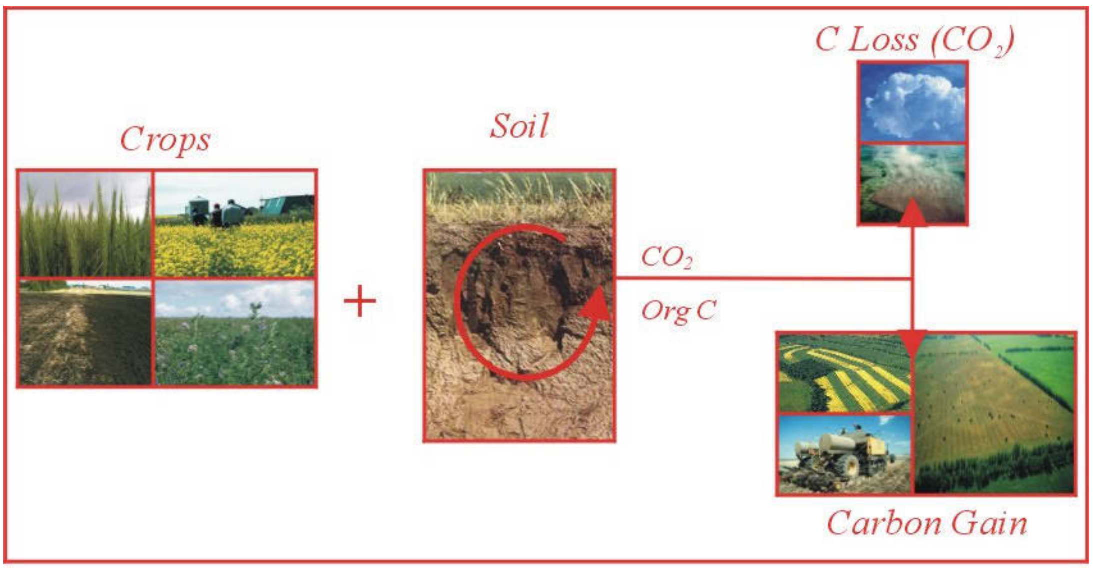
A Preliminary Assessment of Carbon Dioxide and Nitrous Oxide Emissions from Agricultural Soils in Alberta



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Executive Summary

In 1997, Canada became a participant in the Kyoto Accord on Greenhouse Gases (GHG). As a participant, Canada agreed to reduce GHG emissions to 6% below 1990 levels between 2008 and 2012. Based on increases from 1990 to 1997 and assuming business as usual, the reduction now required is estimated to be more than 20%. Alberta's agricultural industry is responsible for 12% of Alberta's GHG emissions. This represents 3% of Canada's total GHG emissions.

Carbon dioxide (CO_2) emission estimates from agricultural soils in Canada are based on model estimates from 15% of the agricultural area. Alternative estimates in Alberta can be made with databases containing soil information, landscape variability and land management data characteristic of a given Ecodistrict. Agriculture is unique because it not only emits carbon (C) but it can store C in soil and vegetation. Carbon emissions from agricultural soils have declined due to increases in conservation practices. However, an accounting system is needed to determine the net flux of C from the agricultural soils as a function of management practices across Alberta.

Nitrous oxide (N_2O) is another important GHG listed in the Kyoto protocol. Globally, agriculture accounts for 70% of the N_2O released via human activity, whereas CO_2 accounts for 25%. Nitrous oxide emissions are spatially variable at all scales. Current N_2O estimates by the Intergovernmental Panel of Climate Change (IPCC) is based upon linear extrapolation between N_2O emission and fertilizer N application and does not consider different crops, soils, or climates.

In order to assess agriculture's impact upon GHG emissions and the potential to sequester C across Alberta, a five compartment, first order decay model consisting of two modules: the soil (S) module and residue (R) module, was developed to estimate gross C emission and net C change from agricultural soil. The model incorporated two tillage systems (conventional (CT) and zero (ZT) tillage), and four cropping systems (fallow, forage, cereals, oilseeds). Sequestering C may affect N_2O emissions. The global warming potential of a molecule of N_2O is 310 times more effective than a molecule of CO_2 over a 100-year period. A model consisting of three modules: (1) crop (2) fertilizer and (3) soil was developed to represent gross N emission from agricultural soils. Landscape position and differences in grain yields characteristic of different soil types were incorporated into the model.

Net change of C can be either positive (+) or negative (-) and is the summation of C inputs (crop residue) and C outputs (gross C emission). A positive number indicates a gain of C and a negative number indicates a loss of C. Carbon sequestration occurs when there is a gain of C. Full system accounting of agricultural soil emissions is important so net gains or losses can be identified. In general, net change of C after five years was greatest in cereal cropping systems under ZT and lowest from fallow systems under CT management.

Carbon sequestration potential did not occur in all Ecodistricts and was dependent on soil type, landscape, and the cropping and tillage systems implemented. The predicted C sequestration rates were lowest in the Black soil zone and highest in the Luvisol soil zone. Using the C sequestration rates predicted by this model, if Kyoto accepts C sinks in the emission inventory for agriculture, the agricultural sector in Alberta would have a C sequestration potential between 4700 and 9000 Gg CO_2 y^{-1}. However, the ability of the soil to store C is not infinite and these numbers should be used with caution for any long-term predictions. If the government is truly

committed to a long-term reduction in GHG emissions, other means of reducing GHG emissions are needed.

Gross C emission for all cropping systems and both tillage systems ranged from -249 kg C ha^{-1} y^{-1} to -3760 kg C ha^{-1} y^{-1}. Gross C emission from all cropping systems (except fallow) increased over time. Conventional till systems had greater annual gross C emissions than did ZT systems. The mean gross emission rate of CO_2 for Alberta was -4157 kg CO_2 ha^{-1} y^{-1} for CT and -3674 kg CO_2 ha^{-1} y^{-1} for ZT. In general, gross CO_2 emissions were highest from Ecodistricts within the Aspen Parkland Ecoregion. Depending on the tillage system used, gross emission of CO_2 from Alberta's agricultural soils is between -38 000 to -43 000 Gg CO_2 y^{-1}. If 50% of Alberta's farmers practice zero till, then Alberta could have an economic gain of $9.5 to $95 million per year (6850 Gg CO_2 y^{-1} would be sequestered).

Model results predicted that gross emissions of N_2O from Alberta were -14 000 Gg CO_2 equivalent y^{-1}. The majority of the N_2O emissions were from the soil and crop residue modules and not from the fertilizer module. This may have implications for an overall GHG budget because in order to sequester C farmers are encouraged to leave crop residue on the surface, however this may have negative results due to the higher emissions of N_2O from the decomposition of crop residue. N_2O emissions were highest from Ecodistricts located in the Aspen Parkland. If Kyoto accepts C sinks of agricultural soils in the emission inventory, and all other things remain equal, the amount of C sequester by soils in Alberta is still not enough to offset the N_2O emission.

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Unit Conversions and Abbreviations

$Pg = 10^{15} g = petagram$

$Tg = 10^{12} g = teragram$

$Gg = 10^{9} g = gigagram$

$Mg = 10^{6} g = megagram$

$kg = 10^{3} g = kilogram$

$CO_2 = C * \frac{44}{12}$

$N_2O = N * \frac{44}{14}$

$CO_2 equivalent = N_2O * 310$

$C = carbon$

$N = nitrogen$

$GHG = greenhouse\ gas$

$SOM = soil\ organic\ matter$

$OM = organic\ matter$

$SGR = straw : grain\ ratio$

$TOC = total\ organic\ carbon$

$ppm = parts\ per\ million$

$ppb = parts\ per\ billion$

1.0 Introduction

Atmospheric concentrations of greenhouse gases (GHG): carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and chlorofluorocarbons (CFCs), have increased since the beginning of the industrial revolution to present day. In particular, atmospheric CO_2 has increased by 27%, from 280 ppm to about 356 ppm now (Smith et al. 1997). Presently the atmospheric concentration of N_2O is about 312 ppb, which is a 15% increase since pre-industrial times (Monteverde et al. 1997). These gases absorb energy re-radiating from the earth thus increasing the atmospheric temperature. Nitrous oxide has a long atmospheric lifetime and its unique absorption bands give N_2O a large global warming potential, approximately 310 times more effective (molar basis) than CO_2 over 100 years (Monteverde et al. 1997).

