolling landforms, having slopes of <5 % (Table 3).

Table 3. Site characteristics including soil parent material, dominant surface landform, dominant sub group and slope class measured on the 43 AESA Soil Quality Benchmark sites located in Alberta, Canada. Values in parentheses represent the percent of sites in a class with n= 43 (includes Site 598, removed from the program in 2002) and the Mid-Boreal Uplands (removed from subsequent analysis).

Landscape features

Parent material	*Sites (%)*	*Surface landform*	*Sites (%)*
Morainal	28 (65)	Undulating	19 (44)
Lacustrine	7 (16)	Rolling	12 (28)
Fluvial	5 (12)	Level	11 (26)
Fluvial/Morainal	3 (7)	Hummocky	1 (2)

Dominant sub group	*Sites (%)*	*Slope class*	*Slope (%)*	*Sites (%)*
Orthic Dark Gray Luvisol	10 (23)	Level	0 – 0.5	4 (9)
Orthic Gray Luvisol	1 (2)	Nearly level	0.5 – 2	7 (16)
Dark Gray Luvisol	8 (19)	Very gentle	2 – 5	19 (44)
Eluviated Black Chernozem	9 (21)	Gentle	5 – 10	4 (9)
Orthic Dark Brown Chernozem	5 (12)	Moderate	10 – 15	4 (9)
Orthic Black Chernozem	2 (4)	Strong	15 – 30	3 (7)
Orthic Brown Chernozem	8 (19)	Very strong	30 – 45	2 (4)

A review of the pedological investigation confirmed that the Alberta Soil Quality Benchmark sites were representative of the dominant Chernozemic and Luvisolic soils found in the agricultural areas of Alberta (T. Brierley, personal communication, Agriculture and Agri-Food Canada, Edmonton, AB), as 56% of the sites were found on Chernozems and 44% were found on Luvisolic soils (Table 3). Ninety percent of the sites had a loamy surface texture (characteristic of central and southern Alberta) with the remainder classified as having sandy textures. Higher clay contents occurred primarily in northwestern Alberta as a result of tills derived from Cretaceous marine shale. Sandy tills occurred throughout the area adjacent to the Precambrian shield in eastern Alberta (Pawluk and Bayrock 1969).

Soil Profile Analysis. Soil sampling by principal horizon was deemed an appropriate method of initially classifying and understanding soil pedogenic processes associated with each benchmark site. Similar to results of Brejda et al. (2000a,b), the majority of initial soil properties were not normally distributed, although log-transformation improved, but did not normalize the data (data not shown). For example, log transformation of 18 different soil characteristics collected from three landscape positions (i.e., N=54) in the A horizon, led to a 49% reduction in the number of non-normal soil parameters. Similarly, log transformation led to a 33% reduction in the number of non-normal B-horizon parameters. This is not surprising as natural systems are typically heterogeneous, and this high variability often translates into high uncertainty with regard to statistical analysis (Parkin and Robinson 1992). Natural systems are typically positively skewed as negative values are often not possible, and data are often constrained to values greater than or equal to zero. As a result of this analysis, it was decided that non-transformed data would be presented in this report, as this form is more readily understandable to the reader.

Analysis of the Initial Pedological Characterization. Results of the pedological characterization were consistent with what was expected for each of the benchmark sites, although they exhibited a great deal of variability (see standard deviation in Table 4 and Table 5). Observed differences tended to occur predominantly in the A horizon, and were the result of farm management practices (data not presented). Sand and clay contents differed across the province, in the A and B horizons, with sand remaining higher in south and central regions of Alberta, and clay being higher in the PL (Table 4), consistent with Pawluk and Bayrock (1969). Differences associated with landscape were essentially confined to the A horizon, which is not surprising due to the potential for soil erosion by wind, water and, prior to the adoption of minimal tillage operations by the cooperators. Generally, upper landscape positions were characterized by coarser soil textures (i.e., sand contents of 38%) and lower landscape positions by finer textures (i.e., silts and clay contents of 39% and 26%, respectively).

Table 4. Mean (standard deviation) sand, silt and clay contents by ecoregion and landscape position (upper, mid and lower) of the A and B horizons measured from the 41 AESA Soil Quality Benchmark sites (Mid-Boreal Uplands site deleted) in Alberta, Canada.

Ecoregion [z]	n [y]	A Horizon			B Horizon		
		Sand	Silt	Clay	Sand	Silt	Clay
		(%)					
PL	27	23.1B [x]	40.0	36.9A	21.7B	27.5	50.8A
		(6.18)	(5.82)	(8.95)	(9.11)	(9.09)	(13.58)
BT	24	38.1A	36.3	25.6B	41.2A	25.8	33.1B
		(16.65)	(11.88)	(10.98)	(18.80)	(12.07)	(13.84)
AP	27	40.8A	38.1	21.1B	38.2AB	30.4	29.8B
		(13.29)	(9.90)	(6.63)	(11.70)	(8.92)	(9.41)
MM	15	49.4A	32.1	18.5B	47.6A	28.2	24.2B
		(11.79)	(7.08)	(5.90)	(15.27)	(9.99)	(10.71)
FG	6	33.1AB	37.5	29.4AB	31.2AB	34.5	34.3AB
		(8.52)	(7.18)	(15.57)	(10.13)	(7.92)	(17.70)
MG	24	41.0A	34.7	24.3B	38.7A	32.9	28.8B
		(7.66)	(5.32)	(3.56)	(10.01)	(7.75)	(5.01)
Landscape position (averaged across all ecoregions) [w]							
Upper	41	38.2A [y]	35.0B	26.8A	37.2	29.1AB	33.8
		(13.52)	(8.05)	(10.25)	(13.35)	(8.48)	(14.29)
Mid	41	37.8A	37.3AB	24.8B	37.2	27.0B	34.9
		(14.73)	(9.35)	(9.84)	(16.16)	(10.17)	(14.92)
Lower	41	35.0B	38.9A	26.1AB	34.7	31.0A	34.3
		(13.44)	(7.98)	(10.51)	(16.22)	(10.67)	(14.95)

[z] PL: Peace Lowland, BT: Boreal Transition, AP: Aspen Parkland, MM: Moist Mixed Grassland, FG: Fescue Grassland, MG: Mixed Grassland.

[y] "n" includes the number of sites per ecoregion multiplied by the three landscape positions (upper, mid and lower). For example, 9 ecodistricts contain benchmark sites in the PL, each with 3 landscape positions for a total of 27 sites.

[x] Values with the same letter within a column are not significantly different ($P<0.05$) from one another.

[w] Includes data from the Mid-Boreal Uplands.

Table 5. Mean (standard deviation) values for cation exchange capacity (CEC), carbonate content ($CaCO_3$), soil pH in water (pHw) and $CaCl_2$ (pHc), soil bulk density (BD), organic carbon (OC), total N, soil test phosphorus (STP) and extractable K by ecoregion and landscape position of the A and B horizons measured from the 41 AESA Soil Quality Benchmark sites in Alberta, Canada.

Ecoregion^{z}	n^{y}	CEC	$CaCO_3$	pHw	pHc	BD	OC	Total N	STP	K
		(cmol kg^{-1})	(%)			(g cm^{-3})	(g kg^{-1})		(mg kg^{-1})	
					A Horizon					
PL	27	29.4A^{x}	0.74B	6.97AB	6.34AB	1.29	34.4A	3.6A	21.3	273CD
		(8.31)	(0.119)	(0.677)	(0.542)	(0.133)	(12.08)	(1.17)	(13.54)	(122.9)
BT	24	24.1A	0.77B	6.51B	5.64C	1.27	31.2A	2.4ABC	14.8	189D
		(13.84)	(0.326)	(0.551)	(0.699)	(0.265)	(32.38)	(2.12)	(14.06)	(115.9)
AP	27	24.6A	0.71B	6.53B	5.95BC	1.23	35.3A	2.9AB	22.8	306BC
		(7.92)	(0.077)	(0.580)	(0.642)	(0.148)	(19.08)	(1.49)	(20.59)	(162.8)
MM	15	19.4AB	0.70B	6.29B	5.79BC	1.26	27.8A	2.4ABC	30.9	433BC
		(6.55)	(n/a)	(0.673)	(0.700)	(0.154)	(12.92)	(0.87)	(23.38)	(193.4)
FG	6	26.1A	0.70B	6.23B	5.75BC	1.31	32.1A	2.7ABC	29.8	570A
		(5.95)	(n/a)	(0.314)	(0.481)	(0.131)	(9.45)	(0.62)	(18.15)	(226.6)
MG	24	16.0B	1.71A	7.35A	6.69A	1.36	10.2B	1.3C	16.4	407BC
		(2.49)	(2.071)	(0.784)	(0.832)	(0.129)	(3.75)	(0.47)	(7.78)	(161.3)
					B Horizon					
PL	27	29.5A	0.76B	7.53	6.62B	1.44	11.3A	1.3A	5.3	199B
		(5.32)	(0.292)	(0.733)	(0.776)	(0.147)	(6.34)	(0.59)	(3.92)	(41.6)
BT	24	18.4B	0.70B	7.05	6.18B	1.52	4.9B	0.5B	9.3	165B
		(8.33)	(n/a)	(0.788)	(0.949)	(0.120)	(4.70)	(0.45)	(24.4)	(73.6)
AP	27	18.5B	0.88B	7.29	6.70AB	1.42	10.7A	1.0AB	5.3	171B
		(5.24)	(0.638)	(0.543)	(0.538)	(0.125)	(9.29)	(0.64)	(11.94)	(59.3)
MM	15	16.9B	1.67AB	7.24	6.67AB	1.40	9.0AB	1.0AB	4.9	222B
		(5.59)	(2.072)	(0.656)	(0.775)	(0.079)	(4.92)	(0.63)	(4.49)	(135.2)
FG	6	25.8AB	0.78B	7.30	6.92AB	1.33	16.2A	1.9A	4.0	370A
		(7.52)	(0.204)	(0.470)	(0.655)	(0.106)	(9.02)	(1.03)	(1.41)	(243.9)
MG	24	18.3B	2.60A	7.79	7.18A	1.45	4.4B	0.9B	6.7	233B
		(4.10)	(4.467)	(0.601)	(0.589)	(0.105)	(3.24)	(0.26)	(7.03)	(111.8)
					Landscape position (averaged across all ecoregions) ^{w}					
					A Horizon					
Upper	41	22.5	1.10	6.78	6.14	1.32A	24.0B	2.4B	22.7	313
		(8.74)	(1.469)	(0.812)	(0.825)	(0.175)	(14.50)	(1.27)	(16.49)	(151.8)
Mid	41	22.2	0.83	6.74	6.02	1.31A	26.8B	2.5B	18.7	300
		(9.64)	(0.683)	(0.695)	(0.729)	(0.161)	(16.80)	(1.39)	(11.91)	(164.1)
Lower	41	24.9	0.83	6.72	6.16	1.21B	35.5A	3.2A	25.3	366
		(10.67)	(0.507)	(0.651)	(0.727)	(0.169)	(26.11)	(1.80)	(20.21)	(215.2)
					B Horizon					
Upper	41	21.4	1.90	7.42	6.74	1.45	8.9A	1.1	4.3B	223
		(7.47)	(3.577)	(0.723)	(0.837)	(0.136)	(7.43)	(0.63)	(3.02)	(131.4)
Mid	41	21.2	1.01	7.41	6.67	1.42	8.3AB	1.1	4.2B	188
		(7.80)	(0.955)	(0.711)	(0.790)	(0.122)	(7.30)	(0.69)	(2.95)	(91.5)
Lower	41	20.0	0.80	7.34	6.65	1.46	6.5B	0.9	11.2A	234
		(7.34)	(0.432)	(0.632)	(0.742)	(0.123)	(6.67)	(0.55)	(22.37)	(93.2)

[z.] PL: Peace Lowland, BT: Boreal Transition, AP: Aspen Parkland, MM: Moist Mixed Grassland, FG: Fescue Grassland, MG: Mixed Grassland.

[y.] “n” includes the number of sites per ecoregion multiplied by the three landscape positions (upper, mid and lower).

[x.] Values with the same letter within a column are not significantly different ($P<0.05$) from one another.

[w.] Includes data from the Mid-Boreal Uplands.

Cation Exchange Capacity (CEC) followed a pattern similar to that of soil texture, with higher values corresponding to areas with high clay contents, such as what was observed in the PL (29.4 cmol kg^{-1} at 36.9% clay content, Table 4 and Table 5). It did not, however, vary in response to landscape position. Calcium carbonate ($CaCO_3$) levels and pH in water and $CaCl_2$ sampled from the A horizon, tended to be greater in the southeast region of the province (i.e., the MG), where values were 1.7%, 7.4% and 6.7%, respectively (Table 5). The B horizon followed a similar pattern for $CaCO_3$ (2.6%) and pH in $CaCl_2$ (pHc = 7.2). The initial investigation of the A and B horizons did not identify any differences in these three parameters with respect to the landscape position.

With respect to soil bulk density (Table 5), a significant difference between landscape position was identified, with only the lower landscape position of the A Horizon being lower (1.2 g cm^{-3}) than either of the mid or upper landscape positions (1.3 g cm^{-3}). A potential explanation for this observation is the higher soil organic carbon (OC) level identified in this position (36 g kg^{-1}, Table 5). Provincially, bulk density ranged from 1.1 to 1.4 g cm^{-3}, although there were no significant regional differences (Table 5).

Soil OC in the A and B horizons tended to be similar across the ecoregions (Table 5). Organic carbon levels were lower in the dry MG, at values of 10.2 and 4.4 g kg^{-1} for the A and B horizons, respectively. Organic carbon was also lower in the upper and mid landscape positions of the A horizon (24 and 26 g kg^{-1}, respectively) presumably as a result of erosion, drier soil conditions and poorer crop growth leading to less residue addition.

The soil quality and fertility parameters, total N, soil test phosphorus (STP) and extractable K also tended to be similar across the province, but were found to be highly variable, with CVs ranging from 57 to 183 % (data not shown). With some exceptions: (i.e., N lower in the MG (1.3 g kg^{-1} and K greater in the FG (570 mg kg^{-1})), soil fertility did not vary in response to ecoregion. With respect to landscape position, total N was found to be greater in the lower landscape position of the A horizon (3.2 g kg^{-1}, Table 5) and STP greater in the lower landscape position of the B horizon (11.2 mg kg^{-1}, Table 5). All other soil fertility parameters, including sulfate (data not shown), remained similar among landscape positions.

Phase Two: Provincial Analyses of Variance

Variability in the Data Set. Coefficients of variation (CVs) were calculated for each landscape position within each sampling depth and ecoregion, thus coefficients of variation would be indicative of variation among years and sites (Table 6). For example, a CV of 299.9% for NH_4-N in the upper landscape position at the 0 to 15 cm sampling depth in the AP ecoregion indicates a high degree of variation in NH_4-N among study years and sampling sites, compared with a much lower CV of 47.8% found in the mid landscape position at the 0 to 15 cm sampling depth in the FG ecoregion (Table 6).

Within each landscape position, sampling depth and ecoregion, CVs were highest for NH_4-N, SO_4-S and NO_3-N. Penney (2004) similarly reported high CVs among ecoregions in N and S related soil parameters. Increased variation in SO_4-S, NH_4-N and NO_3-N would be expected since these fertility measures can change quickly due to the removal of crop residue, rapid mineralization and/or nitrification, and weather patterns preceding sampling. Such soil processes may differ among ecoregion, sampling depth and slope position depending on cropping system and soil-related factors such as temperature, moisture and biological activity.

Among ecoregions, variation was the highest in the AP, BT and MM ecoregions and lowest in the PL ecoregion. This is, in part, contrary to the findings of Penney (2004) who reported that the BT and PL were the ecoregions that exhibited the least variation. Among sampling depths, CVs were higher at the 0 to15 cm sampling depth for EC, NH_4-N and SO_4-S, and were higher at the 15 to 30 cm sampling depth for NO_3-N and STP (Table 6). Among landscape positions, CVs were similar except for SO_4-S, where variability was greater at the lower slope position than at the mid or upper positions (Table 6).

All comparable soil parameters exhibited greater overall variation when compared with the CVs reported by Penney (2004), whose report analyzed the first five years of data from this study. Thus it appears that more years of data has increased the variability in the dataset, which supports the suggestion by Penney (2004) that large changes in soil properties would need to occur before significant trends in changes over time could be detected. This highlights the need for longer-term sampling in unreplicated field-scale studies to better describe the year-to-year variation.

Table 6. Coefficients of variation (CVs) of data, for each landscape position, sampling depth and ecoregion, for soil quality parameters measured from 1998 to 2006 at 41 AESA Soil Quality Benchmark sites in Alberta, Canada.

			Soil Quality Parameter													
			EC	K	NO_3-N	NH_4-N	pHc	pHw	STP	SO_4-S	BD	KCl-NH_4-N	LF	LFC mass	LFN mass	OC
Mean CV (%) for each ecoregion, sampling depth and position																
AP	0 -15	U	58	37	94	300	10	8	31	70	13	211	38	40	75	28
		M	55	35	100	326	5	5	32	85	12	59	59	54	167	27
		L	86	42	66	365	8	6	66	189	11	161	65	80	119	33
	15-30	U	30	40	112	188	7	6	52	64						
		M	40	27	87	276	6	5	55	47						
		L	75	40	70	207	7	5	76	172						
BT	0-15	U	42	43	161	364	6	5	54	79	11	49	36	43	62	49
		M	31	31	73	329	5	4	46	48	13	31	33	36	50	45
		L	46	37	75	262	8	6	63	92	15	24	63	82	259	50
	15-30	U	55	37	244	96	6	5	46	68						
		M	42	48	142	159	6	4	105	64						
		L	31	26	77	261	8	7	73	85						
FG	0-15	U	32	29	57	128	8	7	40	54	12	21	93	114	129	17
		M	84	33	85	48	11	8	24	68	12	36	36	46	111	16
		L	53	16	67	82	5	4	35	66	14	37	88	83	123	18
	15-30	U	38	38	58	87	8	7	17	73						
		M	61	46	65	46	12	9	27	74						
		L	76	20	72	108	6	4	27	88						
MG	0-15	U	43	19	73	158	5	13	45	151	9	60	91	118	149	15
		M	33	22	71	144	7	13	42	79	8	30	76	58	81	16
		L	45	34	85	164	10	15	33	91	10	31	49	46	110	18
	15-30	U	48	20	74	161	5	13	42	168						
		M	56	22	85	170	7	13	40	146						
		L	60	26	78	308	10	14	49	166						
MM	0-15	U	38	35	84	159	12	16	44	152	10	38	90	87	115	25
		M	39	17	89	270	7	12	44	51	9	47	54	64	117	24
		L	35	33	70	197	6	13	32	333	14	26	88	102	96	28
	15-30	U	30	33	69	166	10	8	58	61						
		M	36	21	66	145	7	12	41	52						
		L	38	47	72	161	5	12	34	57						
PL	0-15	U	143	17	66	170	3	4	28	58	9	25	60	38	78	26
		M	23	19	76	109	3	3	29	85	10	23	47	34	70	32
		L	30	21	80	92	2	3	19	54	10	22	62	41	57	18
	15-30	U	27	20	85	121	5	4	43	70						
		M	29	19	80	94	3	2	45	61						
		L	22	26	88	84	3	4	34	54						
Mean CV (%) for ecoregion																
AP			57	37	88	277	7	6	52	104	12	144	54	58	120	29
BT			41	37	129	245	6	5	65	73	13	35	44	54	124	48
FG			57	30	67	83	8	7	28	71	12	31	72	81	121	17
MG			47	24	77	184	7	14	42	134	9	41	72	74	113	16
MM			36	31	75	183	8	12	42	118	11	37	77	84	109	26
PL			46	20	79	112	3	3	33	63	9	23	57	38	68	25
Mean CV(%) for sampling depth																
0-15			51	29	82	204	7	8	39	100	11	52	63	65	109	27
15 -30			44	31	90	158	7	8	48	87						
Mean CV(%) for landscape position																
U			49	31	98	175	7	8	42	89	11	67	68	73	101	27
M			40	28	85	188	6	8	46	72	10	38	54	49	97	29
L			49	32	76	201	7	8	46	125	12	53	65	70	128	29
Mean CV (%) overall																
			47	30	86	181	7	8	44	94	11	52	63	65	109	27

Field Management. As mentioned, the AESA Soil Quality Benchmark sites were chosen to be representative of the ecodistricts and ultimately the ecoregions from which they were selected. In an earlier study on agronomic practices employed in Alberta, Dey (2000) outlined the results of a farm-based survey of county Agricultural Service Board Agricultural Field Men from across the province to characterize production practices that were characteristic to their specific region. It is important to note that the study by Dey (2000) was based on a series of 27 multiple choice questions, which were subsequently ranked and presented graphically in his report. Specifically, Field Men were asked to estimate and report the total number of ecodistricts in their specific ecoregions that fell into certain classes with respect to the percent of total cropland employing the particular practice. A summary of selected results is presented here to provide an operational context to commonly employed agronomic practices on a provincial (whole province) and ecoregion scale. Where applicable, each section is then commented on with respect to the AESA Soil Quality Benchmark Sites, and how they are representative of the work by Dey (2000).