Canada became a participant in the Kyoto Accord on GHG in 1997. As a participant, Canada agreed to reduce net GHG emissions 6% below 1990 levels by the first commitment period, 2008 to 2012 (Janzen et al. 1999). This is equivalent to Canada reducing its net emissions by 140 to 180 Mt CO_2 per year (Sinks Table Options Paper 1999). Current estimates indicate that if "business as usual" is continued, Canada will need to reduce its emissions by about 21% by the first commitment period. The most likely way to meet the Kyoto target is to reduce gross GHG emissions. However, another way is for Kyoto Protocol to recognize carbon (C) sinks in the emissions inventory for agriculture, and to encourage management practices that facilitate C storage. If carbon sinks are accepted, net emissions are projected to be reduced from 1990 levels by 9% in Alberta (AAFRD, 1999a).

1.1 Carbon Dioxide

The prairies of western Canada are approximately 54.4 million ha (Janzen et al. 1998). The agricultural area of Alberta is approximately 11.3 million ha. The prairie grassland soils of Western Canada were estimated to have contained 22 Pg C prior to European settlement (McGill et al. 1981). However, upon conversion to agricultural systems, it has been estimated that 40 to 50% of the original soil organic matter (SOM) was lost (Pennock and Van Kessel 1997). The rapid rate of decline of SOM after initial cultivation diminished gradually over time until the soil approached a new "steady-state", where it no longer lost C (Janzen et al. 1999). Adoption of better management strategies has increased the amount of C stored in the soil. For example, there is evidence that zero tilled (reduced till and minimum till) systems retain more C than conventionally tilled systems (Boehm et al. 2000).

Agricultural soils are unique because they not only store C in soil or vegetation but they emit C as CO_2. The primary source of soil CO_2 is plant root and microbial respiration (Sheppard et al. 1994). As SOM decays, CO_2 is respired and the remaining C is incorporated into microbial tissue (Van Breemen and Feijtel 1990). Direct CO_2 emissions from agricultural soils in Canada in 1996 were estimated to be 1.8 Tg CO_2. This was a decrease from 7.7 Tg CO_2 in 1981, attributed to the conversion from conventional tillage to minimum tillage practices (Desjardins and Riznek 2000).

A variety of models have been developed to estimate these long-term C gains and losses from the soil (McGill 1996). Single component models were initially developed and eventually expanded to incorporate many (five or more) compartments of SOM. Soil organic matter contains fractions with varying decomposition rates. Three SOM compartments decaying according to first order kinetics describe C dynamics (Paul et al. 1997; Post et al. 1999; Voroney et al. 1981;

McGill and Bailey 1999). Carbon oxidation rates are calculated as constant proportions of C quantities (Grant and Rochette 1994). Current CO_2 estimates for Canada are based on CENTURY model output from 15% of the agricultural Soil Landscapes of Canada (SLCs) (Smith et al. 1997). However, these estimates require inputs, which may not be available for all the SLCs across Alberta. Therefore, alternative estimates can be made for Alberta with more detailed databases containing soil information, landscape variability and land management data for each Ecodistrict.

1.2 Nitrous Oxide

Approximately 70% of the N_2O emitted from the biosphere is from soils (Mosier, 1993). The majority of N_2O production from agricultural soils can be attributed to denitrification and nitrification processes (Beauchamp, 1997). Available N and C, aeration, soil water content, temperature, and pH are considered to be the most important factors controlling N_2O production by soil (Lemke et al. 1998a). However, several studies suggest that inherent soil properties (soil texture, OM content) have a stronger influence on N_2O emissions than climate, management, fertilizer or crop (Hénault et al, 1999; Lemke et al. 1998a). Unfortunately, measurement of N_2O emissions from agricultural soils under different climate, tillage management, soil, and crop are poorly quantified, making accurate N_2O emission estimates for the Kyoto Protocol difficult.

One method, proposed by the Intergovernmental Panel of Climate Change (IPCC) to estimate N_2O emissions from soil, separates N_2O sources into four categories: 1) synthetic ferilizer; 2) animal waste; 3) biological N_2 fixation; and 4) crop residue. Estimated total soil emissions using IPCC methodology for agricultural soils in Alberta was 10.69 Gg N_20 y^{-1} (Monteverde et al. 1997). The two largest contributors were from fertilizers and crop residue (80%). The IPCC methodology assumes soil emission estimates from fertilizers are based upon linear extrapolation between N_2O emission and fertilizer N application. IPCC does not consider different crops, soils, or climates, all of which are thought to influence N_2O production (Lemke et al. 1998a). However, comparison between IPCC estimates and actual field values indicated that the IPCC estimates were close to field values for medium textured soils but differed greatly for the finer and coarser textured soils (Lemke et al. 1998a). This comparison reinforced the need to include differences in soil properties for N_2O estimates.

2.0 Objective

Our objective was to develop a model to estimated current and future CO_2 and N_2O emissions over time from agricultural soils in Alberta using readily available inputs. We aimed to include soil properties, landscape position, land use and land management. The output would be maps of gross and net CO_2 and gross N_2O emissions for each Ecodistrict in the agricultural area.

3.0 Materials and Methods

Norwest Labs Ltd. provided data for over 130 000 soil samples taken from farmer field across Alberta between 1993 and 1997 (Appendix 1). We used these data in combination with AGRASID (1998), soil temperature data (Atmospheric Environmental Services, 1984), AGDATA Series (AAFRD 1999b), and Farm Fertilizer Price Protection Program data (AAFRD 1991). Livestock operations, wetlands, pastures or irrigated cropland were not included in the modeling analysis.

3.1 The Carbon Model

3.1.1 Soil Properties

Mean organic carbon values from Ecodistricts were derived from the Norwest data. Statistical analysis (Proc Univariate, SAS 6.1 for Windows) determined that OM values greater than 22% were outliers and were deleted. Norwest Labs Ltd. did not have samples for all Ecodistricts therefore these Ecodistricts could not be included in the analysis. As well, Norwest Labs Ltd. provided OM values for both dryland (0-15 cm) and irrigated (0-30 cm) agriculture. Because depth of sample differs for these two agricultural systems, only dryland agriculture samples were analyzed. These exclusions equated to 13% of the white area. Descriptive statistics for each Ecodistrict are in Appendix 2. The mean OM values for all dryland agricultural was 6% with a standard deviation of 2.3% (Table 1).

Table 1: Descriptive statistics of OM values (%) from Norwest Labs Ltd. data for all Ecodistricts

Mean	Mode	Standard Deviation	Skewness	CV	Min	Max
6.0	5.4	2.3	0.898	37.96	0.9	21.9

A paired t-test determined that the OM values from Norwest Labs Ltd. were significantly higher than the OM values from the National Organic Carbon of Canada database by 1.42% of national values.

3.1.2 Model Description

Carbon emission (as CO_2) from soil is emitted from two sources: 1) from the decomposition of soil C and 2) decomposition of crop residue C or other organic inputs. So a five compartment, first order decay model [Eq.1] consisting of two modules, the soil (S) module and crop residue (R) module, was developed using Stella Software, Version 3.1 (Stella 1997) to estimate gross C emission from agricultural soils (Figure 1).

Equation 1

$$Net\ C\, change = C_0 e^{-kt} - C_0$$

where Net C change is either positive (+) or negative (-)in kg C ha^{-1}; C_o is the initial amount of carbon in the system (kg C ha^{-1}); k is the decay rate (month^{-1}); and t is time (months).

The model contained two tillage systems (conventional and zero tillage), and four cropping systems (fallow, forage, cereals, oilseeds). Differences in landscape for each Ecodistrict and differences in temperature for each Ecoregion were also incorporated. All C emitted from the system was converted to CO_2. Unfortunately, Stella is limited such that it could not handle the amount of data that needed to be processed. Therefore, using Stella as the framework, a program was set up in SAS version 6.1 to calculated gross C emission and net C change.