Summerfallow and Crop Rotation - Provincially, Dey's (2000) results indicate that the greatest number of reporting ecodistricts, with respect to the use of summerfallow, fell in the "0 to 20% of total cropland" class, with the highest use rate occurring in southern Alberta, specifically for the MG and MM, with a high number of survey responses in the "20 to 40% of total cropland" class. Cooler and wetter regions of the province (i.e., AP, FG, BT and PL) typically were either in the "none" or "0 to 20% of total cropland" classes.

Mechanical (i.e., tillage based) and combined (i.e., tillage + herbicide application) forms of summerfallow dominate the landscape, with a higher use of chemical fallow being typical in the MG, and either tillage based or combined forms being used elsewhere in the province. Generally, the use of combined forms of summerfallow in rotation was greater in wetter environments.

In terms of the AESA Soil Quality Benchmark sites, summerfallow was basically restricted to sites located in the MG (Sites: 804, 806, 809, 815, 1828) and MM (Sites: 769, 781), although it did occur in one year at site 688 (BT) and in three years at site 743 (AP).

The survey conducted by Dey (2000) also asked Agricultural Field Men to describe the most common crop rotations used by producers. The results of this question can be found in the data associated with his report, although on examination of his data and a visual comparison to the AESA Soil Quality Benchmark sites (Appendix 5), similarities between the ecoregions were revealed, with a greater use of summerfallow and wheat in rotation in southern Alberta (MG and MM) when compared with the use of oilseeds and forages in rotation in the more central and northerly ecoregions. A summary of the crop rotations employed at each of the AESA Soil Quality Benchmark sites can be found in Appendix 5.

Soil Fertility (N, P, K and S) - Based on a summary of provincial ecodistricts/ecoregions responding to Dey's (2000) survey, and across all crop types, nitrogen (N) is by far the element most applied (average rate of application = 66 kg ha^{-1}, actual nutrient), followed by phosphorus (P) (30 kg ha^{-1}), potassium (K) (12 kg ha^{-1}) and sulfur (S) (10 kg ha^{-1}) across Alberta as chemical fertilizer, although there were no apparent patterns with respect to application methods.

On an element-by-element basis, starting with nitrogen application, ecoregions reporting higher than average values include the MG (76 kg ha^{-1}), the AP (72 kg ha^{-1}) and the PL (79 kg ha^{-1}). All other ecoregions reported using less than average values of this fertilizer element, with the lowest rate being used in the FG (58 kg ha^{-1}). Higher than average P applications occurred in the MG (32 kg ha^{-1}), MM (33 kg ha^{-1}), and PL (36 kg ha^{-1}), and were lower than average elsewhere in the province. Potassium applications were greatest in the AP (19 kg ha^{-1}), and BT (15 kg ha^{-1}) only. Finally, with respect to S application, higher application rates occurred in the MM (14 kg ha^{-1}) and in the AP (13 kg ha^{-1}).

Looking at the total average application rate of N, P, K and S at all AESA Soil Quality Benchmark sites across Alberta, revealed that with the exception of N, nearly half the average rate of P, K, and S was typically applied to the 42 sites as actual. Compared with Dey's (2000) provincial average of 66, 30, 12 and 10 kg ha^{-1} of N, P, K, and S, the AESA Benchmark Sites received only 56, 11, 6, and 5 kg ha^{-1}, respectively.

Livestock Manure - Although the total number of responses was somewhat limited, results of Dey's (2000) survey indicated that the greatest number of ecodistricts (25) reported application of animal manure to less than 5% of their area, although 23 ecodistricts reported application on 5 to 15% of total cropland. No specific ecoregion appeared to report notably different responses to the provincial numbers, although some responses were collected for the "greater than 15% of total cropland" class in the MG (3 ecodistricts reporting of 12 across all application classes), MM (2 of 8), AP (2 of 13), and BT (4 of 10).

Benchmark sites were initially selected to avoid cases where animal manure would be applied; interest was in the chemical fertilizer practices associated with crop production, not manure. However, during the study, animal manure was applied at three separate locations, although this occurred in only one year of the study. Manure was applied at Site 592, High Prairie (in 2002); Site 688, Beauvallon (in 2002); and Site 823, Enchant (in 2000).

Tillage and Tillage Practices - By far, reduced tillage was the dominant form of tillage used in Alberta with the majority of reporting ecodistricts indicating that this practice was employed on more that 40% of total cropland in their area (Dey 2000). At the ecoregion level, ecodistricts all tended to have representation in all classes of total cropland area employing reduced tillage, although the southern areas (e.g., MM) tended to have a higher number of responses in the "60 to 100% of total cropland" class. It is interesting to note, however, that when questioned about the percentage of area under direct seeding (i.e., no tillage), the majority of responses were in the less than 40% of total cropland area classes. This indicated that although a high degree of reduced tillage is employed across Alberta, seldom were crops direct seeded without some form of prior low disturbance operation (e.g., a single pass with a light cultivator). At an ecoregion level, no particular patterns emerged from Dey's (2000) data.

With respect to the timing of tillage operations employed in Alberta, the majority (40 to 100% of total cropland) occurs in the spring. With respect to ecoregions, differences do exist, although the number of reporting ecodistricts for each class was low. For example, by the numbers based on most common occurrence, 40 to 60 % of total cropland tilled in the MG occurs in the spring; whereas, only 20 to 40% of total cropland in the MM is spring cultivated. In comparison 60 to 100% of tillage occurs in the spring in the AP. Interestingly, similar levels of response and patterns were observed when questioned about fall tillage.

All producers in the AESA Soil Quality Benchmark Sites program employed some form of reduced tillage practice during the majority of years that the benchmark sites were operational. However, closer examination of the agronomic data is needed, although a preliminary search revealed cases where producers indicated that they employed a three-pass high disturbance tillage operation, if only for a limited number of years, before returning to some form of low disturbance practice.

Weed Control – Herbicide Application - Based on a summary of provincial ecodistricts responding, when cereal crops were grown, the use of pre-emergence only and post harvest herbicides were the most common practices across the province. A smaller number of ecodistricts report either “pre-emergent + in crop” or “in-crop only” applications, with “in-crop only” being the least common practice for cereal production. Regionally, this pattern was consistent among all ecoregions according to Dey’s (2000) study. For oilseed crops, a similar pattern, both provincially and among ecoregions, was observed although the use of post-emergent herbicides somewhat exceeded the use of pre-emergence herbicides as the most and second most common herbicide application methods. In comparison to Dey’s (2000) work, the AESA Soil Quality Benchmark sites maintained a similar weed control system.

Harvesting and Residue Management - Swathing still dominates the landscape of Alberta with approximately 69% of respondents to the survey reporting this as a dominant harvest method, with the AP and BT responding near 80% of total cropland (Dey 2000). Only in the MG and the PL did the percentage of total cropland straightcut increase to levels near that of the swathing, with each region and type reporting close to 50% of the total cropland area employing that practice. The lowest percent of area straightcut in Alberta occurred in the AP and BT ecoregions, likely due to wetter conditions and the need for the crop to dry to appropriate moisture levels prior to harvest.

As of the date of Dey’s study (2000) burning of crop residue was still widely employed, although all possible categories for residue management (baled, spread, burned and grazed) were somewhat similar. Results were consistent among ecoregions.

Similar to Dey’s work, the majority of the AESA Soil Quality Benchmark sites were swathed prior to harvesting, and residue was left on the field.

Soil Quality Parameter Analysis. The following provides the results obtained from the analysis of 14 different soil parameters that were considered important in terms of characterizing soil quality in Alberta.

Bulk Density - Annually, bulk density (BD) was only measured at the 0 to 15 cm sampling depth, thus the effect of depth was removed from the analysis. Year and ecoregion × year interaction effects were significant ($P<0.002$) for BD. Provincially, BD was the highest in 2000 and 2002, and the lowest in 2003 (Figure 2). There was a pronounced decrease in BD from 2002 to 2003, dropping from 1.36 to 1.18 Mg m^{-3}. High BD levels in 2002 may be a reflection of the province-wide drought that occurred that year, limiting root growth and crop productivity and ultimately leading to an increase in BD (Figure 2). The 2003 growing season was uncharacteristically long, with above normal temperatures and higher precipitation extending into the late summer and early fall (Alberta Agriculture and Rural Development 2008). The resulting increase in crop growth toward the end of 2003 likely led to reductions in BD at the time of sampling.

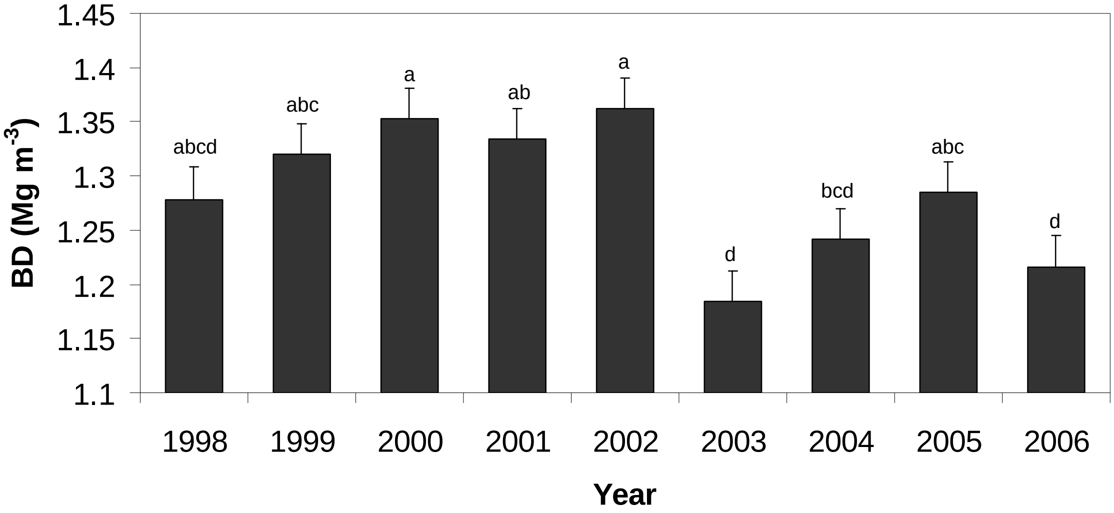

Figure 2. The effect of year on bulk density using data collected from 1998 to 2006 at 41 AESA Soil Quality Benchmark sites located in Alberta, Canada.
Bars with same letter are not significantly different ($P>0.05$); error bars represent the standard error of the mean.

The effect of ecoregion was not significant for BD (Table 7), although ecoregion × year interaction effects were significant ($P<0.003$) (data not shown). In general, ecoregions responded similarly to the effect of year, suggesting that province-wide weather patterns do in fact influence soil BD. An exception to this was observed in the drier MG ecoregion, which often exhibited higher BD than the wetter, cooler regions (AP, PL) over the duration of the study. Regression analysis showed that across the province, BD decreased by about 5% at the lower, mid and upper landscape positions during the study ($R^2=0.09$, $P<0.03$; $R^2=0.07$, $P<0.05$; $R^2=0.07$, $P<0.05$, respectively) (Table 8 and Table 9). Within ecoregions, the BT and PL exhibited a significant decrease in BD, although this decrease occurred at the lower landscape position in the BT and at the upper position in the PL (Table 8 and Table 9). A further explanation for the decreasing BD in the BT was the dramatic increase in the number of sites growing forages (Appendix 5). Forage production, owing to its extensive rooting patterns, not only lowers BD, but often contributes to maintaining the stability in BD values over time.

Landscape position and position × ecoregion interaction effects were significant ($P<0.001$), with greater BD in the upper positions, as described by Penney (2004) (Table 7, Figure 3). Differences in BD among landscape position may be the result of differences in soil texture (Table 4). These differences are often the result of erosion of topsoil from upper landscape positions thereby exposing a more compact subsoil layer. This expected pattern (higher BD in the upper landscape position) was observed in the AP, BT and MG ecoregions, but was not observed in the FG, MM or PL ecoregions (Figure 3). It is likely that the effect of position was not significant in the FG due to high variation among the two sites included in the study. A lack of position effect in the PL could be due to the gentle slopes of the sites, causing the effect of landscape position to be less pronounced.

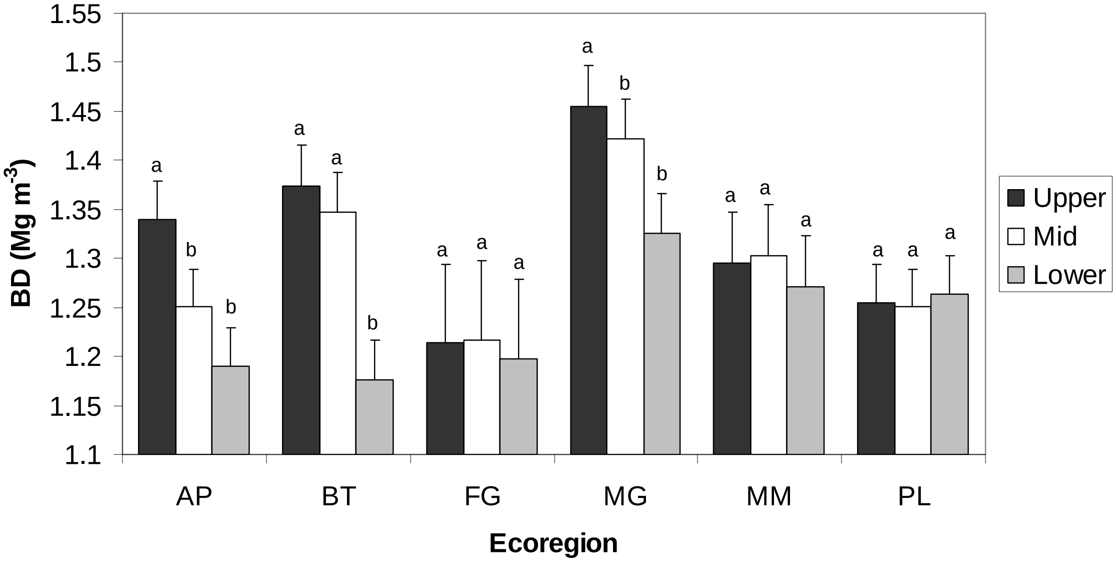

Figure 3. The ecoregion × position interaction effect on bulk density using data collected from 1998 to 2006 at 41 AESA Soil Quality Benchmark sites located in Alberta, Canada.
Bars with same letter are not significantly different (P>0.05); error bars represent the standard error of the mean.

Electrical Conductivity - Although differences in electrical conductivity (EC) exist among Alberta’s soils, particularly in areas with high salinity and/or solonetzic inclusions, of the sites included in this study, EC among ecoregions ranged from 0.34 to 0.58 dS m^{-1}, which is considered to be non-limiting to crop growth (Table 10).

Results of the analyses indicated that the ecoregion × depth interaction effect was significant (P<0.001) for EC, while depth and depth × position effects were not (P>0.05). Ecoregions did not differ for EC according to sampling depth except in the BT, MG and PL ecoregions (Table 10, Figure 4). In the BT and PL, the 0 to 15 cm depth was higher in EC, while in the MG, EC was higher at the 15 to 30 cm sampling depth. Whereas higher salts in the upper soil horizons of drier ecoregions may be the result of capillary rise over time, this is likely not the case in the relatively moist BT and PL ecoregions. Higher EC at the upper sampling depth in the BT and PL may be associated with a high presence of forages in rotation, which often obtain soil water from lower soil depths because of their deep rooting patterns. Removal of deep soil water may then reduce the amount of capillary rise experienced in these areas. Furthermore, sampling may not have occurred to a deep enough depth to capture available salts in these regions of the province. A more typical effect was observed in the MG, where higher salt concentrations were found at the 15 to 30 cm sampling depth, which may be a result of suitable crop management in dry environments.

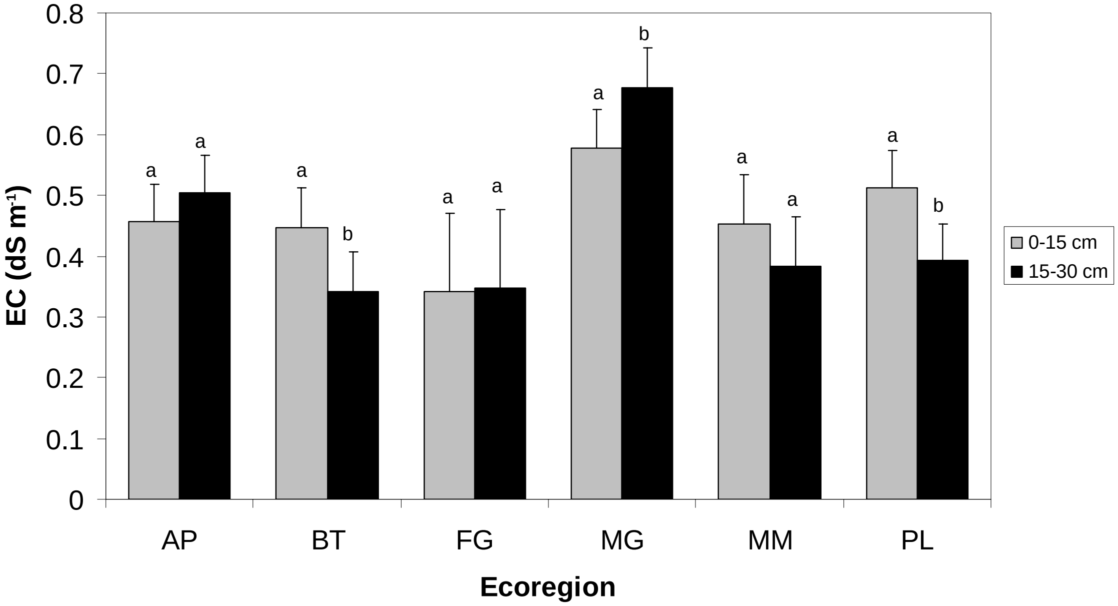

Figure 4. The ecoregion × depth interaction effect on electrical conductivity using data collected from 1998 to 2006 at 41 AESA Soil Quality Benchmark sites located in Alberta, Canada. Bars with same letter are not significantly different ($P>0.05$); error bars represent the standard error of the mean.