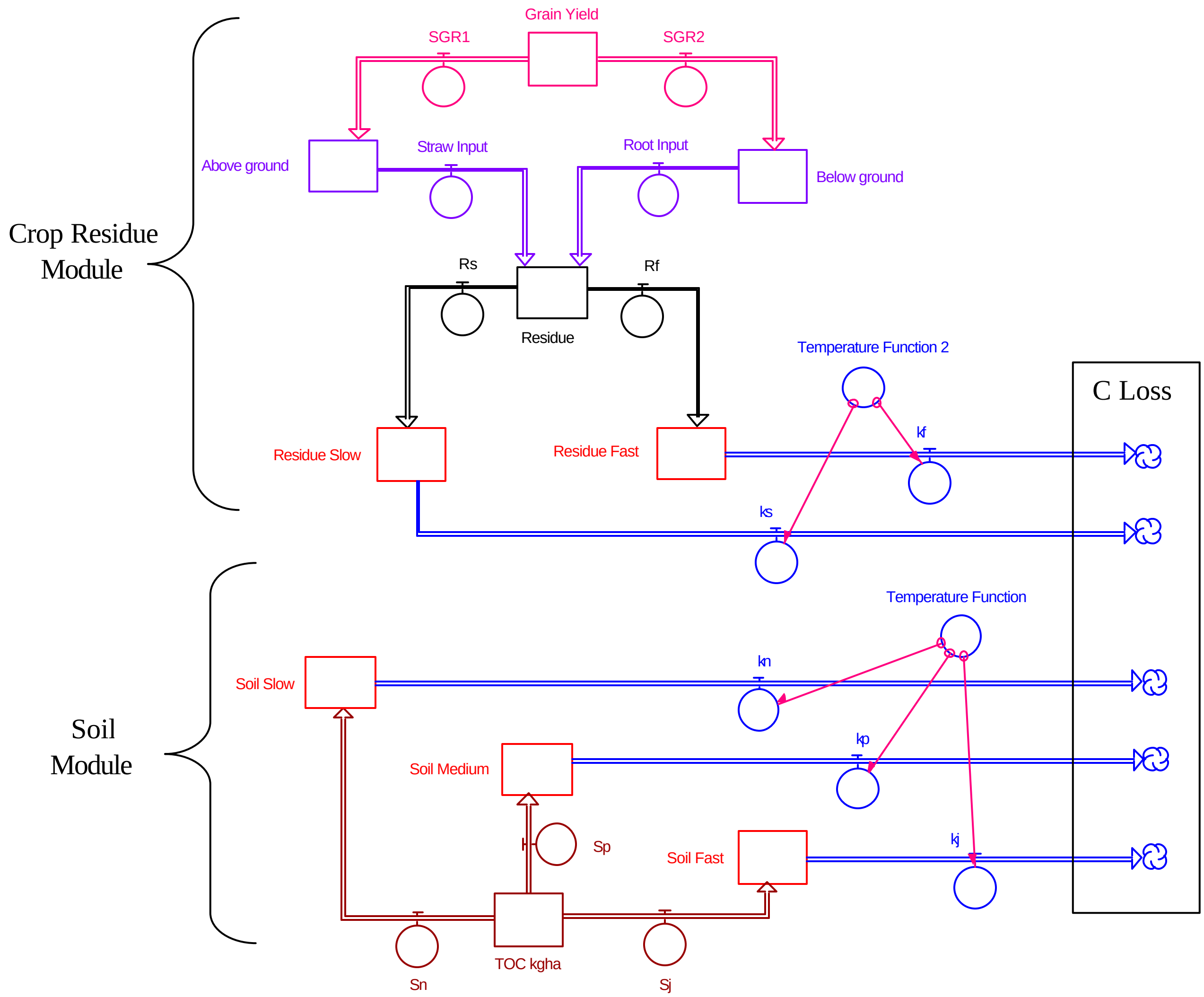

Figure 1: Diagram of C loss from agricultural soils using a five compartment first order decay model with two modules: crop residue and soil. After 12 months, the remaining C from the residue module is transferred into the soil module and partitioned appropriately into the three soil compartments.

3.1.3 Crop Residue Module

3.1.3.1 Tillage Systems

We use two tillage systems to represent tillage practices in Alberta: zero till (ZT) or conventional till (CT). Carbon emission estimates were based on 100% of the agricultural area as either in CT or ZT.

3.1.3.2 Cropping Systems

We used four cropping systems to represent cropping practices in Alberta: cereals, oilseeds, forages, and fallow. Cereals included crops such as wheat, barley, oats; oilseeds included flax and canola; forages include tame hay, alfalfa, and legumes. This separation of cropping systems did not include specialty crops; therefore specialty crops were not included in the analysis. Grain yields (kg ha^{-1}) were estimated from AGDATA Series (AAFRD 1999b) for each Ecoregion and cropping system. The straw to grain ratio (SGR) was taken from Soil Conservation Notes (Agriculture Canada 1987) (Table 2). Even though forages do not have a SGR, it was set at 1 so below ground input could be calculated. Root input estimates were taken from the literature or personal communication (Table 3). The root to shoot ratio for smooth brome was estimated at 1-3:1 (Gerling, 2000). For this model, root input from forages was two times the aboveground biomass.

Table 2: Grain yields for each cropping system

	Grain yields (kg ha^{-1})			
	Cereals	**Oilseeds**	**Forages**	**Fallow**
Mixed Grassland	2400	1700	1600	0
Moist Mixed Grassland	2700	1400	1500	0
Fescue Grassland	2600	1400	1500	0
Aspen Parkland	2500	1300	1000	0
Peace Lowland	2600	1200	1400	0
Straw:grain (SGR)	1.3	2.2	1.0	0

Table 3: Root input estimates for each cropping system

Cropping System	Root Input	Reference
Cereals	0.59	Campbell et al. 1995
Oilseeds	0.30	Thomas Per. Comm.
Forages	2	Gerling 2000
Fallow	0	

Carbon content of straw and root residue was estimated to be 45% (Campbell et al. 2000). Tillage efficiency was calculated to be 80% for both tillage operations using the Crop Residue Management Worksheet (PFRA 1988). This assumes that over the long term 80% of the residue eventually enters the soil, while the remaining 20% remains on the surface.

Generally, 100% of the aboveground straw biomass is not returned to the soil. It is expected that a proportion of this residue is exported off-site for livestock bedding and feed. Therefore, based on Census 1996 data, the proportion of aboveground straw biomass exported for livestock bedding and feed for each Ecoregion was estimated based on the number of cattle in each Ecoregion and cattle straw use [Eq.2 and 3] (Table 4).

Equation 2

$$Strawrequired\left(\frac{Mg}{y}\right) = Total\,Head\,Livestock\,(\#\,head) * \left(Bedding\left(\frac{Mg}{head\,y}\right) + Feeding\left(\frac{Mg}{head\,y}\right)\right)$$

Equation 3

$$\%\,Exported = \frac{\left(\dfrac{Straw\,required\left(\dfrac{Mg}{y}\right)}{Total\,Cultivated\,Area(ha)} \right) * C\,content}{Mean\ total\,residue\ for\,Ecoregion\left(\dfrac{MgC}{ha\,y}\right)}$$

where mean total residue was the mean value of aboveground straw residue for cereals, oilseeds and forages for each Ecoregion (Table 4).

Table 4: Proportion of aboveground biomass (straw) exported for livestock

Ecoregion	Mean Total Residue (kg ha^{-1})	% Exported
Mixed Grassland	1015	6
Moist Mixed Grassland	970	12
Fescue Grassland	955	8
Aspen Parkland	853	17
Peace Lowland	890	20

Total residue input for the model is the summation of the aboveground straw biomass (minus that exported) and the belowground biomass [Eq.4].

Equation 4

$$Total\,residue = [(yield * SGR * C\,cont * Till\,Eff) * (1 - export)] + [(yield * SGR * C\,cont * root\,input)]$$

where yield = Table 2; SGR = Table 2; C cont = 45%; Till Eff = 80%; export = Table 4; root input = Table 3

The result presented from this model predicts the annual gross emission and net C change under a continuous cropping management system for each crop. It does not currently incorporate rotations, however the model could have the capability to do so.

3.1.3.3 Parameters

The crop residue module consists of two compartments: slow (S) and fast decay (F). Constant proportions of total residue C (R_s, R_f) were partitioned into each compartment (Table 5). Each compartment has a specific decay rate (k_s, k_f) following first order kinetics. After 12 months, the remaining C from the residue module is transferred into the soil module as total organic carbon (TOC) and partitioned appropriately into the three soil compartments.