The effect of year was not significant at either sampling depth, while the effect of ecoregion was only significant at the 15 to 30 cm depth. At the 15 to 30 cm sampling depth, salt content was highest in the MG and lowest in the BT (Table 10). It should be noted, however, that the removal of the data from the irrigated sites in the MG rendered the effect of ecoregion non-significant.

Provincially, regression analyses revealed that regression coefficients were not significantly different from zero at either depth or any landscape position, suggesting that there has been no significant change in the EC of Alberta's agricultural soils over time (Table 12 and Table 13). Exceptions to this include: (a) an upward trend in EC in the upper landscape position of the MG ecoregion at the 15 to 30 cm sampling depth ($R^2=0.66$, $P<0.01$), and (b) a downward trend in the lower landscape position of the PL ecoregion at the 0 to 15 cm sampling depth ($R^2=0.59$, $P<0.02$) (Table 9). Differences between these two ecoregions may be a result of different levels of average precipitation across study years (Table 2, ARD 2008). Decreasing EC in the PL may be due to higher rainfall and/or salts being leached deeper into the soil profile (i.e., beyond sampling depth), while increasing EC in the MG could be due to drier weather and increased capillary action bringing salts to the upper soil horizon.

Similar to the findings of Penney (2004), landscape position was not significant for EC at either depth (Table 10), while the ecoregion × position interaction effect was significant at both sampling depths (data not shown). Although EC was variable across ecoregions, it appears as though the significance of the interaction was driven by significant differences in EC between the upper and lower landscape positions in the AP only. Electrical conductivity levels were highest at the lower landscape position in the AP, which was opposite to the general trend (data not shown).

pH - To fully explore the effects of soil pH, measurements made in water (pHw) and calcium chloride (pHc) were investigated, and the results of both are presented in the following discussion. Although measurements made in water are common, soil pH is often measured in calcium chloride, as this measurement better represents the more acidic rhizosphere environment that plants experience in soil (Hendershot et al. 1993).

Similar to EC, soil pH values were found to be in an acceptable range for crop production in Alberta (5.5 to 6.7 for pHc and 6.2 to 7.2 for pHw) (Table 10). As the soil quality parameters pHw and pHc were found to exhibit similar responses to the various treatment effects in the current study, they are discussed jointly as pH. As expected, pHw was greater than pHc by approximately one unit, and the two were highly correlated ($r=0.98$, $P<0.01$) (Table 11).

The effects of depth, depth × ecoregion and depth × position on pH were significant ($P<0.001$). In general, subsoil (i.e., soil from the 15 to 30 cm sampling depth) pH was about 6% higher than in the topsoil (0 to 15 cm sampling depth) (Table 10), likely owing to its closer proximity to the calcareous soil parent materials in Alberta and carbonate leaching from the upper soil horizons. Among ecoregions, pH was lower and more variable at the 0 to 15 cm sampling depth, which reflects the influence of fertilizer and fertility management on soil pH. Among landscape positions, pH tended to be higher in upper landscape positions at both sampling depths (Table 10); however, the effect of position was only significant at the 15 to 30 cm depth (data not shown).

Year had a significant effect ($P<0.001$) on soil pH at the 0 to 15 cm sampling depth, and although variable across years, pH values were generally higher in the late 1990s compared with subsequent study years. This relationship may have been driven by a number of extreme weather years in the early 2000s (e.g., drought in 2002, excessive moisture in spring 2005). At the 15 to 30 cm layer, pHc differed across study years, whereas the effect of year was only significant for pHw when the irrigated sites in the MG were removed (data not shown). Regression analyses revealed no significant provincial trends in pH over time (Table 12 and Table 13), suggesting that the pH of soils across the province has remained relatively stable. However, closer analysis at the ecoregion level revealed subtle differences among landscape positions and sampling depths and ecoregions (Table 9, Table 12 and Table 13). For example, in the 0 to 15 cm layer, the lower landscape position in the FG displayed a decreasing trend in pHw ($R^2=0.93$, $P<0.01$).

At both sampling depths, differences in pH among ecoregions tended to differ ($P<0.05$) only when the irrigated sites of the MG were included in the analysis. Their inclusion increased the pH of the MG relative to other ecoregions (data not shown). Removal of those sites from the analysis eliminated this difference, rendering the effect of ecoregion non-significant. Even with the removal of the irrigated sites in the MG, pH in this ecoregion was somewhat higher relative to other ecoregions, likely owing to lower annual precipitation (Table 2) resulting in less leaching of carbonates from the surface soil layer, and a shallower soil profile (i.e., closer proximity to calcareous bedrock materials). Ecoregion × year was not significant for pH, as ecoregions displayed similar variations in pH across years (data not shown). This observation held true when irrigated sites of the MG were removed.

Consistent with the previous work of Penney (2004), position and position × ecoregion interaction effects were significant at both sampling depths ($P<0.001$), with the upper and mid landscape positions tending toward higher pH values (Table 10). This relationship was variable across ecoregions, however, as shown in Figure 5. The MG, MM and AP illustrated the expected result of higher pH at upper landscape positions, while the BT ecoregion exhibited higher pH at lower landscape positions. Landscape position had no effect in the PL or FG ecoregions.

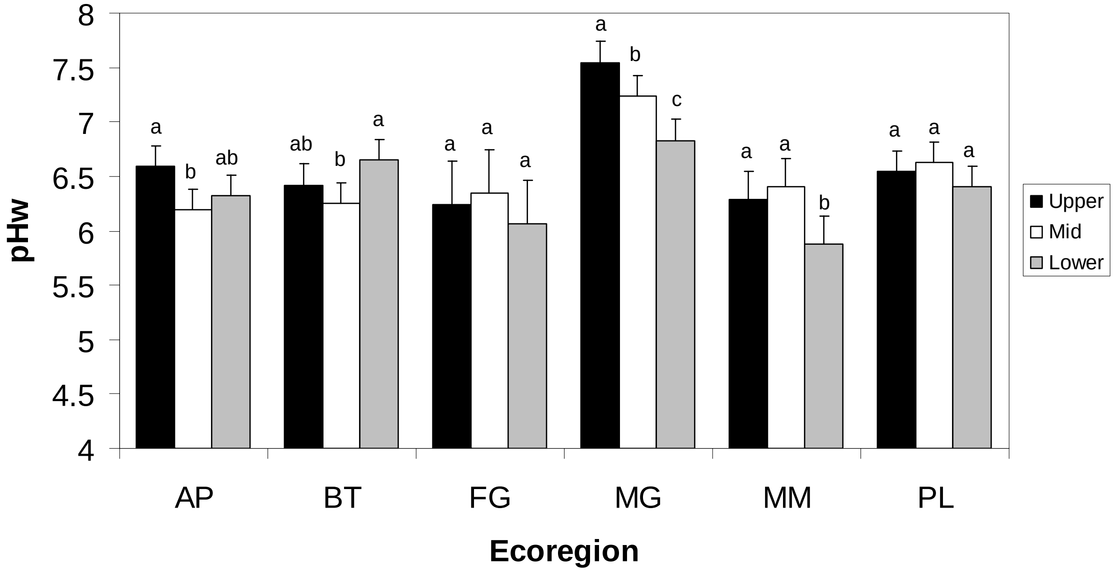

Figure 5. The ecoregion × position interaction effect on pHw at the 0 to 15 cm sampling depth using data collected from 1998 to 2006 at 41 AESA Soil Quality Benchmark sites located in Alberta, Canada.
Bars with same letter are not significantly different ($P>0.05$); error bars represent the standard error of the mean.

Organic Carbon - Organic carbon (OC) was measured at only the 0 to 15 cm depth, thus the effect of depth was removed from the analysis. The effects of year, ecoregion × year and position × year were not significant for OC ($P>0.05$). Regression analyses revealed that provincially and within ecoregions, the slope of the OC regression line was not significantly different from zero (Table 8). The results of these analyses suggest that the OC levels in the province have remained relatively constant over the nine years of the study.

Consistent with the findings of Penney (2004), the effect of ecoregion on OC was significant ($P<0.001$), with soil organic carbon levels in the MM and MG being significantly lower than in most other regions, particularly the PL and AP (Table 7). The warm, dry climate of MG and MM reduces overall crop productivity and organic carbon input to the soil as compared to the cooler and wetter ecoregions of northern Alberta. As well, lower OC in the MG and MM may be related to a greater tendency toward the use of summerfallow in drier regions of the province. Furthermore, this pattern may be driven by differences in regional bulk density. For example, higher bulk densities were observed in the MG, owing to fine textured, clay based soils. Pearson correlation analysis revealed a significant inverse relationship between BD and OC (r=-0.62, *P*<0.001) (Table 11).

In general, the effect of position on OC was significant (*P*<0.001), with higher OC occurring in the lower landscape positions, similar to the findings of Penney (2004) (Table 7). However, the ecoregion × position interaction indicated that this was largely influenced by the northerly AP and BT ecoregions (Figure 6), the ecoregions with the highest land slopes included in the study (Table 14).

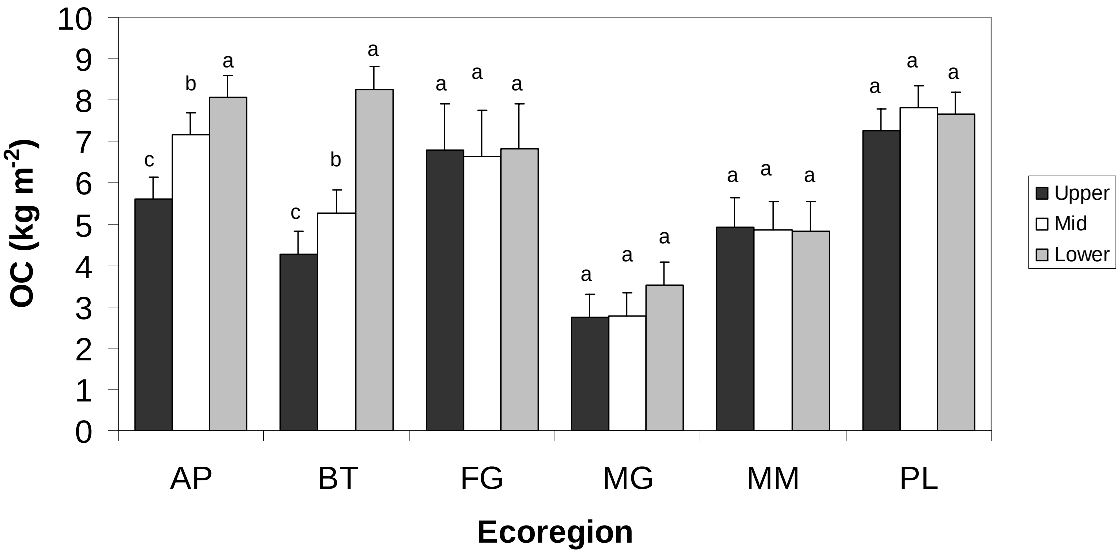

Figure 6. The ecoregion × position interaction effect on organic carbon using data collected from 1998 to 2006 at 41 AESA Soil Quality Benchmark sites located in Alberta, Canada. Bars with same letter are not significantly different (*P*>0.05); error bars represent the standard error of the mean.

Light Fraction Organic Matter - Light fraction organic matter (LF) is considered more responsive or dynamic to environmental and/or management changes and can be used to assess the affect of cropping systems (e.g., crop rotation and tillage) of the overall organic carbon content and persistence in the soil (Gregorich and Ellert 1993, Malhi et al. 2003). As LF was measured only at the 0 to 15 cm sampling depth, the effect of depth was removed from the analysis.

The effects of year, ecoregion and ecoregion × year were significant for LF (*P*<0.01). Overall, LF was extremely variable across ecoregions and years, possibly due to variations in weather and/or crop productivity. Among ecoregions, LF ranged between 4.3 and 8.7 mg g^{-1} (Table 7), and was fairly consistent across years until 2001 when it sharply increased, only to decrease in 2002 (Figure 7). In 2003, another increase in LF occurred, decreasing gradually to 1998 levels over the remainder of the study. These differences in LF across years may be attributed to crop rotation, climate and/or sampling variation. Climatically, dry years such as 2002 result in a lack of crop production and a lack of organic matter breakdown, leading to a reduced LF component in the soil. Sampling variation depends on factors such as how well surface residue is removed and/or where the soil sample was collected (i.e., in the seed row vs. a mid-row position). Regression analyses revealed a significant increase in LF over time in only the mid landscape position of the PL ecoregion ($R^2=0.47$, $P<0.05$) (Table 8 and Table 9).

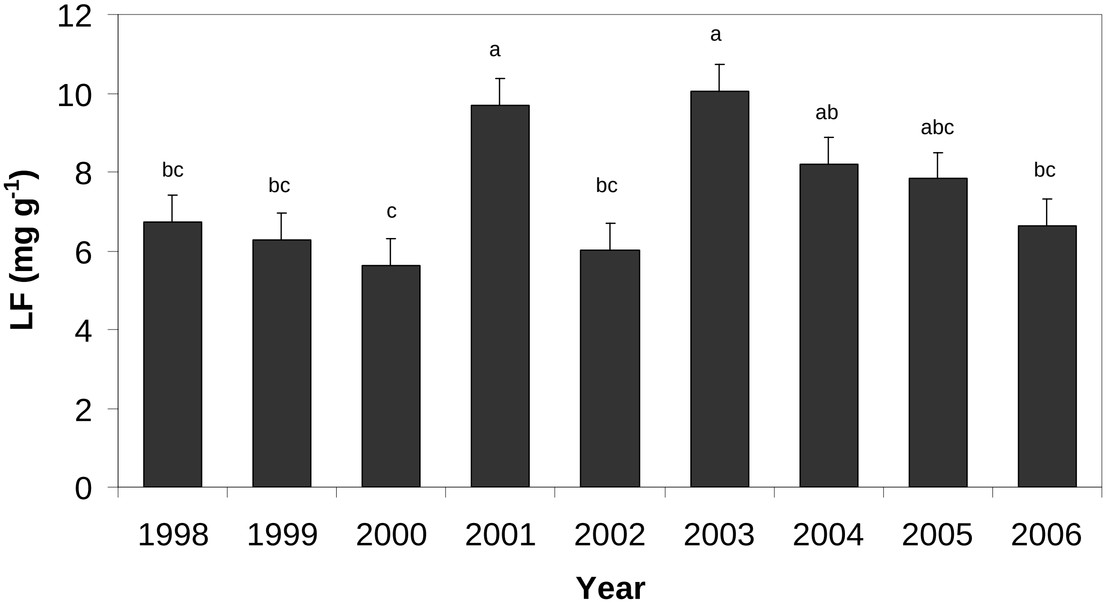

Figure 7. The effect of year on light fraction using data collected from 1998 to 2006 at 41 AESA Soil Quality Benchmark sites located in Alberta, Canada.
Bars with same letter are not significantly different ($P>0.05$); error bars represent the standard error of the mean.

Among ecoregions, LF was generally lower in the MG (Table 7), which differed from the work of Penney (2004) who identified the MM as having the lowest LF. The LF component in the MG is likely lower owing to the dry warm climate in that area; however, the ecoregion effect became non-significant ($P>0.05$) when irrigated sites in the MG were removed from the analysis. Removal of the three irrigated sites caused a further drop in mean LF values in the MG, as expected owing to the removal of highly productive sites from the analysis.

Position and ecoregion × position interaction effects were significant ($P<0.001$). Generally, lower landscape positions exhibited higher LF compared to mid or upper landscape positions (Table 7); however, this effect was only significant in two of the six ecoregions (AP and BT) included in the study (Figure 8). This differs from Penney's (2004) observation where there were no significant differences in LF among landscape positions. Higher LF in lower positions likely reflects increased soil moisture and higher crop productivity relative to higher landscape positions. This effect may have been more pronounced in the AP and BT ecoregions, where the overall slopes of the land tend to be among the steepest in the province (Table 14).

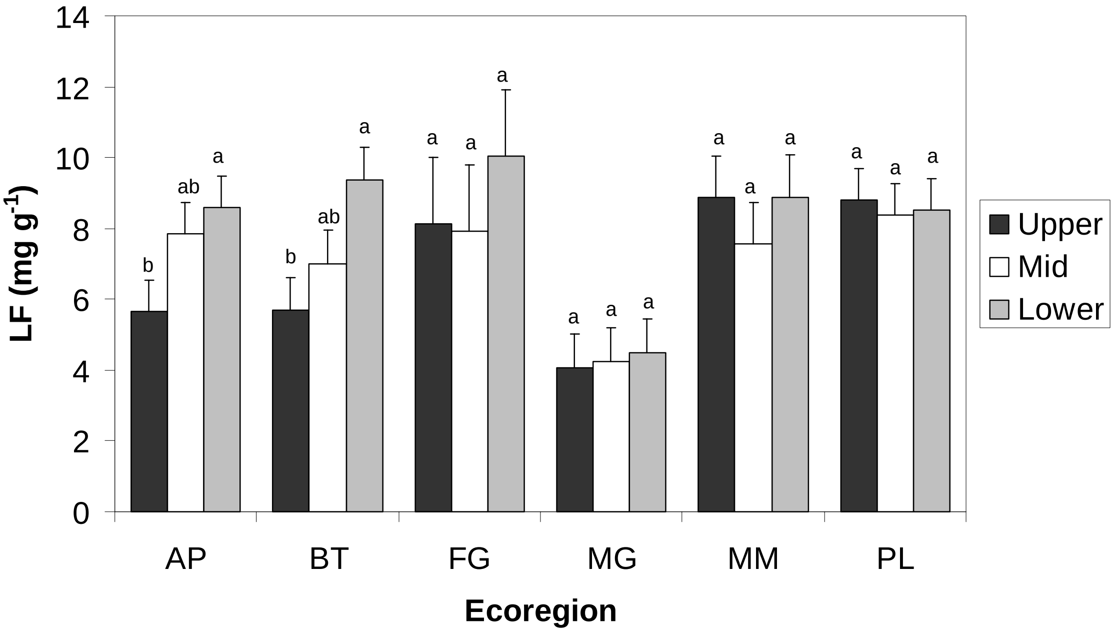

Figure 8. The ecoregion × position interaction effect on light fraction using data collected from 1998 to 2006 at 41 AESA Soil Quality Benchmark sites located in Alberta, Canada.
Bars with same letter are not significantly different (P>0.05); error bars represent the standard error of the mean.

Mass of Light Fraction Carbon - Measurements of mass of light fraction carbon (LFCmass) were taken only at the 0 to 15 cm sampling depth, thus the effect of depth was excluded from the analysis.

The effects of year and year × ecoregion were not significant for LFCmass, likely resulting from the variability associated with the wide range of cropping systems employed over the duration of the study and among ecoregions (Appendix 5). Provincially and within most ecoregions, the regression coefficient was not significantly different from zero for LFCmass (Table 8), suggesting that there were no trends associated with LFCmass in Alberta during the study. The two exceptions to this were in the PL mid landscape position and the MG upper landscape position, where LFCmass increased during the nine-year study period (Table 8 and Table 9).

The effect of ecoregion was significant for LFCmass (P<0.001), where the MG which exhibited lower values (0.65 mg g^{-1}) than other ecoregions (1.53 to 1.82 g mg^{-1}) (Table 7). This may be due to the increased incidence of summerfallow in rotation, leading to lower inputs of OC and LFCmass (Table 7). As expected, organic carbon and LFCmass were found to be positively correlated (r=0.81, P<0.05) (Table 11).

The effects of position and ecoregion × position on LFCmass were significant (P<0.001), with higher levels in the lower landscape positions (Table 7). A closer look at the ecoregion × position interaction (Figure 9) revealed that this was most prominent in the AP and BT, which may be a result of the relatively higher slopes in these ecoregions (Table 14). Steeper slopes can lead to greater organic matter accumulation at lower landscape positions, similarly influencing LFCmass.

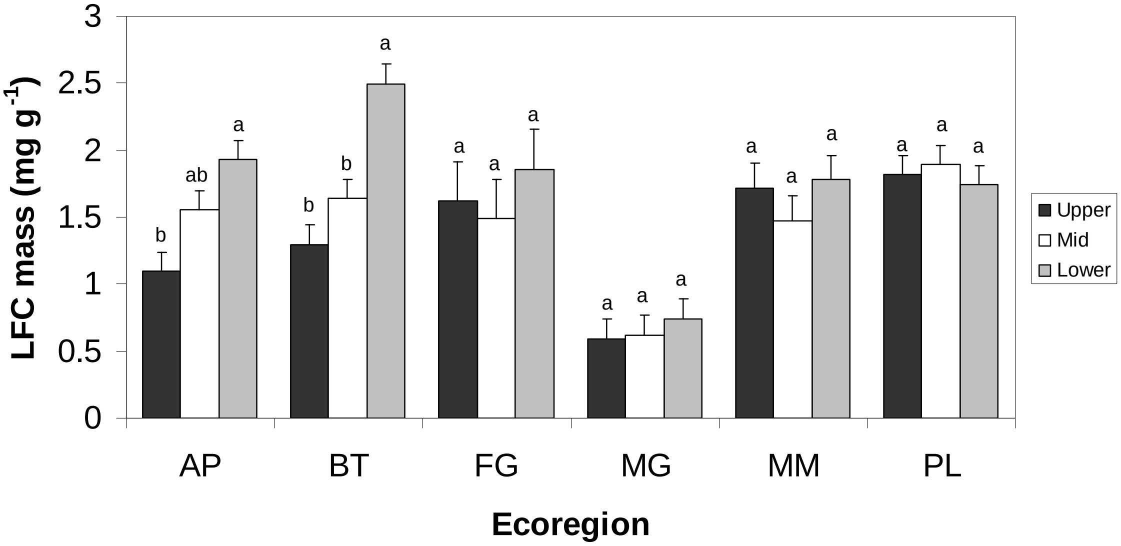

Figure 9. The ecoregion × position interaction effect on mass of light fraction carbon using data collected from 1998 to 2006 at 41 AESA Soil Quality Benchmark sites located in Alberta, Canada.
Bars with same letter are not significantly different (*P*>0.05); error bars represent the standard error of the mean.

Mass of Light Fraction Nitrogen - Similar to LFCmass, measurements of mass of light fraction nitrogen (LFNmass) were also taken only at the 0 to 15 cm sampling depth, thus the effect of depth was excluded from the analysis.

The effect of year was significant (*P*<0.001), likely due to large shifts in weather patterns over time. Mass of light fraction N decreased sharply in 2002 (Figure 10), possibly as a result of reduced N mineralization during the province-wide drought. In 2003, LFNmass levels remained low, which may be reflective of high levels of precipitation leading to N leaching or denitrification prior to sampling in the late fall of 2003. Soil LFNmass sharply increased in 2004 and began to decrease steadily toward the pre-2002 levels. Further, regression analysis revealed no significant trends in LFNmass across the province or within individual ecoregions (Table 8). This highlights the need for annual sampling to identify and quantify fluctuations in soil quality measures.

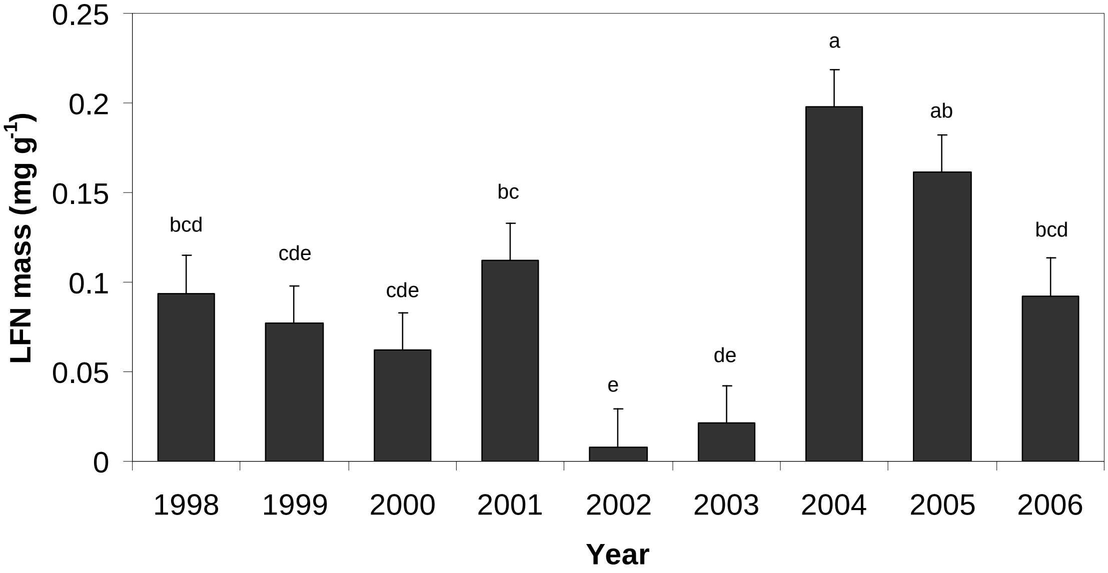

Figure 10. The effect of year on mass of light fraction nitrogen data using collected from 1998 to 2006 at 41 AESA Soil Quality Benchmark sites located in Alberta, Canada.
Bars with same letter are not significantly different (*P*>0.05); error bars represent the standard error of the mean.

Ecoregion and ecoregion × year interaction effects were not significant (*P*>0.05), with ecoregions responding similarly to yearly fluxes (data not shown). This supports the theory that weather patterns common to the entire province may play an important role in LFNmass variability.

Similar to LFCmass, position and position × ecoregion effects were significant for LFNmass, with generally higher LFNmass contents at the lower landscape position (Table 7). Again, a closer look at the ecoregion × position interaction reveals that this was most prominent in the AP and BT (data not shown), which may be a result of the relatively higher landscapes in these ecoregions.

Nitrate Nitrogen - Overall, the effects of depth, ecoregion × depth and position × depth were significant ($P<0.05$) for residual nitrate nitrogen (NO_3-N) sampled in the fall, following crop harvest. As expected, NO_3-N levels tended to be higher at the 0 to 15 cm sampling depth (6.6 to 13.3 mg kg^{-1}) than at the 15 to 30 cm depth (4.4 to 9.0 mg kg^{-1}) (Table 10). Within ecoregions and landscape positions, NO_3-N levels were also more variable in the 0 to 15 cm layer (data not shown). Higher NO_3-N levels at the 0 to 15 cm sampling depth is typical of the increased mineralization common to upper soil horizons, which may be warmer, better aerated and with higher levels of biological activity relative to lower soil horizons. The observed provincial NO_3-N levels at the 0 to 15 cm sampling depth are similar to average available soil NO_3-N levels of 5 to 15 mg kg^{-1} as reported for stubble fields in Alberta (Kryzanowski 1993).

Although residual NO_3-N levels were generally similar across years, the effect of year was significant at both depths (Figure 11). This was due to lower NO_3-N concentrations in 2005 compared with 2002 and 2003. Higher NO_3-N soil concentrations in 2002 may be due to reduced crop uptake under the drought conditions experience that year, while higher levels in 2003, could be due to increased crop productivity (i.e., increased crop residue production) and increased mineralization under the long, warm fall season experienced in Alberta that year. Lower levels in 2005 may be a result of a wetter growing season leading to denitrification and/or increased leaching of NO_3-N from the soil. Regression analysis revealed no significant change in soil NO_3-N concentration during the nine-year study at the provincial level, as regression coefficients were not significantly different from zero at either sampling depth (Table 12 and Table 13). Further analysis revealed there to be a significant decrease in NO_3-N the upper landscape position of the PL at the 0 to 15 sampling depth (R^2=0.55, $P<0.02$) and an increase in NO_3-N the lower and mid landscape positions in the FG at the 15 to 30 cm depth (Table 9, Table 12 and Table 13).

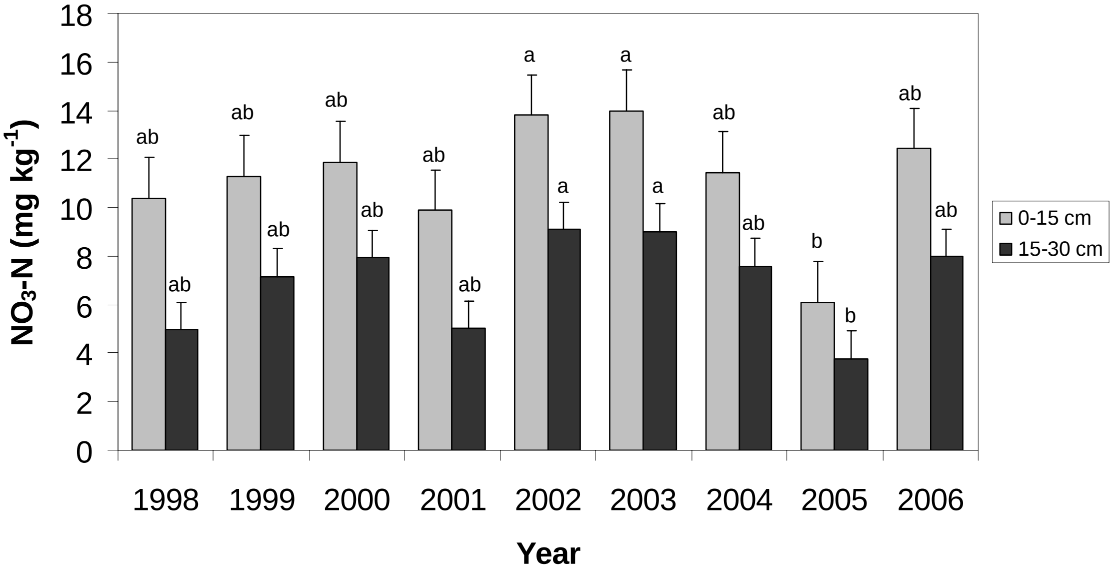

Figure 11. The effect of year on nitrate at the 0 to 15 cm and 15 to 30 cm sampling depths, using data collected from 1998 to 2006 at 41 AESA Soil Quality Benchmark sites located in Alberta, Canada.

Bars with same letter are not significantly different (*P*>0.05); error bars represent the standard error of the mean.

Ecoregion and ecoregion × year interactions effects were not significant for NO_3-N at either depth, though the data illustrates the high level of variability in N levels within and between ecoregions over time. It is interesting to note that in 2001 and 2005, NO_3-N levels appear to be lower in all ecoregions, for unknown reasons.

At both sampling depths, landscape position and landscape position × ecoregion were significant. Overall, the lower landscape positions (12.5 mg kg^{-1} at 0 to 15 cm, 7.8 mg kg^{-1} at 15 to 30 cm) tended to be higher in NO_3-N than the upper position (9.6 mg kg^{-1} at 0 to 15 cm, 6.0 mg kg^{-1} at 15 to 30 cm) (Table 10), although the position × ecoregion interaction effect reveals that in most ecoregions, NO_3-N was not significantly higher in the lower landscape position. This is similar to what was observed by Penney (2004). Exceptions were seen in the AP and MG at the 0 to 15 cm depth (Figure 12) and in the AP in the 15 to 30 cm depth (data not shown).

Though not significantly different from other ecoregions, it is interesting to note that NO_3-N levels were generally lower in the BT (Table 10), which may be due to a higher concentration of forage crops and, depending on species, less fertilizer application as these crops are often capable of fixing atmospheric nitrogen (i.e., alfalfa forages). However, forage crops do tend to take up soil nitrogen throughout the growing season (i.e., they are considered luxury consumers of available residual soil nitrogen, as nitrogen fixation is an energy demanding plant process), resulting in lower fall soil NO_3-N levels. With respect to nitrogen in soils under annual cereal and oilseed production, it may undergo mineralization after the crop is harvested, leading to higher NO_3-N levels at the time of sampling in the fall.

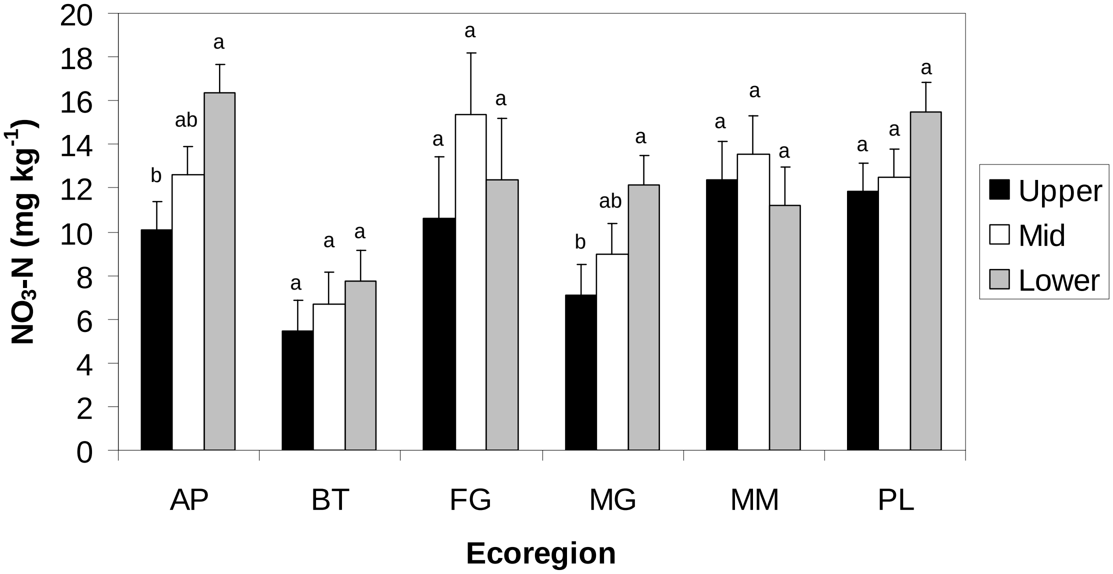

Figure 12. The position × ecoregion interaction effect on nitrate at the 0 to 15 cm sampling depth, using data collected from 1998 to 2006 at 41 AESA Soil Quality Benchmark sites located in Alberta, Canada.
Bars with same letter are not significantly different ($P>0.05$); error bars represent the standard error of the mean.

Ammonium Nitrate - The effect of depth, depth × year and ecoregion × depth were all significant ($P<0.001$) for ammonium nitrate (NH_4-N). Overall, NH_4-N was higher at the 0 to 15 cm level (1.22 to 5.42 mg kg^{-1}) than at the 15 to 30 cm depth (0.76 to 2.14 mg kg^{-1}) (Table 10). A closer look at the depth × ecoregion interaction suggests that large differences in NH_4-N between the 0 to 15 and 15 to 30 cm sampling depths occur in the AP and FG ecoregions, but not in the other four ecoregions examined in this study. The significant depth × year interaction appears to be driven by an anomalous increase in soil NH_4-N levels in 2003, which was proportionately higher at the 0 to 15 cm sampling depth than at the 15 to 30 cm depth (Figure 13).

Within each sampling depth, the effect of year was significant ($P<0.002$) for NH_4-N. At the 0 to 15 cm depth, NH_4-N was significantly higher in 2003 than in all other years, while in the lower depths, 2003 was significantly higher in NH_4-N than in 2000, 2004, 2006 (Figure 13). The fall of 2003 was unusually long, with above average temperature and precipitation (ARD 2008), likely resulting in greater mineralization of organic matter and greater availability of NH_4-N, particularly at the 0 to 15 cm sampling depth. Provincially, regression coefficients for NH_4-N were not significantly different from zero at either sampling depth, suggesting that Alberta's soil NH_4-N levels, although variable, have remained fairly constant over the nine years of the study (Table 12 and Table 13). However, there was a significant decrease in NH_4-N in the upper landscape position of only the MM ecoregion in the 0 to 15 cm layer ($R^2=0.53$, $P<0.03$) (Table 9 and Table 12).

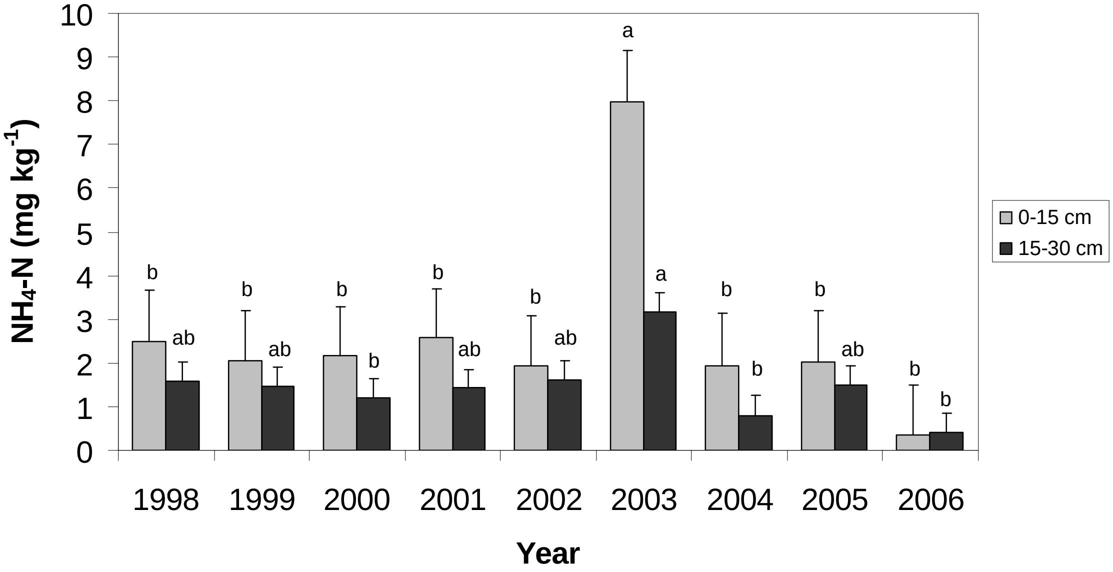

Figure 13. The effect of year on ammonium at the 0 to 15 cm and 15 to 30 cm sampling depths, using data collected from 1998 to 2006 at 41 AESA Soil Quality Benchmark sites located in Alberta, Canada.
Bars with same letter are not significantly different ($P>0.05$); error bars represent the standard error of the mean.

The effect of ecoregion was not significant for NH_4-N at either sampling depth ($P>0.05$); however, a significant ecoregion × year interaction at the 0 to 15 cm sampling depth was detected. This interaction appeared to be driven by high soil NH_4-N levels in the AP and FG in 2003, suggesting that the effect of the warm, wet fall weather on NH_4-N was more prominent in those ecoregions (data not shown).

Landscape position was only significant at the 0 to 15 cm sampling depth ($P<0.01$), where NH_4-N levels were higher at the mid landscape position than at the lower and upper landscape positions (Table 10). A closer look at the ecoregion × position interaction effect at the 0 to 15 cm sampling depth suggests that the differences in NH_4-N among landscape positions were driven by an unusually high level of NH_4-N in the mid landscape position of the FG (data not shown). None of the other five ecoregions differed in NH_4-N at any of the three landscape positions, suggesting that in general, landscape position had little effect on soil NH_4-N content, as was reported by Penney (2004).