Table 5: Input parameters for the residue module

	Conventional Till (proportion)	Zero Till (proportion)	Decay Rate (month^{-1})	Reference
Slow (S) compartment	0.28	0.72	0.00675	Campbell et al. 1998
Fast (F) compartment	0.72	0.28	0.1667	Campbell et al. 1998

3.1.4 Soil Module

3.1.4.1 Landscape Distribution of Carbon

Distribution of TOC across the landscape varies. Emission of C from soil is dependent on the TOC in the soil. In order to estimate gross C emissions accurately, quantification of the distribution of C across the landscape needs to be estimated. To do this, a representative soil landscape model was identified for each Ecodistrict, based upon distribution and areal extent of soil landscapes displayed in AGRASID. The soils and landscape described by the representative soil landscape model represented the entire Ecodistrict. The landscape models were segmented into four slope positions: upper, middle, lower and depression. Areal extent, % slope, and slope length characteristics were assigned to each segment of the landscape model. Soil attributes within a soil landscape model were allocated to the most likely landscape position based on a Series of Likelihood Tables (Brierley Pers. Comm.). These tables identify the likelihood of soil attributes (drainage, salinity, calcareousness, texture of parent material, and soil subgroup variant) to occur in a landscape position. For example, a poorly drained soil is more likely to be associated with the depressional landscape position than an upper slope position. With this background information in place (soil attributes allocated to each landscape position and areal extent), the variability of % organic C and depth of A horizon data may be linked to the representative soil landscape model for each Ecodistrict.

Using the OM data (%) from Norwest Labs Ltd. to represent the mid-slope position, organic C (%) was calculated [Eq.5]. Using the soil landscape model, the distribution coefficient of organic C (DC) was calculated relative to the mid-slope position for each Ecodistrict [Eq.6]. Depth of A horizon varies with landscape position. Norwest Labs Ltd. data were based on samples from a 15 cm depth. Therefore the distribution coefficient of depth (DD) used 15 cm as the mid-slope A horizon depth to calculate the relative differences in depth across the landscape between slope positions for each Ecodistrict [Eq.6]. Depressional areas (which represented 10% of the cultivated area) were omitted because agricultural operations generally do not occur in these areas.

Bulk density estimates (Table 6) were based on soil texture from the Land Suitability Rating System for Agricultural Crops (Pettapiece, 1995). The TOC (kg C ha^{-1}) for each slope position was then calculated using the organic C (%) from Norwest Labs Ltd., DC, bulk density, and DD [Eq.7].

Equation 5

$$OC_{NW} = OM_{NW} * 0.57$$

where OC_{NW} = % organic C from Norwest Labs Ltd.; OM_{NW} = % OM from Norwest Labs Ltd.; 0.57 is the C fraction of organic matter.

Equation 6

$$DC_{up} = \frac{\%OrgC_{up}}{\%OC_{NW}} \qquad DD_{up} = \frac{Depth_{up}}{Depth_{mid}}$$

$$DC_{mid} = \frac{\%OrgC_{mid}}{\%OC_{NW}} \qquad DD_{mid} = \frac{Depth_{mid}}{Depth_{mid}}$$

$$DC_{low} = \frac{\% OrgC_{low}}{\% OC_{NW}} \qquad DD_{low} = \frac{Depth_{low}}{Depth_{mid}}$$

where DC_{up}, DC_{mid}, and DC_{low} = distribution coefficient of organic C for the upper, middle and lower slope positions, respectively; DD_{up}, DD_{mid} and DD_{low} = distribution coefficient of depth for the upper middle and lower slope positions, respectively; % $OrgC_{up,mid,low}$= % organic C from each landscape model for each Ecodistrict.

Table 6: Bulk density estimates used for the following soil textures

Texture*	Mg m^{-3}
C, C(L), C(O), C(SL,O), C-L, C-L(O)	1.05
L, L-CL, L-SiL, L-SL, L-CL(C,S), L-CL(S,C), L-CL(SL), L-C(S), L(CL), L(S), L(S,O), L(SL),	1.25
S(SL), S(SL,O), S-L, S-O, S-O(SL), O-S(CL), S-SL(O)	1.40
SL(L), SL(S), SL(S,L), SL(S,O), SL-L	1.35
SiC(L,O), SiC-O(CL), SiC-SiL	1.10
All other textures (SiL and L)	1.20

*C = clay, L = loam, S = sand, O = organic, Si = silt

Equation 7

$$TOC_{up} = OC_{NW} * DC_{up} * rb * (DD_{up} * depth) * \frac{10^3 kg}{Mg} * \frac{10^4 m^2}{ha}$$

$$TOC_{mid} = OC_{NW} * DC_{mid} * rb * (DD_{mid} * depth) * \frac{10^3 kg}{Mg} * \frac{10^4 m^2}{ha}$$

$$TOC_{low} = OC_{NW} * DC_{low} * rb * (DD_{low} * depth) * \frac{10^3 kg}{Mg} * \frac{10^4 m^2}{ha}$$

where OC_{up}, OC_{mid}, $OC_{,low}$ = kg C ha^{-1}; DC_{up}, DC_{mid}, and DC_{low} = distribution of organic C for upper, middle, and lower slope positions, respectively; ?b = bulk density (Mg m^{-3}) (Table 6); DD_{up}, DD_{mid}, and DD_{low} = distribution of A horizon depth for upper, middle and lower slope positions respectively; depth = 0.15 m.

The TOC (kg C ha^{-1}) for each Ecodistrict was the summation of the TOC in the upper, middle and lower slope positions multiplied by landscape proportion within that landscape [Eq.8].

Equation 8

$$TOC_{total} = (TOC_{up} * \% landscape_{up}) + (TOC_{mid} * \% landscape_{mid}) + (TOC_{low} * \% landscape_{low})$$

where TOC_{total} = kg C ha^{-1}; % $landscape_{up,}$ $landscape_{mid,}$ $landscape_{low}$ = proportion of landscape in upper, middle and lower slope position, respectively

3.1.4.2 Parameters

The soil module consists of three compartments: slow (N), medium (P) and fast decay (J). Constant proportions of soil TOC_{total} (S_n, S_p, S_j) were partitioned into each compartment (Table 7). Each compartment has a specific decay rate (k_n, k_p, k_j) following first order kinetics.

Table 7: Input parameters for the soil module

	Slow (N)	Medium (P)	Fast (J)	Reference
Proportion	0.40	0.45	0.15	Hyvönen et al. 1998
Decay rate (month^{-1})	0.0000583	0.0014167	0.049	McGill et al. 1981

3.1.5 Temperature Function

Monthly soil temperature data recorded by Atmospheric Environmental Services (1984) was used to estimate monthly soil temperatures for each Ecoregion by selecting a representative site within that Ecoregion. The temperatures reported were maintained under permanent grass and represent ZT conditions. Temperature for CT systems was adjusted to be 2°C warmer from May to September (Howard Pers. Comm.) because of the lower amount of surface residue. Using the monthly soil temperature data, an equation for the annual temperature cycle was derived using Table Curve Version 4.07 (SPSS 1996) [Eq.9]. This allowed the model to predict monthly soil temperature for any month.

Equation 9

$$ST = a + b\sin\left(2p\,\frac{month}{d} + c\right)$$

where ST = monthly soil temperature (°C); a, b , c, and d are constants (Table 8); month is represented by a number (January = 1, February = 2, March = 3….).

Table 8: Soil temperature constants for each Ecoregion

Ecoregion (Representative site)	Conventional Till	Zero Till
Aspen Parkland (Lacombe)		
a	8.4112021	7.8721943
b	12.596092	11.973662
c	3.5703318	3.5889065
d	10.261809	10.309119
Mixed Grassland (Vauxhall)		
a	10.024322	8.9108888
b	15.188586	13.999809
c	3.8137133	3.8722168
d	11.018523	11.192705
Moist Mixed Grassland (Lethbridge)		
a	10.103168	8.9822738
b	13.545921	12.361118
c	3.8212251	3.8892819
d	11.022985	11.227751
Peace/Boreal Lowland (Beaverlodge)		
a	6.7462739	5.6632632
b	11.282123	10.058709
c	3.6082401	3.6565056
d	10.568745	10.724876

A temperature function (T_d) was then calculated from the monthly soil temperatures [Eq.10] for each tillage system. A warmer soil would have a temperature function closer to 1 whereas a colder soil would have a temperature function closer to 0. The temperature function is then multiplied by Eq.1 to adjust the amount of net C changes.