Hot KCl Extractable Ammonium Nitrogen - Hot KCl extractable ammonium nitrogen (KCl - NH_4-N) was measured on the soils sampled from the AESA Soil Quality Benchmark sites to provide a better estimate of total potential nitrogen mineralization throughout the growing season (Campbell et al. 1997). This analysis was done to support one of the initial goals of the AESA Soil Quality Benchmark Sites program – to provide data to test and validate soil and crop models. Quite often, better estimates of nitrogen availability are required for modeling purposes, and KCl - NH_4-N provides the necessary level of additional detail. As this data was being collected for specific purposes, it was only measured from the 0 to 15 cm depth, thus the effect of depth was removed from the analysis.

All treatment effects were significant ($P<0.02$) for KCl - NH_4-N, with the exception of the position × year interaction effect. Analysis of the year effect illustrated the natural variability of the mineralizable component associated with KCl - NH_4-N, with no identifiable overall trend. For example, KCl - NH_4-N was greatest in 2000 and 2002, and lowest in 2005, although the range during the nine-year period was less than 9 mg kg^{-1} (Figure 14). Regression analysis confirmed the absence of any trend over time, where the slope of the regression line was not significantly different from zero, either provincially or by ecoregion (Table 8).

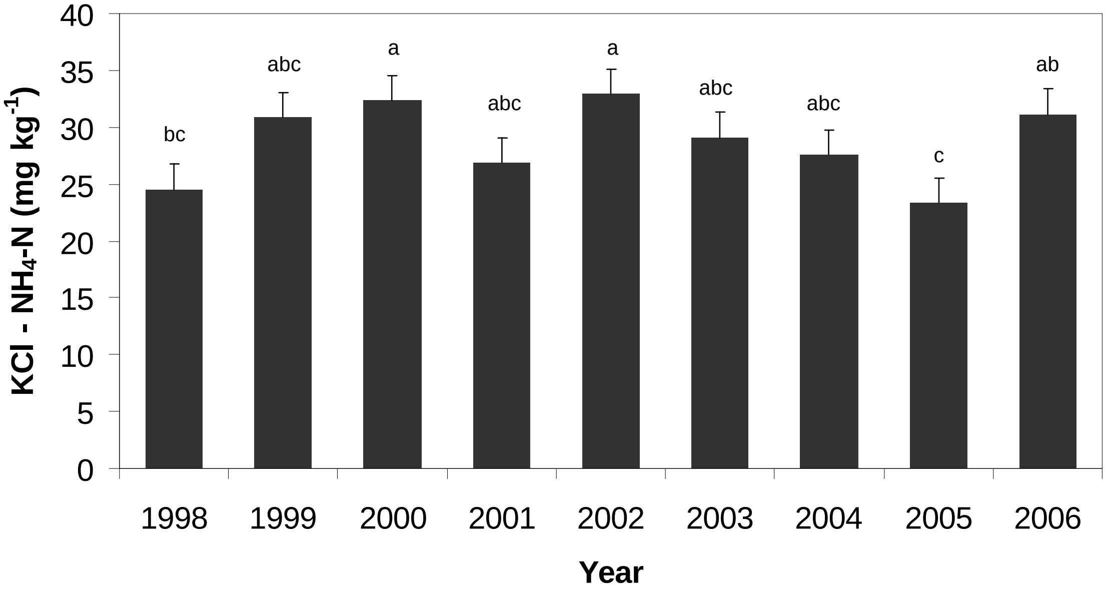

Figure 14. The effect of year on hot KCl extractable ammonium nitrogen using data collected from 1998 to 2006 at 41 AESA Soil Quality Benchmark sites located in Alberta, Canada. Bars with same letter are not significantly different ($P>0.05$); error bars represent the standard error of the mean.

At the regional level, KCl - NH_4-N appeared to follow climatic patterns and soil organic carbon levels in the province, with correlation analysis confirming the strong relationship between KCl - NH_4-N and organic carbon ($R^2 = -0.92$, $p = 0.01$). The analysis also revealed that the MG and MM ecoregions (typically drier with lower soil organic carbon) had among the lowest mineralizable KCl - NH_4-N, while the AP ecoregion (typically wetter and higher in soil organic carbon) was among the highest (Table 7). The MG exhibited the lowest KCl - NH_4-N among ecoregions, possibly attributable to the use of summerfallow in rotation in the MG. This observation supports the work of Penney (2004).

The ecoregion × year interaction effect for KCl - NH_4-N was significant, revealing greater year to year variability in soil KCl - NH_4-N in the more northerly ecoregions of the province (AP, PL and BT) (Figure 15). In the MG, increases in KCl - NH_4-N in 2005 and 2006 may be attributable to less summerfallow in rotation, as was observed from 2005/2006 crop management records.

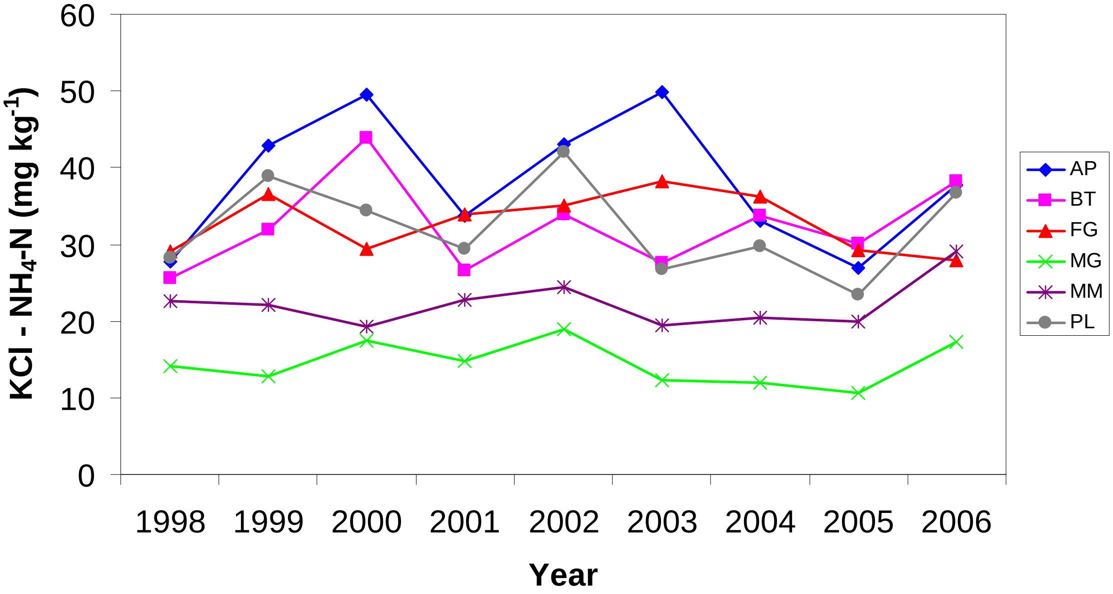

Figure 15. The ecoregion × year interaction for hot KCl extractable ammonium nitrogen, using data collected from 1998 to 2006 at 41 AESA Soil Quality Benchmark sites located in Alberta, Canada.

Overall, KCl - NH_4-N levels were significantly higher at the lower landscape position (32.2 mg kg^{-1}) than at the upper position (25.2 mg kg^{-1}) (Table 7), although the ecoregion × position interaction effect suggests that this was more pronounced in the AP, BT and MG ecoregions, where mean land slopes were the among the highest of ecoregions included in this study at 7.1%, 5.0% and 3.3%, respectively (Table 14). Penney (2004) similarly reported higher KCl - NH_4-N levels at the lower landscape position.

Soil Test Phosphorus - The availability of soil test phosphorus (STP) is influenced by soil pH levels, with STP becoming less available to plants at extremes of the pH scale (Brady 1990). In the current study, we can assume that STP availability was not limited by the pH of soils at the study sites, as all sites fall within the optimal range (pH 6 to 7) for STP availability.

Depth and its associated interaction effects were significant (P<0.002), with the exception of position × depth. Soil test phosphorus concentrations throughout the province ranged from 16.7 to 25.8 mg kg^{-1} at the 0 to 15 cm depth, and from 8.6 to 13.0 mg kg^{-1} at the 15 to 30 cm depth, indicating STP buildup in the 0 to 15 depth compared to the 15 to 30 cm (Table 10). As the benchmark sites are predominantly reduced till, STP tends to become stratified in the upper soil layer owing to low water solubility, low movement (plant uptake results from phosphorus movement by diffusion depending on soil moisture and temperature) and fertilizer application.

The range of STP values observed at the 0 to 15 cm layer is similar to the 12 to 24 mg kg^{-1} range reported by Kryzanowski (1993) for stubble fields in Alberta. The findings of the current study and that of Kryzanowski (1993) support Manunta et al. (2000) who reported that most soils in Alberta are deficient (<7.5 to 12.5 mg kg^{-1}) or marginal (12.5 to 25 mg kg^{-1}) in STP (Kryzanowski et al. 1988).

The effect of year was significant at both sampling depths, with the data showing a gradual increase in STP concentration over the duration of the nine-year study (Figure 16), which may indicate increased fertilizer use and reflects the observed increase in provincial fertilizer sales (Alberta Agriculture and Food 2006). Overall, STP concentrations at the 0 to 15 cm depth were fairly similar between years, except in 2002 and 2004, where STP concentrations were significantly higher than those observed in 1999 (Figure 16). At the 15 to 30 cm sampling depth, similar trends were observed, although STP in 2003 was significantly higher than 1998 and 1999 (Figure 16).

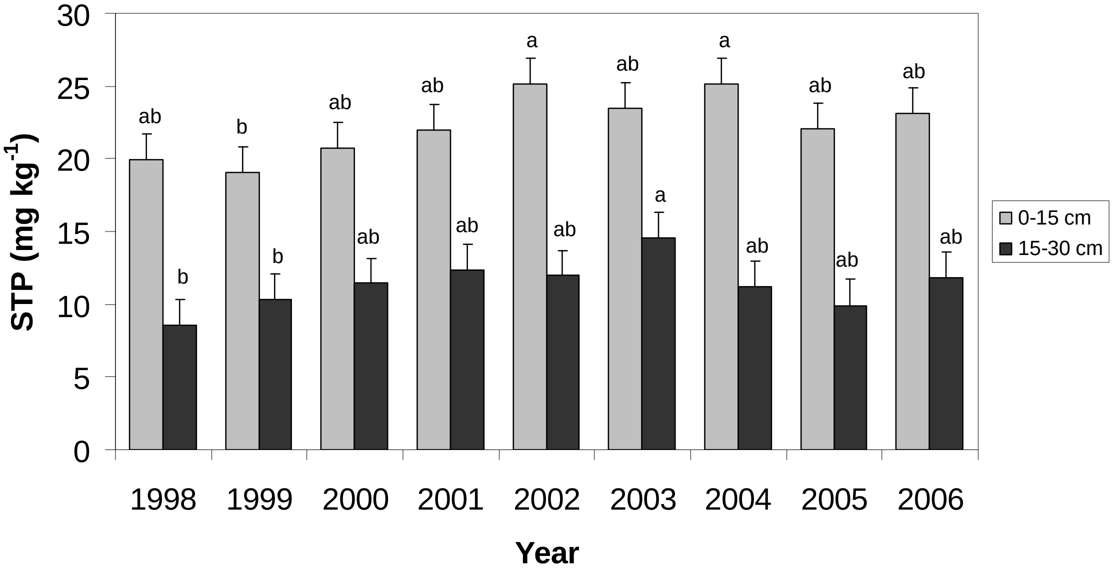

Figure 16. The effect of year on soil test phosphorus (STP) concentration at the 0 to 15 cm and 15 to 30 cm sampling depths using data collected from 1998 to 2006 at 41 AESA Soil Quality Benchmark sites located in Alberta, Canada.
Bars with same letter are not significantly different (*P*>0.05); error bars represent the standard error of the mean.

Regression analysis on the provincial data revealed that the STP levels across the province significantly increased in the lower landscape position only, by 19% at the 0 to 15 cm depth (R^2=0.09, $P<0.03$) and by 28% at the 15 to 30 cm (R^2=0.07, $P<0.05$) sampling depth over the duration of the study (Table 9, Table 12 and Table 13). Subsequent analyses conducted at the ecoregion level reveal, however, that significant increases in soil STP concentrations occurred in the upper landscape position of the BT, at all three landscape positions of the MG, and in the lower and mid landscape positions of the PL at the 0 to 15 cm sampling depth (Table 9 and Table 12). Significant increases in STP at all three landscape positions of the MG support the earlier findings of Manunta et al. (2000), who also observed that most of the statistically significant increases in STP occurred in southern Alberta. At the 15 to 30 cm sampling depth, significant increases occurred in the lower landscape position of the AP and in the mid landscape position of the PL depth (Table 9 and Table 13).

While ecoregion and ecoregion × year interaction effects were not statistically significant at either depth, the data captured the natural variability that is typical to the province (Kryzanowski 1993). Large spikes in STP in some ecoregion-years (data not shown) could also be attributed to sampling variability, which may have resulted from the inclusion of samples taken on or near fertilizer bands under reduced and no-till cropping systems.

Landscape position and position × ecoregion interaction effects were significant ($P<0.001$) for STP concentration at both sampling depths (data not shown). As described by Penney (2004), higher levels of STP occurred in the lower landscape position compared to the mid or upper landscape positions (Table 10). This is likely attributed to one of the three main sources of STP loss, particulate erosion, which tends to occur in a down-slope direction (PPI 2003). Within ecoregions, landscape position effects were significant only in the AP, BT and MG, thereby creating a significant position × ecoregion interaction (Figure 17). Landscape position effects may be more pronounced in these ecoregions, as they are among the ecoregions with the steepest slopes (Table 14).

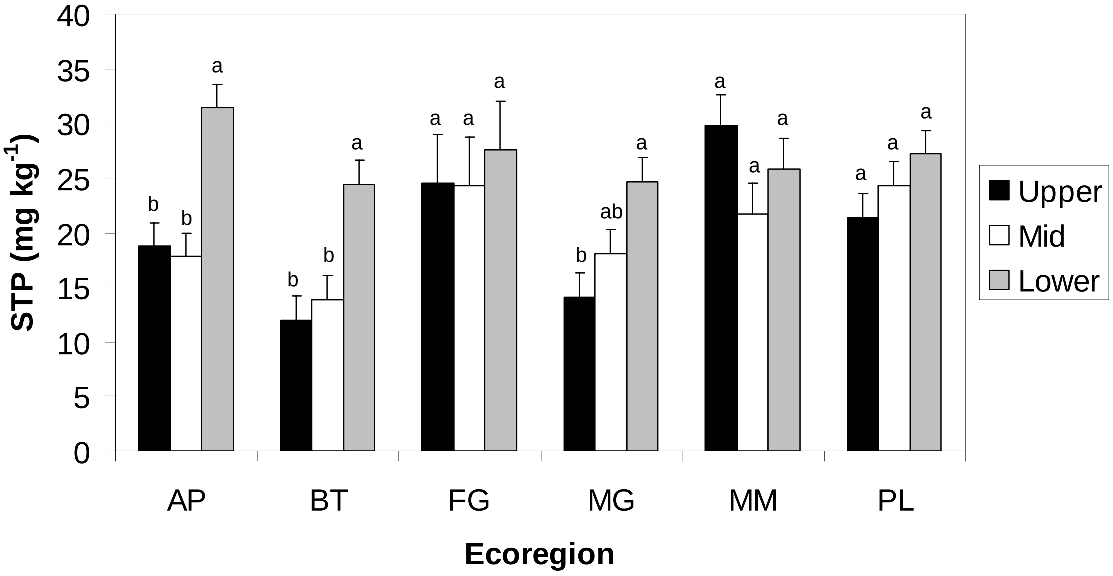

Figure 17. The position × ecoregion interaction effect on soil test phosphorus (STP) at the 0 to 15 cm sampling depth, using data collected from 1998 to 2006 at 41 AESA Soil Quality Benchmark sites located in Alberta, Canada.
Bars with same letter are not significantly different ($P>0.05$); error bars represent the standard error of the mean.

Potassium - Similar to STP, major losses of potassium (K) from the soil occur as a result of crop harvest, runoff and erosion (PPI 2003). Although soil K is abundant, much of it remains relatively unavailable for plant uptake, hence most K is applied as fertilizer (Brady 1990). Since moisture is needed for K to move and become plant available, drought and excessive moisture conditions reduce K uptake by a growing crop (PPI 2003).

Across ecoregions, soil K levels ranged from about 203 to 511 mg kg^{-1} (Table 10), which is similar to the 175 to 425 mg kg^{-1} range of soil K levels observed previously in stubble fields of Alberta (Kryzanowski 1993). The effects of depth and its associated interactions were significant (*P*<0.001). Overall, soil K levels were lower (243 mg kg^{-1}) at the 15 to 30 cm sampling depth compared to the 0 to 15 cm depth (331 mg kg^{-1}) (Table 10). As K is involved in osmoregulation (e.g., stomatal opening and closure, turgor pressure) most K taken up by plants ends up in structural components (e.g., straw) and is often returned to the field after crop harvest (Marshner 1995, PPI 2003). As such, K tends to be enriched in the upper soil layers. In addition, owing to limited mobility, K applied as fertilizer tends to become stratified in the upper soils layer (Brady 1900).

At both sampling depths, the effect of year on K levels was highly variable, although significant (*P*<0.001) (Figure 18). Regression analyses did not reveal a significant trend across the province at either depth, although within the BT, a significant increase in K was observed at both sampling depths in the upper landscape position (Table 9, Table 12 and Table 13). This suggests that soil K levels in Alberta have stayed relatively constant during the last nine years of the study.

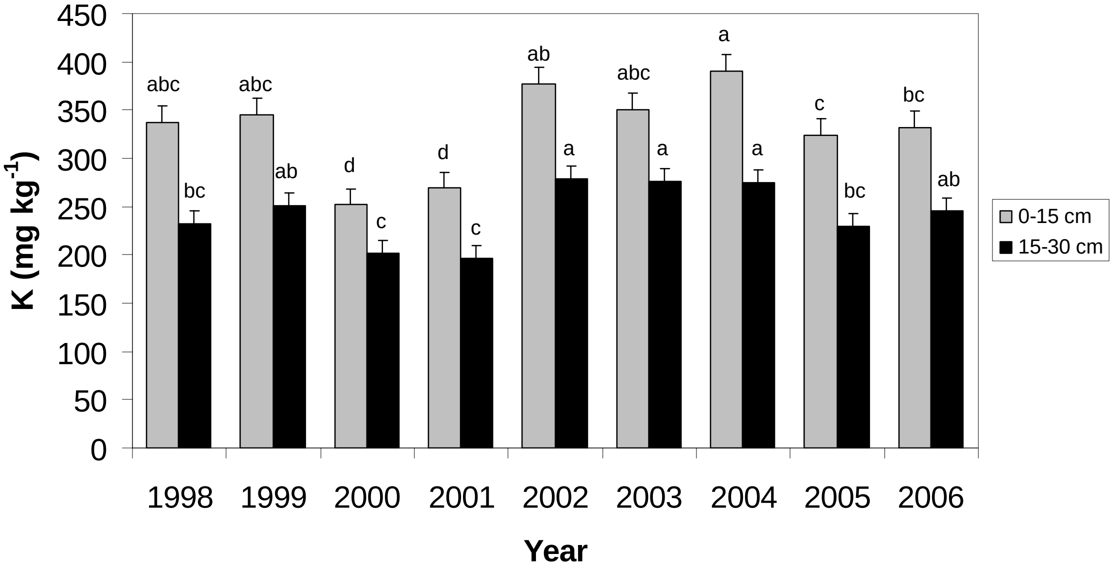

Figure 18. The effect of year on potassium at both sampling depths, using data collected from 1998 to 2006 at 41 AESA Soil Quality Benchmark sites located in Alberta, Canada.
Bars with same letter are not significantly different (*P*>0.05); error bars represent the standard error of the mean.

Ecoregion was significant (*P*<0.001) for K at both depths, where soil K concentrations were higher in the southern regions (FG, MG, MM), compared with the northern regions (BT, AP, PL) (Table 10). Soil K levels may be higher in more southerly regions due to climatic, management and pedogenic factors. Since soil K must be carried to plants in water, crops growing in the drier southern ecoregions may not take up as much K compared with crop plants in the wetter northern ecoregions, thus soil K levels appear higher at the end of the growing season in the FG, MG and MM ecoregions. Higher soil K levels in the southern ecoregions of Alberta may also be related to poor soil aeration caused by minimum tillage systems, which are more common in these southern regions as a moisture retention strategy (PPI 2003). Finally, differences between soil K levels in these ecoregions may be related to the amount and type of clay minerals from which the soil formed (pedogenesis processes). Similar to what was observed by Penney (2004), the BT ecoregion exhibited the lowest K levels (Table 10). This is consistent with summaries of routine soil fertility data collected on stubble fields in Alberta, where the more northerly Gray Luvisolic soils displayed soil K concentrations of 125 to 200 mg kg^{-1} compared to 325 to 425 mg kg^{-1} in the Brown and Dark Brown soils (Kryzanowski 1993). Ecoregion × year interaction effects were not significant, with ecoregions responding similarly to the effects of year (data not shown).

Position and ecoregion × position were significant at both sampling depths, where K tended to be higher at lower landscape positions (Table 10). Soils located in lower landscape positions tend to be moister, with greater productivity and crop residue production, leading to increased K levels in the soil. Furthermore, past cultivation practices may have led to greater erosion of topsoil from upper landscape positions. Although this trend was observed in all ecoregions, significant differences in K levels among landscape positions were variable. For example, at the 0 to 15 cm sampling depth, the effect of landscape position was not significant in the PL, BT, MM and FG (Figure 19).

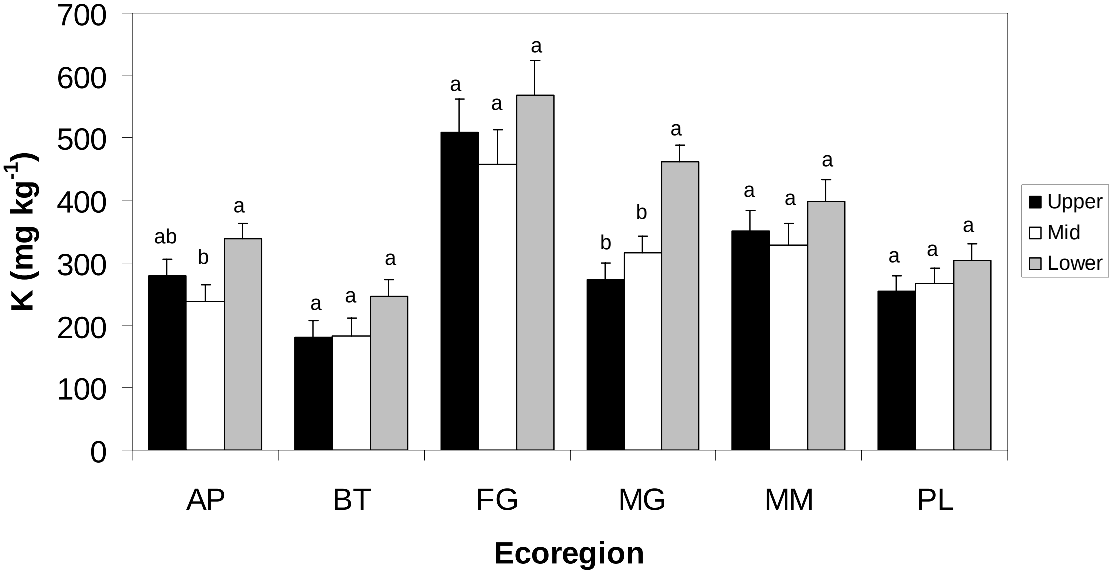

Figure 19. The ecoregion × position interaction effect on potassium at the 0 to 15 cm sampling depth using data collected from 1998 to 2006 at 41 AESA Soil Quality Benchmark sites located in Alberta, Canada.
Bars with same letter are not significantly different (*P*>0.05); error bars represent the standard error of the mean.

Sulfate Sulfur - Soil sulfate sulfur (SO_4-S) levels displayed a high degree of variability, ranging from 5.3 to 26.5 mg kg^{-1} across ecoregions (Table 10). These values are similar to the range of soil SO_4-S values for stubble fields in Alberta, as reported by Kryzanowski (1993), which ranged from about 6 to 21 mg kg^{-1}. Sulfates are highly mobile, soluble compounds, and are highly influenced by soil moisture (Brady 1990). As a result, SO_4-S values tend to be variable among ecoregions and years. Coefficients of variation for SO_4-S across ecoregions ranged from 36%-292% (Table 6).

Ecoregion × depth and position × depth interaction effects were significant ($P<0.02$) for SO_4-S (data not shown). However, the ecoregion × depth interaction was driven by a very high subsoil concentration of SO_4-S in the AP (Figure 20). This phenomenon may be associated with moisture movement as snow melt may lead to an accumulation of SO_4-S into lower areas. The same effect of depth on SO_4-S concentration was observed in the drier MG, and although it was not statistically significant, may be attributed to high underlying gypsum levels associated with a shallow profile rather than water movement through the soil profile.

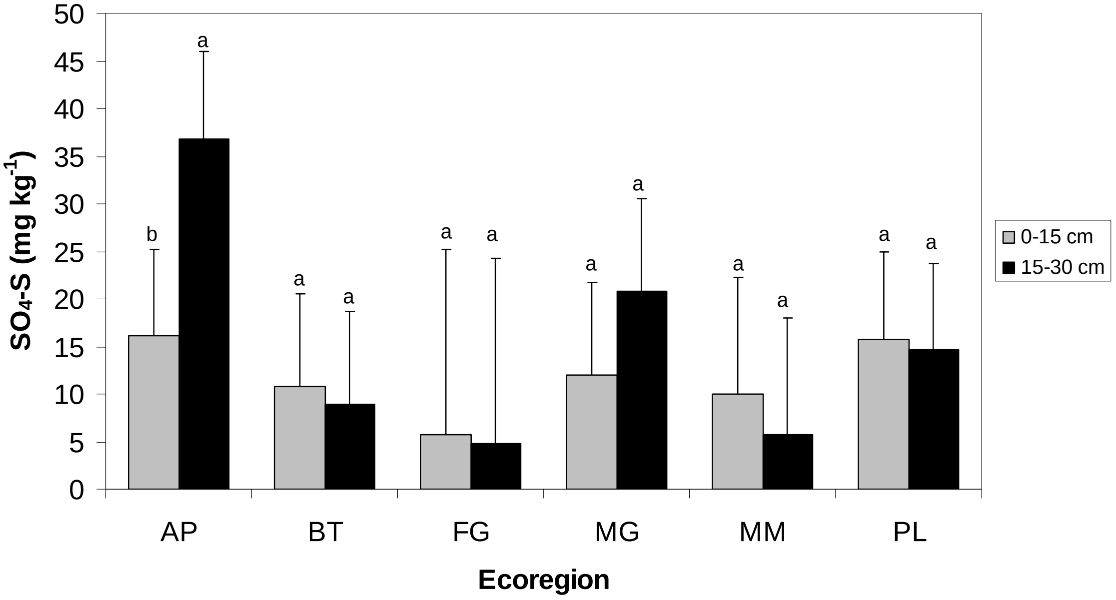

Figure 20. The ecoregion × depth interaction effect on sulfate sulfur using data collected from 1998 to 2006 at 41 AESA Soil Quality Benchmark sites located in Alberta, Canada.
Bars with same letter are not significantly different ($P>0.05$); error bars represent the standard error of the mean.

Position × depth interaction effects showed that SO_4-S levels differed between 0 to 15 cm and 15 to 30 cm sampling depths at the lowest landscape position, but were more similar at the mid and upper landscape positions (Figure 21).

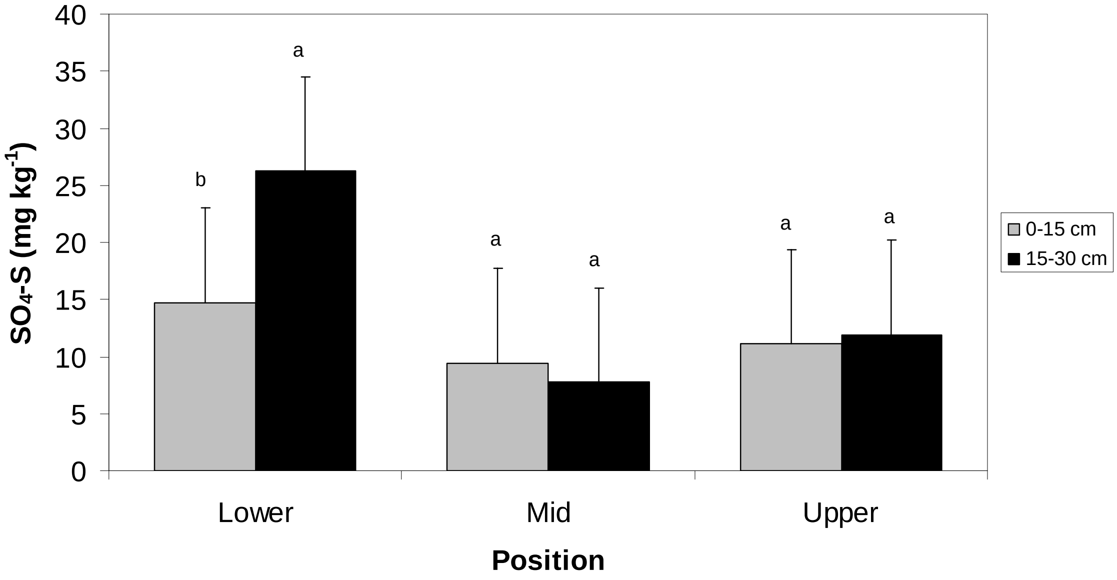

Figure 21. The position × depth interaction effect on sulfate sulfur using data collected from 1998 to 2006 at 41 AESA Soil Quality Benchmark sites located in Alberta, Canada. Bars with same letter are not significantly different ($P>0.05$); error bars represent the standard error of the mean.

The effects of year, ecoregion or ecoregion × year were not significant ($P>0.05$) for SO_4-S at either sampling depth (data not shown). Regression analyses revealed no provincial trends in SO_4-S across years, likely due to extreme variability in the data. However, in the upper landscape position of the BT at the 15 to 30 cm depth, a significant increase was measured ($R^2=0.56$, $P<0.02$) (Table 9 and Table 13).

Consistent with the findings of Penney (2004), the effect of landscape position was significant at both depths ($P<0.05$), with SO_4-S levels significantly higher at the lower landscape position (Table 10). However, this overall trend was caused by very high concentrations of SO_4-S in the lower landscape position of the AP, as indicated by significant ecoregion × position interactions at both depths (data not shown).

The Role of Field Management on Soil Quality Parameters

Although the collected agronomic data (i.e., management practices) were not analyzed as part of this report, research has been conducted that may assist in explaining some of the observed relationships described above (Penney 2004, Watson et al. 2007). Penney's initial analysis of five years of data (1998-2002) revealed that there appeared to be no significant effect of cropping system on any of the soil parameters investigated, although it is not indicated how this determination was made. Penney (2004) indicated that the data were somewhat limited in making this observation, suggesting that a more detailed analysis was required.

A more extensive analysis was commenced in 2005, resulting in the completion of a preliminary report on the agronomic production practices of the AESA Benchmark Sites (Watson et al. 2007). Multivariate analyses (e.g., canonical discriminate analysis (CDA)) were performed on the 1998 to 2005 agronomic data, revealing a number of results that helped explain the observed differences in soil parameters discussed in this report. The agronomic analysis by Watson et al. (2007) revealed that management practices on participating farms tended to be driven by soil characteristics, highlighting the importance of the soil resource in annual production systems in Alberta. This observation was supported by further analysis of the data, that revealed that farm type (i.e., grain, mixed, livestock, forage production) tended not to be chosen based on location (i.e., ecoregion), year to year variation, climate or soil characteristics *per se*, but once established within any given ecoregion (and soil type), farm practices were significantly affected by soil attributes at the site.

Canonical discriminate analysis, a statistical method that determines whether two or more groups can be distinguished based on a set of variables, indicated that production practices differed among ecoregions, but were, again, often related to soil characteristics (e.g., fertility level). Canonical correlations suggested strong regional relationships with certain management practices. For example, farms in the AP and PL tended to discriminate based on high fertility requirements and in the PL, by late spring fertilizer application dates, likely owing to the relatively cool, wet climate in the Peace Region of Alberta. In the BT, farms tended to have greater application rates of SO_4-S and K, and greater overall fall fertilizer applications. The uniqueness of the drier MG ecoregion was revealed, through its use of deeper seeding depths, an increased use of specialty crops (e.g., sugar beets and corn) and the use of wheat-fallow rotation sequences. Although limited in the number of observations, the FG tended towards farms requiring an increased application rate of phosphorus and generally later fall fertilizer applications. Interestingly, the MM was not distinguished by any agronomic practices relative to the other ecoregions in the study.

Also using CDA, Watson et al. (2007) identified yearly differences in production practices, specifically among 1998, 2000, 2002, 2003, and 2004, with 2002 being markedly different from all other years in the study. This supports the previous discussions on the importance of climatic variability and its affect on soil parameters, as 2002 was the driest year of the study period (1998 to 2005). Production practices, such as seeding date and total fertilizer applied to the fields were correlated with the year 2002, indicating that producer behaviour was markedly different that year than in others. Other identified correlations with year included differences in tillage types with 2001 and 1998, late fall crop harvests in 2003 and 2004 (supporting the long wet fall observed in 2003) and a move towards production of more “standard” crops (i.e., barley, wheat, oats, and canola as opposed to specialty crops like sugar beet) in 2004.

Finally, CDA identified that those farms within the AESA Soil Quality Benchmark Sites classed as predominantly livestock operations were managed differently from those classified as grain-based operations. Furthermore, mixed farming operations (i.e., operations with livestock and grain) were managed differently from all other farm types in the study. As an example of this difference, grain farms were different from mixed farming operations based on the use of later spring fertilizer packages and the date of pre-seeding herbicide applications, presumably resulting from differences in the ownership of livestock.

The reports of Penney (2004) and Watson et al. (2007) provided a number of explanations for the results presented in this report; however, further study and analyses are needed to improve their applicability and level of precision. This will require the inclusion of additional farm management data collected from other similar studies, such as that conducted by Dey (2000). Once achieved, it may be possible to construct a “correlation layer” of crop management data or agronomic production practices that, through GIS, could be better used to explain observed differences in soil parameters across Alberta during the study period.

Table 7. Ecoregion and landscape position least squares means for soil quality parameters measured at the 0 to 15 cm sampling depth (BD, KCl - NH_4-N, LF, LFCmass, LFNmass and OC), collected from 1998 to 2006 at 41 AESA Soil Quality Benchmark sites located in Alberta, Canada.

	Soil quality parameter					
	BD ($Mg\ m^{-3}$)	KCl - NH_4-N ($mg\ kg^{-1}$)	LF ($mg\ g^{-1}$)	LFCmass ($mg\ g^{-1}$)	LFNmass ($mg\ g^{-1}$)	OC ($kg\ m^{-2}$)
Ecoregion						
AP	1.26	38.3	7.36	1.53	1.06	6.95
BT	1.30	32.4	7.35	1.81	1.12	5.93
FG	1.21	32.9	8.70	1.66	1.02	6.74
MG	1.40	14.5	4.27	0.65	0.69	3.01
MM	1.29	22.2	8.43	1.66	1.07	4.87
PL	1.26	32.2	8.57	1.82	1.14	7.58
SED^z eco	0.067	5.00	1.423	0.189	0.152	0.939
Position						
Upper	1.32	25.2	6.87	1.36	0.96	5.27
Mid	1.30	28.8	7.16	1.45	1.01	5.76
Lower	1.24	32.2	8.32	1.76	1.08	6.53
SED pos	0.011	0.73	0.394	0.088	0.040	0.113

^{z} SED=standard error of the difference between two means for ecoregion (eco) and landscape position (pos).

Table 8. Significance of the slopes of the linear regressions (soil property vs. year of sampling) from zero, for entire provincial data and individual ecoregions for parameters measured at only one depth.

	Provincial	AP	BT	FG	MG	MM	PL
BD	***LMU^z	ns	*L	ns	ns	ns	*U
LF	ns	ns	ns	ns	ns	ns	*M
LFCmass	ns	ns	ns	ns	*U	ns	*M
LFNmass	ns	ns	ns	ns	ns	ns	ns
KCl - NH_4-N	ns	ns	ns	ns	ns	ns	ns
OC	ns	ns	ns	ns	ns	ns	ns

^{z} L,M and U correspond to significance at the lower (L), mid (M) or upper (U) landscape position, respectively.

*, **, *** denotes significance at P<0.05, 0.01 and 0.001, respectively

Table 9. Regression equations ($y=mx+b$) for statistically significant regressions of soil quality parameters over time.

Ecoregion	Parameter	Position	m	b	R^2	*P*
Provincial	BD	L	-0.012	25.8	0.09	0.03
	BD	M	-0.012	24.4	0.07	0.05
	BD	U		25.6	0.07	0.05
	STP (0 to 15 cm)	L	0.579	-1131.5	0.09	0.03
	STP (15 to 30 cm)	L	0.474	-933.7	0.07	0.05
AP	pHc (0 to 15 cm)	M	-0.032	70.0	0.51	0.03
	STP (15 to 30)	L	0.832	-1648.2	0.67	0.01
BT	BD	L	-0.019	39.9	0.47	0.04
	K (0 to 15 cm)	L	10.446	-20733.0	0.48	0.04
	STP (0 to 15cm)	U	0.563	-1115.3	0.52	0.03
	K (15 to 30 cm)	U	6.719	-13295.0	0.49	0.04
	pHc (15 to 30 cm)	U	0.029	-53.5	0.59	0.02
	pHw (15 to 30 cm)	M	0.033	-60.4	0.56	0.02
	pHw (15 to 30 cm)	U	0.031	-56.1	0.59	0.02
	SO_4-S(15 to 30 cm)	U	0.521	-1035.3	0.56	0.02
FG	pHc (0 to 15 cm)	L	-0.074	154.1	0.89	0.01
	pHw (0 to 15 cm)	L	-0.076	159.5	0.93	0.01
	NO_3-N (15 to 30 cm)	L	1.449	-2892.0	0.48	0.04
	NO_3-N (15 to 30 cm)	M	1.449	-2892.0	0.48	0.04
	pHw (15 to 30 cm)	L	-0.041	89.3	0.53	0.03
MG	STP (0 to 15 cm)	L	1.331	-2639.4	0.70	0.01
	STP (0 to 15 cm)	M	0.791	-1565.5	0.72	0.01
	STP (0 to 15 cm)	U	0.621	-1229.9	0.75	0.01
	EC (15 to 30 cm)	U	0.028	-55.1	0.66	0.01
	LFCmass	U	0.079	-158.5	0.50	0.01
MM	NH_4-N (0 to 15 cm)	U	-0.316	634.4	0.53	0.03
PL	BD	U	-0.014	30.3	0.57	0.02
	LF	M	0.733	-1458.9	0.47	0.05
	LFCmass	M	0.139	-277.0	0.54	0.03
	EC (0 to 15 cm)	L	-0.024	49.2	0.59	0.02
	NO_3-N (0 to 15 cm)	U	-1.055	2124.1	0.55	0.02
	pHc (0 to 15 cm)	M	-0.027	59.4	0.55	0.03
	STP (0 to 15 cm)	L	0.809	-1592.9	0.78	0.01
	STP (0 to 15 cm)	M	0.926	-1830.5	0.65	0.01
	STP (15 to 30 cm)	M	0.528	-1050.4	0.76	0.01

Table 10. Ecoregion and landscape position least squares means for soil quality parameters measured at two sampling depths (EC, K, NO_3-N, NH_4-N, pHc, pHw, STP, SO_4-S), arranged by sampling depth.