Equation 10

$$T_d = t + \left(\frac{u}{\left| 1 + \exp\left(-\frac{\left(ST - w + \frac{x}{2} \right)}{y} \right) \right|} \right) * \left(1 - \frac{1}{1 + \exp \frac{\left(-\left(ST - w - \frac{x}{2} \right) \right)}{z}} \right)$$

where T_d = temperature function (between 0 and 1); t, u, w, x, y, and z are constants (Table 9); ST = soil temperature (°C) from either tillage system

Table 9: Temperature function constants

Constants	Temperature Function (T_d)
t	0.0024077901
u	1.1796872
w	32.732851
x	18.707456
y	7.1063182
z	1.0041744

3.2 The Nitrogen Model

The majority of N_2O is emitted from soil. However, other sources of N_2O emissions have been identified such as decomposition of crop residue and fertilizers. Therefore, a model consisting of three modules: (1) crop (2) fertilizer and (3) soil modules was developed to represent N emission from agricultural soils (Figure 2). Using data from AGRASID a landscape function could be included.

Unfortunately, it is difficult to predict N_2O concentrations in soil air and soil solution with changes in soil temperature. As temperature increases, the solubility of N_2O decreases but microbial activity and gas diffusion increases (Heincke and Kaupenjohann 1999). In forest soils, N_2O concentrations in the soil solution have been reported to be the highest during the summer season for a clear-cut forest. Conversely, N_2O concentration peaked during the coldest season at an undisturbed forest location (Heincke and Kaupenjohann 1999). Generally, there is a flush of N_2O emission from agricultural soils in the spring. It is hypothesized that this is a result of N_2O build up in unfrozen subsoil over winter, which is subsequently released when the upper horizon thaws (Heincke and Kaupenjohann 1999). The correlation between annual soil temperature and rate of N_2O emission is unclear and was not included in this analysis.

Due to the high temporal and spatial availability of N_2O emissions (Heincke and Kaupenjohann, 1999), and the lack of available data, it was not possible to develop a model over time. Therefore, an annual estimate based on available data is presented.

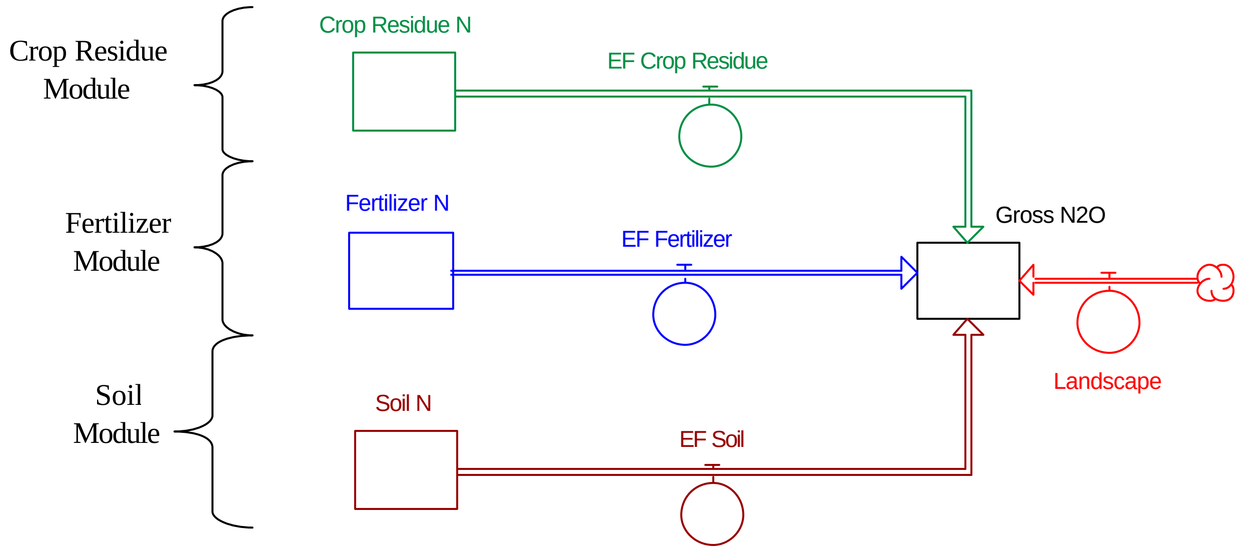

Figure 2: Diagram of gross N emission from an agricultural system (EF = emission factor)

3.2.1 Crop Residue Module

Decomposition of crop residues contributes to N_2O emissions. Using the revised 1996 IPCC/OECD methodology (Monteverde et al. 1997), N_2O emissions from the decomposition of crop residues (kg N y^{-1}) were calculated [Eq.11].

Equation 11

$$N_2O - N_{cropresidue} = crop\ residue * N\ content * Area * EF$$

where crop residue = aboveground straw biomass calculated in the carbon model for each cropping system (kg ha^{-1} y^{-1}); N content for non-legumes (cereals and oilseeds) = 0.015 kg N kg^{-1} dry biomass; N content for forages = 0.025 kg N kg^{-1} dry biomass; Area = Ecodistrict area (ha); EF = emission factor of 0.0125.

3.2.2 Fertilizer Module

There are several studies that indicate a positive correlation between N inputs into soils and N_2O emissions (Heincke and Kaupenjohann 1999). Currently, IPCC/OECD methodology includes fertilizer specific emission rates for N_2O (Monteverde et al. 1997). However, there is evidence that the fertilizer type has less effect on the level of N_2O emission than soil conditions (Hénault et al. 1999). Mosier (1993) argued that there was insufficient data to support different N_2O emission coefficients from either different fertilizers or crops. Therefore, a universal emission factor for all fertilizers was used.

Fertilizer use, application rates and fertilizer types are not only difficult to quantify but data are not always available on a regional basis. Fortunately, data from the Farm Fertilizer Price Protection Program (AFFRD 1991) allowed us to estimate fertilizer N application rates for each Ecodistrict (Appendix 3). Farm Fertilizer Price Protection Program recorded the amount of fertilizer, type, legal land location (of the farmer's residence), and area of land to which the fertilizer was applied. We set the area of land to be fertilized as land surrounding the legal land location of the farmer, and the fertilizer would be kept in the same Ecodistrict as that location. Therefore, N_2O emissions from fertilizers (kg N y^{-1}) were calculated using IPCC methodology [Eq.12].

Equation 12

$$N_2O - N_{fertilizer} = fertilizer\ use * Area * EF$$

where fertilizer use (kg N ha^{-1} y^{-1})(Appendix 3); Area = Ecodistrict Area (ha); EF = 0.006 (mean emission factor for all fertilizer types used by IPCC);

3.2.3 Soil Module

Nitrous oxide emission from soil is difficult to quantify. Fluxes of N_2O from soil vary widely across time and space (Lemke et al. 1998b). Between 16 - 60% of the annual estimated N_2O-N loss is thought to occur during and just following snow melt in the spring (Lemke et al. 1998b). The episodic nature of N_2O emissions make any attempts to quantify emissions dependent on site specific conditions at the time of measurement. Bouwman (1996) proposed a simple equation to relate total annual N_2O-N emissions from fertilized fields to the N fertilizer applied, but points out that it was based on five estimates from unfertilized plots. Liu (1995) used soil order specific emission rates (Table 10) ranging from 0.26 – 1.58 kg N_2O-N ha^{-1} y^{-1}.

Table 10: Nitrous oxide emission rates for each soil order

Soil Order	Emission Rate (kg N_2O-N ha^{-1} y^{-1})
Chernozem	1.07
Solonetzic	0.45
Luvisolic	0.27
Brunisolic	0.47
Gleysolic	0.26
Organic	1.58

* as reported by Liu 1995

What is needed is a coefficient that determines the proportion of total soil N that is denitrified to N_2O. Then site-specific N content values could be used to predict N_2O emissions. However, these data are not available. So, the emission rates that were provided by Liu (1995) were used to calculate N_2O-N emission for each Ecodistrict [Eq.13]. The proportion of soil orders within each SLC was provided by AGRASID, which allowed the N_2O emission (kg N y^{-1}) for each SLC to be calculated. The proportion of SLC within an Ecodistrict was also provided by AGRASID and the total N_2O emission for each Ecodistrict was calculated.

Equation 13

$$N_2O - N_{SLC} = \sum Prop\ SLC_{soilorder} * Emission\ Rate_{soilorder} * Area_{SLC}$$

$$N_2O - N_{soil} = \sum N_2O - N_{SLC} * PropEcodistrict_{SLC}$$

where N_2O-N_{SLC} = total N_2O-N emission for a SLC (kg N y^{-1}); Prop $SLC_{soilorder}$ = proportion of SLC allocated to a specific soil order; Emission $rate_{soilorder}$ = Table 10; $Area_{SLC}$ = SLC Area(ha); Prop $Ecodistrict_{SLC}$ = proportion of Ecodistrict the SLC occupies.

3.2.4 Nitrous Oxide Emissions Across the Landscape

Treating each Ecodistrict as a heterogeneous landscape, gross N_2O emissions (kg N_2O y^{-1}) for each Ecodistrict was the summation of N_2O emissions from fertilizers, crop residues and soil [Eq.14].

Equation 14

$$Gross\,N_2O = \left(N_2O - N_{cropresidue} + N_2O - N_{fertilizer} + N_2O - N_{soil}\right) * \frac{44\,N_2O}{14\,N_2O - N}$$

where $N_2O\text{-}N_{cropresidue}$ *= Eq.11;* $N_2O\text{-}N_{fertilizer}$ *= Eq.12;* $N_2O\text{-}N_{soil}$ *= Eq.13;* $\frac{44}{14}$ *= conversion factor to convert N to* N_2O

As described earlier, the soil landscape model determined the proportion of landscape in upper, middle or lower slope position for each Ecodistrict. The gross N_2O emissions for each landscape position was then determined [Eq.15].

Equation 15

$$N_2O_{up} = Gross\,N_2O * prop_{up}$$
$$N_2O_{mid} = Gross\,N_2O * prop_{mid}$$
$$N_2O_{low} = Gross\,N_2O * prop_{low}$$

where N_2O_{up}*,* N_2O_{mid} *and* N_2O_{low} *=* N_2O *emission from upper, middle and lower slope positions respectively;* $prop_{up}$*,* $prop_{mid}$ *and* $prop_{low}$ *= proportion of landscape in upper, middle and lower slope positions respectively.*

Many studies indicate a positive correlation between increasing water content in the soil and rising concentration of N_2O in soil solution. Available water was on average four cm greater in soils on the backslope and footslope positions than on the summit or shoulder positions (Hanna et al. 1982). Therefore, emissions of N_2O from soil may be indirectly connected with landscape position (Heincke and Kaupenjohann 1999). Mosier et al. (1991) found that N_2O emissions were two times higher in the lower slope position than the mid slope position regardless of fertilization. They also stated that N_2O emissions from the mid slope and lower slope positions were two to four times greater in 1990 than 1981/82, most likely due to wetter conditions in 1990. Corre et al. (1996) observed a consistent landscape-scale pattern of N_2O emissions; footslope positions had higher N_2O fluxes than shoulder positions. As a first approximation we set N_2O emissions to be two times greater in the lower slope positions than in the middle or upper slope positions [Eq.16].

Equation 16

$$N_2O_{land} = N_2O_{up} + N_2O_{mid} + \left(N_2O_{low} * 2\right)$$

where N_2O_{land} *= total* N_2O *emission (kg* N_2O y^{-1}*) with landscape taken into consideration*

4.0 Results and Discussion

The results presented here do not include emissions from livestock operations, wetlands, pastures, or irrigated croplands. An Ecodistrict/Ecoregion map is found in Appendix 4 for reference. Throughout this discussion, specific Ecodistricts are referred to and represent different regions of the province. A major city or town is identified for each Ecodistrict and their associated Ecoregion and soil zone is presented in Table 11.

Table 11: Geographical reference of four Ecodistricts

Ecodistrict	Nearest Town	Ecoregion	Soil Zone
586	High Level (and area)	Peace/Boreal Transition	Luvisol
727	Edmonton (and area)	Aspen Parkland	Black Chernozem
793	Lethbridge (and area)	Moist Mixed Grassland	Dark Brown Chernozem
828	Taber (and area)	Mixed Grassland	Brown Chernozem

4.1 Carbon Model

4.1.1 Carbon Sequestration

Norwest soil test observations within the '93-'97 period were used as initial data for individual model runs for a five year period. Gross C emission rates and C sequestration rates for each tillage system and cropping system were predicted over five years for a continuous cropping system (Appendix 5). For example, the results presented for cereal systems represent a continuous cereal system over five years. However, Ecodistricts are not composed of one cropping system and are a combination of cropping systems. Therefore, the results presented for Ecodistricts are calculated on an area basis and consider the proportion of each cropping system in the Ecodistrict (Appendix 6).

Net change of C can be either positive (+) or negative (-) and is the summation of C inputs (crop residue) and C outputs (gross C emission). A positive number indicates a gain of C and a negative number indicates a loss of C. Carbon sequestration occurs when there is a gain of C. Full system accounting of agricultural soil emissions is important so net gains or losses can be identified (Figure 3). Note that the amount of C inputs required for C sequestration to occur can be as high as 300 times greater than the amount of C sequestration attained (Appendix 7).

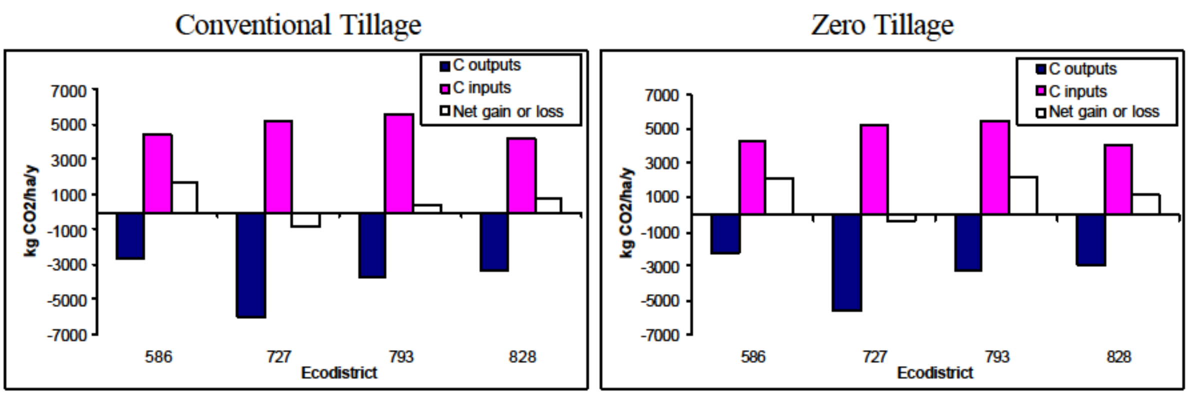

Figure 3: Full C accounting of agricultural soils for both tillage systems for four Ecodistricts in Alberta

In general, net change of C after five years was greatest in cereal cropping systems under ZT and lowest from fallow systems under CT management (Figure 4). The net change of C ranged from -2087 to 951 kg C ha^{-1} y^{-1} for both tillage systems (Table 12). The net change of C was greater in ZT systems than CT systems for each cropping system, indicating that ZT system may sequester more C. Note all cropping systems have the potential to lose C and all cropping systems (except fallow) have the potential to gain C independent of tillage systems.