	0 to 15 cm sampling depth								15 to 30 cm sampling depth							
	EC (dS m^{-1})	K (mg kg^{-1})	NO_3-N (mg kg^{-1})	NH_4-N (mg kg^{-1})	pHc	pHw	STP (mg kg^{-1})	SO_4-S (mg kg^{-1})	EC (dS m^{-1})	K (mg kg^{-1})	NO_3-N (mg kg^{-1})	NH_4-N (mg kg^{-1})	pHc	pHw	STP (mg kg^{-1})	SO_4-S (mg kg^{-1})
Ecoregion																
AP	0.46	285.4	13.0	4.7	5.6	6.4	22.7	15.3	0.51	195.8	8.8	1.9	6.13	6.85	12.2	37.4
BT	0.45	203.1	6.6	1.5	5.6	6.4	16.7	10.8	0.34	158.1	4.4	1.2	5.89	6.72	12.9	9.0
FG	0.34	511.8	12.8	5.4	5.5	6.2	25.5	5.8	0.35	394.1	9.0	2.1	6.04	6.76	11.5	4.8
MG	0.58	349.8	9.4	1.2	6.7	7.2	18.9	12.3	0.68	259.9	6.7	1.6	6.90	7.45	11.7	20.9
MM	0.45	359.2	12.4	1.6	5.6	6.2	25.8	10.1	0.38	257.5	7.6	1.3	6.03	6.68	12.8	5.7
PL	0.51	274.7	13.3	1.2	5.8	6.5	24.3	15.7	0.39	193.2	5.2	0.8	6.12	6.91	8.6	14.7
SED eco	0.098	43.25	3.28	2.06	0.35	0.34	6.28	6.81	0.131	35.43	2.30	0.61	0.333	0.306	3.53	26.50
Position																
Upper	0.48	307.4	9.6	2.2	5.9	6.6	20.1	11.0	0.45	227.8	6.0	1.4	6.36	7.07	9.5	12.6
Mid	0.46	298.3	11.6	3.5	5.8	6.5	20.0	8.8	0.43	221.7	6.9	1.3	6.25	6.95	9.4	8.9
Lower	0.45	386.3	12.5	2.2	5.7	6.4	26.9	15.2	0.44	279.9	7.8	1.7	5.95	6.68	16.1	24.8
SED pos	0.029	9.79	0.59	0.45	0.04	0.04	1.07	1.90	0.030	7.24	0.41	0.18	0.043	0.039	0.81	6.16

[z] SED=standard error of the difference between two means for ecoregion (eco) and landscape position (pos)

Table 11. Pearson correlation coefficients and associated *P* values associated with soil quality parameters measured from 1998 to 2006 at 41 AESA Soil Quality Benchmark sites located in Alberta, Canada.[z]

	pHc	EC	NH_4-N	KCl - NH_4-N	NO_3-N	STP	K	SO_4-S	BD	OC	LF	LFCmass	LFNmass
pHw	0.98	0.61	-0.50	-0.65	-0.57	-0.68	-0.33	0.36	0.87	-0.66	-0.92	-0.86	-0.83
	<0.01	0.03	0.10	0.16	0.06	0.02	0.30	0.25	0.03	0.15	0.01	0.03	0.04
pHc		0.68	-0.49	-0.79	-0.46	-0.57	-0.21	0.33	0.91	-0.78	-0.92	-0.91	-0.89
		0.01	0.11	0.06	0.13	0.05	0.51	0.29	0.01	0.07	0.01	0.01	0.02
EC			-0.24	-0.58	0.06	0.01	-0.15	0.57	0.84	-0.53	-0.73	-0.63	-0.53
			0.45	0.23	0.85	0.97	0.63	0.05	0.03	0.28	0.10	0.18	0.28
NH_4-N				0.59	0.59	0.52	0.62	-0.13	-0.67	0.45	0.33	0.18	0.14
				0.22	0.04	0.08	0.03	0.70	0.14	0.37	0.52	0.74	0.80
KCl - NH_4-N					0.27	0.18	-0.17	0.14	-0.81	0.92	0.64	0.74	0.77
					0.60	0.73	0.74	0.79	0.05	0.01	0.17	0.09	0.07
NO_3-N						0.87	0.66	-0.04	-0.57	0.47	0.52	0.22	0.23
						<0.01	0.02	0.90	0.24	0.35	0.29	0.68	0.66
STP							0.58	-0.22	-0.64	0.40	0.68	0.35	0.32
							0.05	0.48	0.17	0.43	0.14	0.50	0.53
K								-0.49	-0.32	-0.09	0.17	-0.18	-0.30
								0.14	0.54	0.87	0.75	0.73	0.56
SO_4-S									0.26	0.17	-0.22	-0.07	0.08
									0.62	0.74	0.68	0.89	0.87
BD										-0.88	-0.91	-0.81	-0.76
										0.02	0.01	0.05	0.08
OC											0.79	0.82	0.83
											0.06	0.05	0.04
LF												0.92	0.88
												0.01	0.02
LFCmass													0.98
													<0.01

[z] highlighted blocks represent significant ($P<0.05$) correlations.

Table 12. Significance of the slopes of the linear regressions (soil property vs. year of sampling) from zero, for entire provincial data and individual ecoregions at the 0 to 15 cm depth.

	Provincial	AP	BT	FG	MG	MM	PL
EC	ns	ns	ns	ns	ns	ns	**L[z]
K	ns	ns	*L	ns	ns	ns	ns
NH_4-N	ns	ns	ns	ns	ns	*U	ns
NO_3-N	ns	ns	ns	ns	ns	ns	*U
pHc	ns	*M	ns	***L	ns	ns	*M
pHw	ns	ns	ns	***L	ns	ns	ns
STP	*L	ns	*U	ns	***LMU	ns	**LM
SO_4-S	ns	ns	ns	ns	ns	ns	ns

[z] L,M and U correspond to significance at the lower (L), mid (M) or upper (U) landscape position, respectively.

*, **, *** denotes significance at $P<0.05$, 0.01 and 0.001, respectively.

Table 13. Significance of the slopes of the linear regressions (soil property vs. year of sampling) from zero, for entire provincial data and individual ecoregions at the 15 to 30 cm depth.

	Provincial	AP	BT	FG	MG	MM	PL
EC	ns	ns	ns	ns	**U[z]	ns	ns
K	ns	ns	*U	ns	ns	ns	ns
NH_4-N	ns	ns	ns	ns	ns	ns	ns
NO_3-N	ns	ns	ns	*LM	ns	ns	ns
pHc	ns	ns	*U	ns	ns	ns	ns
pHw	ns	ns	**M *U	*L	ns	ns	ns
STP	*L	***L	ns	ns	ns	ns	**M
SO_4-S	ns	ns	*U	ns	ns	ns	ns

[z] L,M and U correspond to significance at the lower (L), mid (M) or upper (U) landscape position, respectively.

*, **, *** denotes significance at $P<0.05$, 0.01 and 0.001, respectively.

Table 14. Mean, standard error and variance for the overall slope of each ecoregion included in the AESA Soil Quality Benchmark Sites program (1998 to 2006).

Ecoregion	Mean slope (%)	Std. error	Variance
Aspen Parkland (AP)	7.1	1.46	19.1
Boreal Transition (BT)	5.0	0.85	5.7
Fescue Grassland (FG)	2.0	1.00	2.0
Mixed Grassland (MG)	3.3	0.56	2.5
Moist Mixed Grassland (MM)	6.2	2.54	32.2
Peace Lowland (PL)	2.6	0.50	2.3

CONCLUSION

The AESA Soil Quality Benchmark Sites program is unique in that it has assembled an extensive soils information database that has been collected annually at three landscape positions (i.e., catena sequences) from the main agricultural ecoregions in Alberta. In doing so, this data base provides a spatial and temporal baseline from which to characterize the state of soil quality across Alberta's agricultural land resource.

The first phase of this report provides a detailed description of the 1997 protocol used in the selection and monitoring of the AESA Soil Quality Benchmark sites. The program design differed from that of other soil quality programs in a number of ways, primarily because it incorporated annual stratified sampling by depth and landscape position across all of the main agricultural ecoregions in Alberta. Of the 43 sites initially selected, only two did not conform fully with the description provided by the *Agricultural Region of Alberta Soil Inventory Database*, *The Canadian System of Soil Classification* and *The National Ecological Framework for Canada*, and a third site, although characterized, was removed from the program prior to annual sampling for unexplained reasons. This resulted in a program consisting of 42 benchmark sites spatially allocated in agricultural areas between Buffalo Head Prairie in northern Alberta to Pincher Creek in southern Alberta. Furthermore, the majority of the sites were representative of the areas from where they were selected, thus results were extrapolated across similar ecoregions of the province.

Results from the initial site characterization of the AESA Soil Quality Benchmark Sites program conducted between 1998 and 2000 tended to be quite comparable across all seven agricultural regions. As mentioned, the 42 selected sites were representative of the ecoregions from which they were selected, with only two having higher organic matter then expected (as indicated by colour). Generally, soil texture, CEC, $CaCO_3$ content, and soil pH reflected regional differences in quaternary geology in Alberta. Sandier textured soil profiles with higher soil pH were located in southern Alberta with finer textured soils exhibiting higher CEC being located on the Cretaceous marine shales of the Peace Lowland. Owing to climatic and vegetative differences among the ecoregions, OC levels were higher in the Peace Lowland when compared to the Moist Mixed Grassland. Similar results were observed for total soil N, although for other soil nutrients the variability was too high to make this conclusion. As only limited data were available for the Mid Boreal Uplands and Fescue Grassland, caution is needed in making inferences about these particular locations based on the available information from this study.

The second phase of the report established mean soil parameter values for year of sampling, ecoregion, landscape position and sampling depth. These values were used to examine temporal and spatial effects on soil quality for the nine-year study. In general, differences in soil quality across the province were primarily driven by landscape position, sampling depth and variations among years. To a lesser extent, differences in a number of soil quality parameters were also detected among ecoregions.

Landscape position effects were clearly the largest driver of fluctuations in soil quality across Alberta. Differences in soil quality among the different landscape positions (upper, mid and lower slope positions) were highly dependent on ecoregion, which may reflect climatic trends and/or management practices common to the ecoregion. For parameters that were measured at two sampling depths, sampling depth was often a significant driver of differences in soil quality, which reflect the effects of management, weather and different soil processes that occur at upper (0 to 15 cm) and lower (15 to 30 cm) soil depths. In many cases, the effect of year was significant on the various soil quality measures. Ecoregions also differed in some soil quality parameters (e.g., organic carbon), although soil quality fluctuations among ecoregions did not differ according to year, suggesting that ecoregions responded similarly to year-to-year variation. This indicates that differences at the ecoregion level reflected long-term climatic trends and other factors (e.g., management), rather than year-to-year variations in weather.

Linear regression analyses on soil quality parameters over time revealed few significant trends. Provincially, only bulk density and STP concentration showed significant trends between 1998 and 2006, which was likely reflective of site management that includes reduced tillage and the increased use of forages in rotation. Between 1998 and 2006, provincial bulk density appears to have decreased and STP concentrations appear to have increased. The lack of significant trends elsewhere in the provincial dataset suggests that soil quality has stayed relatively constant from 1998 to 2006 for the majority of parameters measured. At the ecoregion level, regional trends over time were identified, although these appear to be confined mostly to the more northerly regions of the province. For example, significant regression coefficients were more common in ecoregions with cooler, wetter climates (i.e., Boreal Transition and Peace Lowland).

The soil quality benchmark sites represented the backbone to the AESA Soil Quality Program. As such, they have provided extensive baseline soil information collected at a landscape scale that has been used extensively by researchers in western Canada. For example, the quality of the benchmark design and the data collected have resulted in peer reviewed publications, and has attracted interest and collaboration from scientists at the universities of Manitoba, Alberta and Agriculture Agri-Food Canada. For example, although not reported here, the University of Manitoba, through an NSERC strategic grant, have calculated adsorption coefficients for the herbicide 2,4-D and estrogenic compounds (endocrine disruptors) for all of the Alberta benchmark sites. This is the only dataset of its kind in Canada and will prove useful in the future as concerns continue to increase regarding chemical loadings and movement potential in the environment.

When integrating the concepts of soil quality into concepts associated with environmental and/or agricultural sustainability, most of the parameters considered in this report were not limiting to crop production, nor did they approach significant threshold values that may have been detrimental to the health of the crop and/or the environment. For example, despite concerns associated with phosphorus loading and contamination of surface waters, results from these 42 predominantly non-livestock producing fields concur with previous studies that soil phosphorus is often deficient or marginal, at best, on much of the agricultural land in Alberta.

Farm practices based from the documented agronomic history collected from the AESA Soil Quality Benchmark Sites, have remained relatively stable over the nine years that soil monitoring took place in Alberta. Preliminary analysis of the agronomic data with respect to the observed changes in soil quality appeared to indicate that farm management did play a role in some of these changes, although further research on the agronomic data is necessary to directly correlate certain farm management practices to changes in soil quality. However, as no major changes in agronomic practices were observed to have occurred, no drastic changes in soil quality were expected or observed.

In conclusion, although limited in time frame with respect to changes in many soil quality parameters, the results of this study on agricultural land in Alberta is still a good news story. In general, it appears that agricultural production using farm practices currently employed by many producers across the province has not had a negative impact on the soil resources of Alberta’s agricultural areas.

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APPENDICES

Appendix 1. Alberta Environmentally Sustainable Agriculture (AESA) soil quality monitoring program publications list (January 1, 1998 through December 31, 2007).

Founding documents

Conservation and Development. 1998. *Proceedings of the Soil Quality Workshop, January 30-31, 1998.* Conservation and Development Branch, Alberta Agriculture, Food and rural Development, Edmonton, AB. 84 p.

Assessment

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Card, S. 2004. *Evaluation of two field methods to estimate soil organic matter in Alberta soils.* Prepared for Alberta Environmentally Sustainable Agriculture Soil Quality Monitoring Program. Alberta Agriculture Food and Rural Development, Conservation and Development Branch. Edmonton, AB. 36p.

Hall, C. 2003. *The Soil Quality Indices Literature: Compiler's Report - SQI Literature Project 2003.* Prepared for Alberta Environmentally Sustainable Agriculture Soil Quality Monitoring Program. Alberta Agriculture Food and Rural Development, Conservation and Development Branch. Edmonton, AB. 86p. (incl. associated digital ProCite databases)

Keyes, D. 2005. *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. Edmonton, AB. 81p.

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Science Development

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(Note: Not all reports are readily available in paper copy)
Many reports are available online at www.agric.gov.ab.ca/soilquality

Appendix 2. Data structuring and SAS code for provincial analyses of variance.

Provincial analysis

Dataset for the analyses were arranged in the univariate format represented in the abridged example below.

Table A2.1 Truncated sample data showing recommended data format (in Microsoft Excel) for performing provincial-level analyses of variance.

SITE	ECO	POS	DEPTH	CROP	YEAR	pHw
586	PL	U	TOP	Wheat	1998	7.2
586	PL	M	TOP	Wheat	1998	7.2
586	PL	L	TOP	Wheat	1998	7.1
586	PL	U	SUB	Wheat	1998	7.1
586	PL	M	SUB	Wheat	1998	7.7
586	PL	L	SUB	Wheat	1998	7.7
588	PL	U	TOP	Wheat	1998	8.3
588	PL	L	SUB	Canola	1999	7.2
590	PL	U	TOP	Canola	1999	6.3
590	PL	M	TOP	Canola	1999	6.4
590	PL	L	TOP	Canola	1999	6.2
590	PL	U	SUB	Canola	1999	7.5
590	PL	M	SUB	Canola	1999	7.2
590	PL	L	SUB	Canola	1999	6.9
591	PL	U	TOP	Oats	1999	6.7
591	PL	M	TOP	Oats	1999	7.5
591	PL	L	TOP	Oats	1999	6.9
591	PL	U	SUB	Oats	1999	7.1
591	PL	M	SUB	Oats	1999	8.2
678	BT	U	TOP	Canola	2000	6.1
678	BT	M	TOP	Canola	2000	5.7
678	BT	L	TOP	Canola	2000	6.5
678	BT	U	SUB	Canola	2000	6.3
678	BT	M	SUB	Canola	2000	5.9
678	BT	L	SUB	Canola	2000	6.9

SAS code for analyzing response variables monitored at different depths

The statistical analysis described below is based on the assumption that the data is normally distributed. Data can be tested for normality and transformed using the methodology described in Appendix 2. Below is the mixed model SAS code for analyzing response variables monitored at different depths, such as pH in water (pHw). The LSMEANS option can be expanded to also include all the interactions in the MODEL statement. Note: Data in example is truncated.

```
Title 'MIXED MODEL ANALYSES OF pHw';
Data UNI;
INPUT SITE ECO$ POS$ DEPTH$ CROP$ YEAR PHW;
cards;
586   PL    U     TOP   Wheat 1998  7.2
586   PL    M     TOP   Wheat 1998  7.2
586   PL    L     TOP   Wheat 1998  7.1
586   PL    U     SUB   Wheat 1998  7.1
586   PL    M     SUB   Wheat 1998  7.7
586   PL    L     SUB   Wheat 1998  7.7
588   PL    U     TOP   Wheat 1998  8.3
588   PL    M     TOP   Wheat 1998  8.3
588   PL    L     TOP   Wheat 1998  6.5
588   PL    U     SUB   Wheat 1998  8.7
588   PL    M     SUB   Wheat 1998  8.4
588   PL    L     SUB   Wheat 1998  6.3
800   FG    U     TOP   Barley      2004  6
800   FG    M     TOP   Barley      2004  5.7
800   FG    L     TOP   Barley      2004  6.1
800   FG    U     SUB   Barley      2004  6.5
800   FG    M     SUB   Barley      2004  6.1
800   FG    L     SUB   Barley      2004  6.7
;
options pageno=1;
 proc mixed data=UNI METHOD=REML CL ALPHA=.05;
class SITE ECO POS DEPTH CROP YEAR;
model PHC = YEAR ECO YEAR*ECO POS YEAR*POS ECO*POS DEPTH
YEAR*DEPTH   ECO*DEPTH DEPTH*POS  /DDFM=SATTERTH;
random SITE(ECO) YEAR*SITE(ECO) CROP(SITE ECO) YEAR*CROP(SITE ECO)
POS*SITE(ECO)  POS*CROP(SITE ECO) ;
lsmeans YEAR/PDIFF adjust=TUKEY CL ALPHA=.05;
lsmeans ECO/PDIFF adjust=TUKEY CL ALPHA=.05;
lsmeans ECO*YEAR / PDIFF adjust=TUKEY CL ALPHA=.05;
lsmeans DEPTH/PDIFF adjust=TUKEY CL ALPHA=.05;
lsmeans POS/PDIFF adjust=TUKEY CL ALPHA=.05;
lsmeans ECO*POS / PDIFF adjust=TUKEY CL ALPHA=.05;
lsmeans ECO*DEPTH / PDIFF adjust=TUKEY CL ALPHA=.05;
lsmeans POS*DEPTH / PDIFF adjust=TUKEY CL ALPHA=.05;

run;
```

The variables are specified in the INPUT statement in the order they appear in the data.

The $ sign specifies the categorical variables.

Specifies for the Restricted-Maximum Likelihood (REML) method in estimating missing data.

The effective degree of freedom is calculated using the Satterthwaite approximation.

This statement shows the random (error) terms.

The model statement above shows the analyses of variance with the degree of freedom determined by the Satterthwaite approximation (Rao and Scott 1981; Johnson and Rust 1992). Multiple comparisons of fixed effect least square means are conducted using Tukey’s HSD and corrected for unbalanced replication using the Tukey-Kramer adjustment at α = 0.05. The ‘LSMEANS’ statement gives us an overall estimate of the means of the observation in the particular class based on the data fit to the model specified. It is different from the arithmetic mean of the total observed values in cases where missing observations occur. Confidence intervals provide an initial rough-and-ready, intuitive assessment of (1) the best estimate of the underlying pattern of population means, and (2) the degree to which the observed pattern of sample means should be taken seriously as a reflection of the underlying pattern of population means (Loftus and Masson 1994). When the confidence limits are closer to the observed means, it implies that the observed pattern in the means should be taken seriously, a more divergent confidence limit from the means indicates a greater degree of variation in the observations used to estimate the means and a need for additional statistical methods to make conclusions about the data.

SAS code for analyzing response variables monitored at one depth

Response variables measured at only one depth (i.e., topsoil) include bulk density (BD), light fraction (LF), light fraction carbon and nitrogen mass (LFCmass and LFNmass), percent light fraction carbon and nitrogen (LFC% and LFN%), hot KCl extractable ammonium-N (KCl - NH_4-N), organic carbon (OC) and organic matter (OM). The SAS code below represents the analysis for response variables such as bulk density monitored at one depth:

```
Title 'MIXED MODEL ANALYSES FOR BD';
Data BD;
Input SITE$ ECO$ POS$ DEPTH$ CROP$ YEAR$ BD;
cards;
586   PL    U     TOP   Wheat 1998  1.284
586   PL    M     TOP   Wheat 1998  1.3679
586   PL    L     TOP   Wheat 1998  1.4154
586   PL    U     TOP   Canola      1999  1.33
586   PL    L     TOP   Canola      1999  1.36
586   PL    M     TOP   Canola      1999  1.38
586   PL    L     TOP   Peas  2001  1.29
678   BT    L     TOP   Canola      1999  0.89
678   BT    U     TOP   Canola      1999  1.08
678   BT    M     TOP   Canola      1999  1.11
678   BT    M     TOP   Canola      2000  1.1
678   BT    U     TOP   Canola      2000  1.25
678   BT    L     TOP   Canola      2000  1.29
678   BT    L     TOP   Barley      2002  0.91
678   BT    M     TOP   Barley      2002  0.99
678   BT    U     TOP   Barley      2002  1.03
678   BT    L     TOP   Canola      2004  0.98
678   BT    M     TOP   Canola      2004  1.18
678   BT    U     TOP   Canola      2004  1.25
678   BT    U     TOP   Wheat 2005  1.08
;
options pageno=1;
proc mixed data=BD METHOD=REML CL ALPHA=.05;
   class SITE ECO POS CROP YEAR;
   model BD = YEAR ECO YEAR*ECO POS YEAR*POS ECO*POS/ DDFM=SATTERTH;
   random SITE(ECO) CROP(SITE ECO) YEAR*SITE(ECO) YEAR*CROP(SITE ECO)/;
   lsmeans ECO / PDIFF adjust=TUKEY CL ALPHA=.05;
   lsmeans ECO*YEAR / PDIFF adjust=TUKEY CL ALPHA=.05;
   lsmeans POS / PDIFF adjust=TUKEY CL ALPHA=.05;
   lsmeans YEAR / PDIFF adjust=TUKEY CL ALPHA=.05;
   lsmeans POS*ECO / PDIFF adjust=TUKEY CL ALPHA=.05
run;
```

Appendix 3. Data structuring and SAS code for the regression analyses.

SAS Code for basic linear regression analysis

```
Title 'REGRESSION ANALYSES FOR INDIVIDUAL ECOREGIONS';
data all;
input SITE  ECO   POS   DEPTH CROP  YEAR  PHW   BD;
cards;
727   AP    U     SUB   Peas  1998  6.9   .
727   AP    M     SUB   Peas  1998  6.4   .
727   AP    L     SUB   Peas  1998  6.6   .
727   AP    U     SUB   Canola      1999  6.6   .
727   AP    M     SUB   Canola      1999  5.8   .
727   AP    L     SUB   Canola      1999  5.9   .
727   AP    U     SUB   Barley      2000  6.7   .
727   AP    M     SUB   Barley      2000  5.9   .
727   AP    L     SUB   Barley      2000  5.7   .
727   AP    U     SUB   Barley      2001  7.14  .
727   AP    U     TOP   Canola      2002  7.4   0.87
727   AP    M     TOP   Canola      2002  6     0.86
727   AP    L     TOP   Canola      2002  5.7   0.85
727   AP    U     TOP   Barley      2003  6.7   0.9585
727   AP    M     TOP   Barley      2003  5.9   0.7724
727   AP    L     TOP   Barley      2003  5.8   0.7188
727   AP    U     TOP   Barley      2004  7.1   1.2906
727   AP    M     TOP   Barley      2004  6.1   1.0952
727   AP    L     TOP   Barley      2004  6     1.1675
727   AP    U     TOP   Barley      2005  6.8   1.1578
727   AP    M     TOP   Barley      2005  5.8   1.2014
727   AP    L     TOP   Barley      2005  5.6   1.0941
727   AP    U     TOP   Canola      2006  6.4   1.5372
727   AP    M     TOP   Canola      2006  6.5   1.3713
727   AP    L     TOP   Canola      2006  6.5   1.1972
680   BT    U     TOP   Canola      1998  6.5   1.7969
680   BT    M     TOP   Canola      1998  6.6   1.576
680   BT    L     TOP   Canola      1998  6.6   1.7969
680   BT    U     TOP   Barley      1999  7     1.57
680   BT    M     TOP   Barley      1999  6.8   1.6
680   BT    L     TOP   Barley      1999  6.8   1.5
680   BT    U     TOP   BarForag    2000  6.5   1.69
;
;
options pageno=1;

proc sort data=ALL;
by depth eco;
run;
```

In order to use the BY statement, data must first be sorted in the proper order (i.e., DEPTH and ECOREGION).

```
proc reg data=ALL;
model BD=YEAR;
run;
```

The regression of bulk density (BD), (measured at only one depth) on year of sampling (YEAR) for the entire province can be generated using these statements.

```
proc reg data=ALL;
by depth;
model PHW=YEAR;
```

The regression of pH in water (pHw) (measured at two depths) on year of sampling (YEAR) for the entire province can be generated using these statements. Note that the BY statement is used to generate two regression equations, one for the 0-15 cm sampling depth and one for the 15-30 cm sampling depth.

```
run;

proc sort data=ALL;
by eco depth;
run;
```

Again, the data needs to be sorted. Since we want to run the following regression analyses for each ecoregion, we sort by ECOREGION first, then by DEPTH.

```
proc reg data=ALL;
by eco;
model BD=YEAR;
run;
```

The regression of bulk density (BD), (measured at only one depth) on year of sampling (YEAR) for each ecoregion can be generated using these statements. The BY statement is used to generate six regression equations, one for each ecoregion.

```
proc reg data=ALL;
by eco depth;
model PHW=YEAR;
run;
```

The regression of pH in water (pHw) (measured at two depths) on year of sampling (YEAR) for each ecoregion can be generated using these statements. The BY statement is used to generate twelve regression equations, one for each combination of ECOREGION and DEPTH.

The estimate for YEAR in the SAS output statement gives the slope of the regression line, while the *P*-value tests the null hypothesis that the slope is equal to zero. Hence, a *P*- value less than 0.05 signifies that at $\alpha = 0.05$, we can reject the null hypothesis, meaning that the slope is significantly different from zero. The 'INTERCEPT' value in the SAS output statement represents the value of the intercept in the regression equation, while the *P*-value can be used to the test the null hypothesis that the intercept is equal to zero. Regression lines can be charted in excel from the derived equation:

$$y = mx + b \qquad [1]$$

Where *y* is the value of the response variable, *m* is the slope estimate, *x* is the value of the independent variable (YEAR), and *b* is the estimate for the INTERCEPT.

In order to compare the regression coefficients of two different groups or regression lines, we need a statistical model, which describes the relationship of the response variable *y*, and the explanatory variable *x*, for the two groups, indexed by "indicator" or "dummy" variables *z*. Dummy variables can take on finite values such as 1, 0, or –1, and only serve as an indicator to represent different groups. A dummy variable with a value of 0 can be regarded as omitted group in the statistical model, while the dummy variable with the value of 1 can be regarded as the selected group. Using the following statistical model, we can test for differences between the slopes of the two regression lines (Larsen, 2006; White et al., 2007):

$$y_i = \beta_0 + \beta_1 x_i + \beta_2 z_i + \beta_3 x_1 \times z_i + \varepsilon_i \qquad [2]$$

Assuming equal variances between the two groups, ε_i represents the identically normally distributed error terms. In order to compare, for example, the regression lines of bulk density (BD) vs. YEAR between the Mixed Grassland (MG) and the Peace Lowland (PL) ecoregions, we create a dummy variable called 'DUMMY' (coded 0 for the MG and 1 for the PL), and a variable ‘DUMMYYEAR’ (defined as the product of ‘DUMMY’ and ‘YEAR’). From equation [2] above, Y_i represents the response variable (BD), β_0 is the intercept of the omitted group (MG), β_1 is the slope for the omitted group (MG), x_i is the variable YEAR, β_2 is the intercept of the selected group (PL) minus that of the omitted group, z_i is the dummy variable, $\beta_3$is the slope of selected group minus the slope of the omitted group and ε_i is the error term.

SAS code for comparing regression coefficients between ecoregions

We run the model below with the group effect (ECO), the YEAR effect (x_i) and the interaction to make this test:

```
Title 'COMPARING SLOPES OF REGRESSION LINES BETWEEN TWO PROVINCES';
Data BD;
Input SITE$ ECO$ POS$ DEPTH$ CROP$ YEAR BD;

cards;
586   PL    U     TOP   Wheat 1998  1.284
586   PL    M     TOP   Wheat 1998  1.3679
586   PL    L     TOP   Wheat 1998  1.4154
615   MB    U     TOP   Forage      2001  1.19
615   MB    M     TOP   Forage      2001  1.38
615   MB    L     TOP   Forage      2002  0.59
684   BT    M     TOP   WheForag    2001  1.14
684   BT    L     TOP   WheForag    2001  1.19
684   BT    U     TOP   WheForag    2001  1.22
746   AP    U     TOP   Canola      2004  1.27
746   AP    M     TOP   Wheat 2005  1.11
746   AP    L     TOP   Wheat 2005  1.16
793   MM    M     TOP   Forage      2005  1.26
793   MM    L     TOP   Forage      2005  1.28
793   MM    U     TOP   Forage      2005  1.30
798   FG    L     TOP   Wheat 1998  0.9982
798   FG    U     TOP   Wheat 1998  1.0419
798   FG    M     TOP   Wheat 1998  1.1964
2828  MG    U     TOP   Corn  2000  1.54
2828  MG    M     TOP   Corn  2000  1.54
2828  MG    M     TOP   Canola      2001  1.36
;

options pageno=1;
data BD2;
  set BD;
  DUMMY = . ;
  IF ECO = "PL" then DUMMY = 1;
  IF ECO = "MG" then DUMMY = 0;
  DUMMYYEAR = DUMMY*YEAR;
  RUN;
  PROC REG DATA=BD2;
  MODEL BD=YEAR DUMMY DUMMYYEAR;
RUN;
```

A new data set, called ‘BD2’ is created, which includes the new variable ‘DUMMY’, automatically set to a value of ‘.’. The ‘DUMMY’ variable is assigned a value of 1 for all data points in the PL ecoregion, and a value of 0 for all data points in the MG ecoregion. Finally, the ‘DUMMYYEAR’ variable is created.

The variable DUMMY represents the dummy variable z_i in the regression model [2] above and tests for β_2 above. The term DUMMYYEAR is the interaction $x_i \times z_i$ in equation [2], and tests the null hypothesis $B_a = B_b$, where B_a is the regression coefficient (slope) for the PL and B_b

is the regression coefficient for second group MG. If the t-value is significant, it will indicate that the regression coefficient B_a is significantly different from B_b. The dummy variable code can be changed to reflect any comparison we might be interested in. For example, for a comparison between the regression coefficients between the Aspen Parkland data (AP) and the Moist Mixed Grassland (MM) the following statement will be used instead of the above:

```
 options pageno=1;
data BD2;
  set BD;

  DUMMY = . ;
  IF ECO = "AP" then DUMMY = 1;
  IF ECO = "MM" then DUMMY = 0;

  DUMMYYEAR = DUMMY*YEAR;
  RUN;
  PROC REG DATA=BD2;
  MODEL BD=YEAR DUMMY DUMMYYEAR;
RUN;

run;
quit;
```

There is no need to create a new dataset to show only data from the two ecoregions in consideration, because the only the new dataset created by the specified dummy variables is used in the analyses. Alternatively, if we are using data from only the two ecosystems we are interested in performing a comparative analyses, we could test for these differences without the use of dummy variables using the PROC GLM code below:

```
proc glm data=BD;
   class ECO;
   model BD=YEAR ECO YEAR*ECO/ solution e;
   output out=otest p=pred;
run;
quit;
```

Appendix 4. Data structuring and SAS code for the correlation analysis.

```
data corr;
input Eco$  depth$      EC    K     NO3   NH4   pHc   pHw   STP   ;
cards;
AP    0-15  0.46  285.4 13    4.7   5.59  6.37  22.7
BT    0-15  0.45  203.1 6.6   1.5   5.64  6.44  16.7
FG    0-15  0.34  511.8 12.8  5.4   5.46  6.21  25.5
MG    0-15  0.58  349.8 9.4   1.2   6.67  7.2   18.9
MM    0-15  0.45  359.2 12.4  1.6   5.61  6.19  25.8
PL    0-15  0.51  274.7 13.3  1.2   5.77  6.52  24.3
AP    15-30 0.51  195.8 8.8   1.9   6.13  6.85  12.2
BT    15-30 0.34  158.1 4.4   1.2   5.89  6.72  12.9
FG    15-30 0.35  394.1 9     2.1   6.04  6.76  11.5
MG    15-30 0.68  259.9 6.7   1.6   6.9   7.45  11.7
MM    15-30 0.38  257.5 7.6   1.3   6.03  6.68  12.8
PL    15-30 0.39  193.2 5.2   0.8   6.12  6.91  8.6
;
proc corr data=corr;
run;
```

Appendix 5. Crop rotations at the AESA Soil Quality Benchmark sites.

Site	Town	Ecoregion	1998	1999	2000	2001	2002	2003	2004	2005	2006
586	**Buffalo Head Prairie**	**PL**	wheat	canola	wheat	pea	barley	peas	canola	wheat	peas
588	**Manning**	**PL**	wheat	canola	wheat	pea	wheat	canola	wheat	canola	wheat
590	**Spirit River**	**PL**	barley	canola	barley	barley	canola	canola	barley	canola	forage-canola
591	**Worsley**	**PL**	canola	oats	canola	canola	canola	oats	canola	barley	barley
592	**High Prairie**	**PL**	canola	barley	barley+oats	pea	barley	oat/barley	canola	barley	barley
593	**Fairview**	**PL**	pea	wheat	pea	wheat	peas	pea/canola	wheat	peas	oats
594	**Bonnyville**	**PL**	-	canola	canola	barley	forage	forage	barley	forage	forage
595	**Falher**	**PL**	canola	wheat	canola	wheat	wheat	canola	wheat	canola	wheat
599	**Sexsmith**	**PL**	-	wheat	canola	wheat	canola	barley	canola	wheat	canola
678	**Boyle**	**BT**	wheat	canola	canola	wheat	barley	canola	canola	wheat	canola
680	**Bonnyville**	**BT**	canola	barley	barley+grass	forage	forage	forage	forage	forage	forage
681	**Dapp**	**BT**	canola	barley + grass	forage	forage	forage	forage	forage	forage	forage
684	**Carvel**	**BT**	barley	canola	wheat	wheat+forage	forage	forage	forage	forage	forage
687	**Warspite**	**BT**	wheat	barley	canola	wheat	canola	canola	barley	canola	peas
688	**Beauvallon**	**BT**	barley	fallow	barley	canola	peas	oats	canola	barley	barley
692	**Tomahawk**	**BT**	forage	oats	oats+forage	forage	forage	forage	forage	forage	forage
703	**Westerose**	**BT**	forage	forage	forage	forage	forage	forage	forage	forage	forage
1615	**Smith**	**MB**	oats	oats+grass	forage	forage	forage	forage	forage	forage	forage
727	**Wetaskiwin**	**AP**	peas	canola	barley	barley	canola	barley	barley	barley	canola
728	**Hairy Hill**	**AP**	wheat	barley	canola	wheat	barley	canola	wheat	barley	canola
730	**Mannville**	**AP**	wheat	barley	canola	pea	wheat	wheat	barley	canola	wheat
738	**Killam**	**AP**	barley	pea	wheat	canola	forage	forage	forage	forage	forage
739	**Chauvin**	**AP**	wheat	canola	wheat	barley	canola	wheat	wheat	barley	oats
740	**Bashaw**	**AP**	-	barley	canola	wheat	barley	canola	wheat	canola	wheat
743	**Provost**	**AP**	wheat	fallow	canola	wheat	fallow	wheat	wheat	wheat	fallow
744	**Lacombe**	**AP**	-	wheat	wheat	canola	wheat	wheat	canola	wheat	wheat
746	**Carstairs**	**AP**	barley	barley	barley	barley	barley	barley	canola	wheat	wheat
798	**Beiseker**	**FG**	wheat	barley	barley	canola	wheat	wheat	wheat	canola	wheat
800	**Pincher Creek**	**FG**	barley	barley	barley	barley	barley	barley	barley	barley	barley
769	**Veteran**	**MM**	barley	fallow	canola	wheat	peas	wheat	wheat	canola	wheat
781	**Three Hills**	**MM**	wheat	fallow	barley	pea	wheat	canola	barley	peas	wheat
786	**Hanna**	**MM**	wheat	canola	forage	forage	forage	forage	forage	forage	forage
791	**Vulcan**	**MM**	barley	wheat	wheat	wheat	wheat	canola	barley	peas	wheat
793	**Claresholm**	**MM**	wheat	wheat	wheat	wheat	forage	forage	forage	forage	forage
804	**Veteran**	**MG**	wheat	fallow	mustard	barley	fallow	oats	wheat	fallow	mustard
806	**Chinook**	**MG**	-	mustard	fallow	wheat	chick peas	wheat	fallow	mustard	wheat
809	**Oyen**	**MG**	canola	fallow	wheat	fallow	wheat	fallow	wheat	fallow	wheat
812	**Tilley**	**MG**	wheat	Wheat alfalfa	alfalfa	alfalfa	forage	forage	forage	wheat	wheat
815	**Dunmore**	**MG**	fallow	wheat	fallow	wheat	forage	forage	forage	forage	forage
823	**Enchant**	**MG**	wheat	wheat	beans	wheat	beans	wheat	sugar beets	beans	wheat
1828	**Etzikom**	**MG**	wheat	wheat	wheat	fallow	wheat	fallow	wheat	fallow	wheat
2828	**Taber**	**MG**	-	-	corn	canola	corn	wheat	corn	canola	wheat