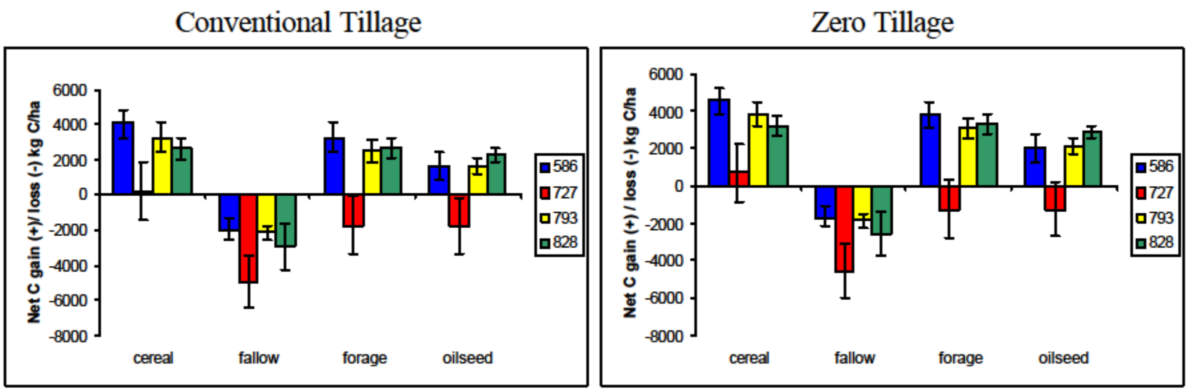

Figure 4: Net change of C (kg C ha^{-1}) after five years of continuous cropping for all cropping systems and two tillage systems

Table 12: Range of net change of C (kg C ha^{-1} y^{-1}) after five years for each continuous cropping system in Alberta*

	Conventional Tillage			Zero Tillage		
	Mean	**Minimum**	**Maximum**	**Mean**	**Minimum**	**Maximum**
Cereals	440	-60	900	565	-55	950
Fallow	-695	-1495	-290	-610	-1385	-250
Forage	200	-2085	715	330	-1645	810
Oilseed	35	-1135	655	155	-830	745

* numbers rounded to the nearest 5

Reported sequestration rate estimates (kg CO_2 ha^{-1} y^{-1}) by Smith et al. (1999) as cited in Boehm et al. (2000) were based on CENTURY output of 15% of SLCs across Canada. Estimates by McConkey (1999) as cited in Boehm et al. (2000) were based upon pooled plot data and took into consideration differences in soil texture (Table 13). Both authors predicted that C sequestration potential increases from the Brown to Dark Brown to Black soil zones. Neither author reported sequestration rates for the Luvisol soil zone.

Table 13: C sequestration rates (kg CO_2 ha^{-1} y^{-1}) for each soil zone as cited in Boehm et al. (2000)

Soil Zone	**Desjardin No Till**	**McConkey No Till**
Brown	220	730
Dark Brown	440	730
Black	540	1340
Grey Luvisol	NR**	NR

* numbers taken from Boehm et al. 2000
** NR: not reported by authors

Mean C sequestration rates predicted from this model indicated that C sequestration is dependent on the soil type, landscape, cropping system and tillage system implemented for each Ecodistrict. There is a wide range of C sequestration rates within each Ecoregion (Table 14) making it difficult to generalize one specific C sequestration rate for each Ecoregion (or soil zone). However, with this variability in mind, a different trend was predicted than presented in Table

13; C sequestration rates were lowest in the Black soil zone and highest in the Luvisol soil zone. The C sequestration rates were calculated for each Ecodistrict (Appendix 5) and took into consideration the proportion of each cropping system (Appendix 6) in that Ecodistrict (Figure 5).

Table 14: Range of C sequestration rates (kg CO_2 ha^{-1} y^{-1}) for each Ecoregion

Ecoregion (soil zone)	Conventional Till			Zero Till		
	Mean	Min	Max	Mean	Min	Max
Mixed Grassland (Brown)	391	-1339	1915	776	-647	2356
Moist Mixed Grassland (Dk Brown)	528	-831	2163	1022	-182	2508
Aspen Parkland (Black)	-72	-2173	1005	392	-1676	1216
Peace / Boreal Transition (Luvisol)	1093	-645	2551	1687	219	3077

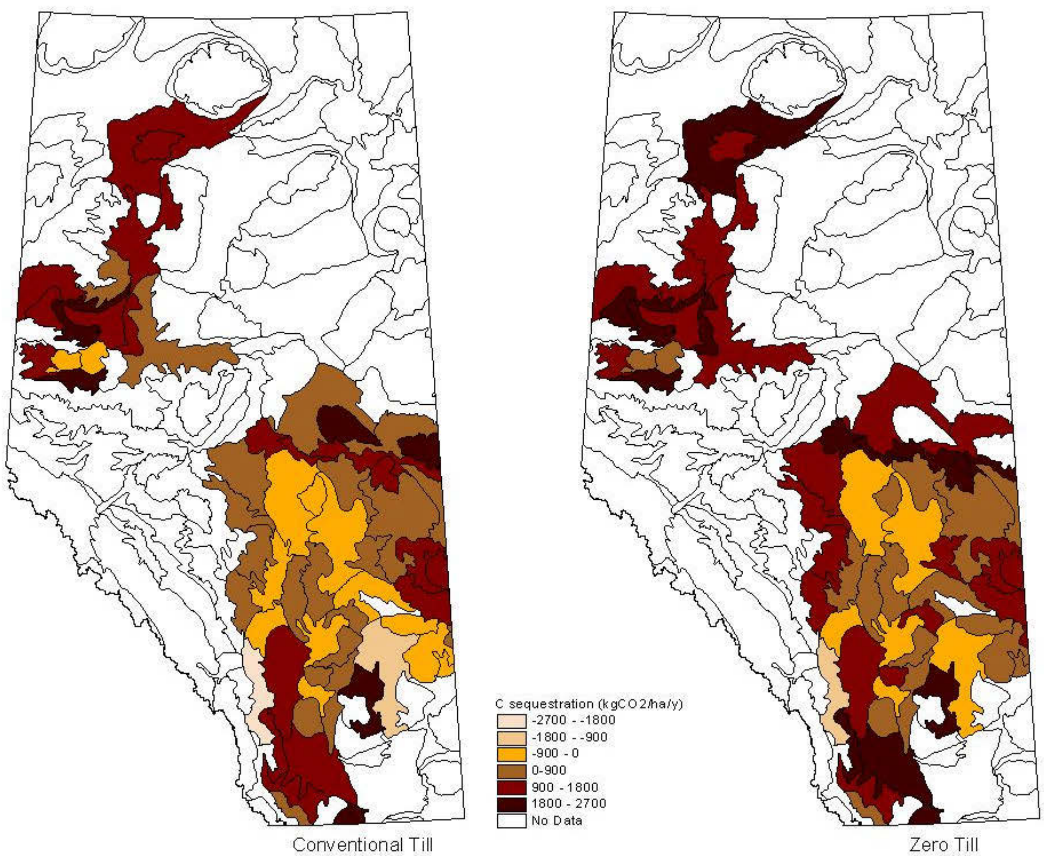

Figure 5: Comparison of C sequestration rates (kg CO_2 ha^{-1} y^{-1}) between conventional and zero tilled systems for Alberta

In general, Ecodistricts that indicated the lowest C sequestration potential were located in the Aspen Parkland Ecoregion (Black soil zone). Smith et al. (1997) estimated soil organic C loss to be two to four times higher from the Black Chernozem or Luvisol orders than any other soil orders because of the high native carbon contents. CENTURY predicted greater losses by decomposition from soils with initially high masses of soil organic C than from those with lower masses of soil organic C (McGill and Bailey 1999).

For those Ecodistricts that did indicate a C sequestration potential, annual rates predicted from this model ranged from 16 to 2551 kg CO_2 ha^{-1} y^{-1} (4 to 696 kg C ha^{-1} y^{-1}) for CT systems and from 59 to 3077 kg CO_2 ha^{-1} y^{-1} (16 to 839 kg C ha^{-1} y^{-1}) for ZT systems. In comparison, measurements of soil C gain on a continuously cropped, Orthic Grey Luvisol soil in Breton, Alberta, after 51 years was 326 kg C ha^{-1} y^{-1} (Izaurralde et al. 2000). Sequestration rates were reported for a continuous corn system in Kentucky, which measured a C gain of 900 kg C ha^{-1} y^{-1} under conventional till and 514 kg C ha^{-1} y^{-1} under no till after 14 years (Ismail et al. 1994). An average increase of 1100 kg C ha^{-1} y^{-1} were measured at five sites in Texas, Kansas and Nebraska, on previously cultivated land sown to grass after 5 years (Nyborg et al. 1999).

4.1.1.1 Model Testing

Data from three long-term sites (Breton, Ellerslie, Three Hills) located in different Ecoregions in Alberta were used to test this model. Model inputs were OM%, bulk density, crop type, Ecodistrict and Ecoregion (Table 15). The model predicted that the Breton site had the greatest net changes of C, followed by Three Hills and then the Ellerslie site (Table 16). The predicted values for all sites are within the same magnitude of the reported values.

Table 15: Initial input parameters for model for three long term sites in Alberta

Site	Ecodistrict	OM (%)	Bulk Density (Mg m^{-3})	Crop type	Ecoregion
Breton	692	2.30	1.4	Cereal	Peace / Boreal Transition
Ellerslie	727	10.7	1.0	Cereal	Aspen Parkland
Three Hills	781	3.28	1.2	Cereal	Moist Mixed Grassland

Table 16: Predicted net change of C compared to reported net change of C for three long term sites in Alberta

Site	Ecodistrict	Predicted Values (kg C ha^{-1} y^{-1})		Reported Values (kg C ha^{-1} y^{-1})	Reference
		CT	ZT		
Breton	692	809	912	261 to 415*	Solberg et al. 1997
Ellerslie	727	-121	-5	-38 to 123*	Solberg et al. 1997
Three Hills	781	480	621	1452	Sauvé et al. unpublished 2000

Values are a range of no straw retained to all straw retained on site

4.1.2 Gross Carbon Emissions

The rate of gross C emission for all cropping systems and both tillage systems ranged from -249 kg C ha^{-1} y^{-1} to -3760 kg C ha^{-1} y^{-1} (Table 17). The rate of gross C emission increased over time for the forage cropping system (Figure 6). The cereal and oilseed cropping systems had the same trend while the rate of gross C emission from the fallow system decreased with time. The rate of gross C emissions for these cropping systems (cereal, forage and oilseed) were higher because these systems received annual C inputs while the fallow system did not. Higher C inputs results in higher amounts of C decomposition therefore the rate of gross C emission is higher. The lower rate of gross C emission in year one is because there was no addition of residue C the previous year (year 0), therefore the gross C emission was lower for year one. This being the case, year one data was omitted from any mean C emission calculations.

Table 17: Range of annual gross C emission (kg C ha^{-1} y^{-1}) for each cropping system

Cropping System	Conventional Tillage			Zero Tillage		
	Mean	Minimum	Maximum	Mean	Minimum	Maximum
Cereal	-1171	-1705	-757	-1036	-1497	-644
Fallow	-687	-1483	-290	-606	-1374	-249
Forage	-1199	-3760	-678	-1060	-3313	-577
Oilseed	-1081	-1049	-2637	-955	-2325	-500

Gross C emission was greater from CT systems than ZT systems for the cereal and oilseed cropping systems (Figure 7). Fallow and forage cropping systems followed the similar trend. However, this trend was not statistically significant. Changing tillage management from CT to ZT indicated a decrease in gross C emission for all Ecodistricts.

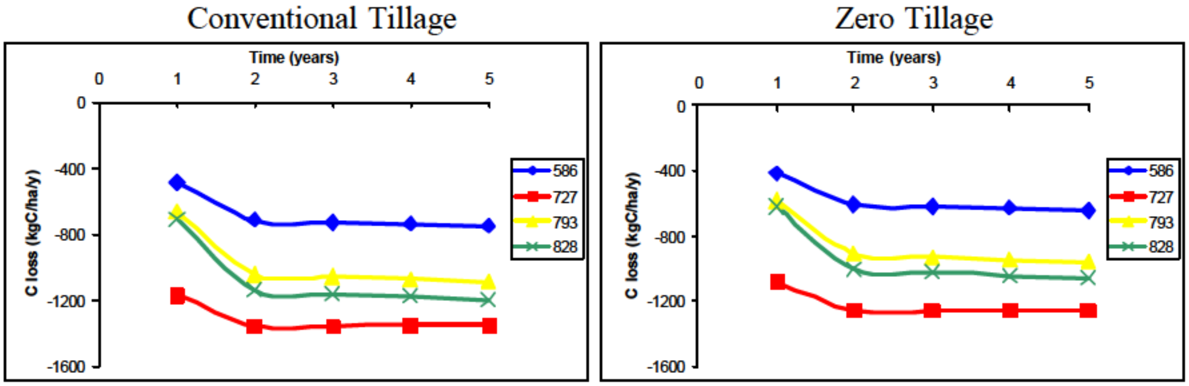

Figure 6: Annual gross C emission (kg C ha^{-1}) from a forage system over five years for four Ecodistricts

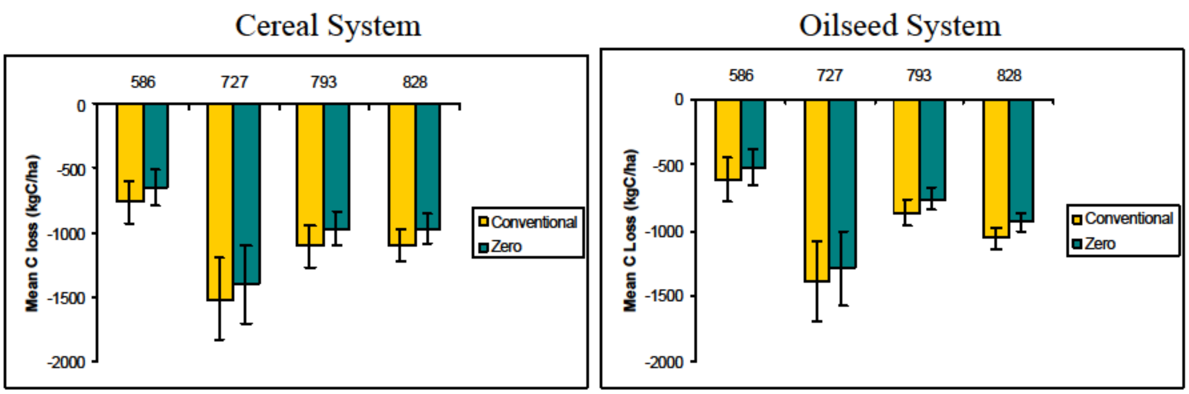

Figure 7: Annual gross C emission (kg C ha^{-1}) from a cereal and oilseed cropping system for four Ecodistricts

Decomposition of soil or residue C results in an emission of C from the system. For some Ecodistricts, the proportion of C emitted from residue decomposition was as high as 55% (Figure 8). Therefore gross C emission rates were calculated from both the soil and residue modules. The mean gross CO_2 emission rate for Alberta was -4157 kg CO_2 ha^{-1} y^{-1} for CT (Figure 9) and -3674 kg CO_2 ha^{-1} y^{-1} for ZT. Using the cultivated area of each Ecodistrict, the proportion of area in each cropping system, and the conversion of factor $\left(\frac{44CO_2}{12CO_2-C}\right)$ to convert from C to CO_2, gross CO_2 emissions were calculated for each Ecodistrict (Appendix 7). When the cultivated area for each Ecodistrict is taken into consideration, small differences in emission rates become more apparent (i.e. Ecodistricts 703 and 727) (Figure 10). In general, gross CO_2 emissions were highest from Ecodistricts within the Aspen Parkland Ecoregion (Figure 11). Most likely this is related to the higher initial soil organic C content.

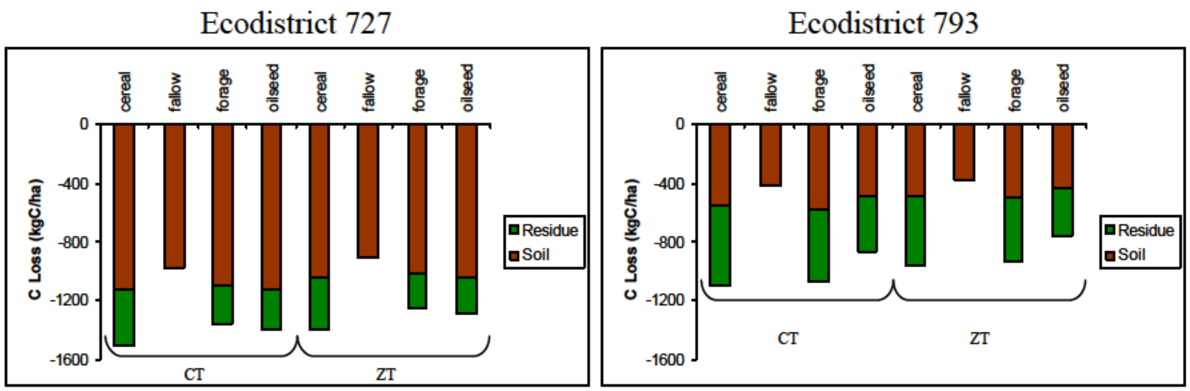

Figure 8: Mean gross C emission rates (kg C ha^{-1} y^{-1}) from the residue and soil modules for Ecodistrict 727 and 793 after five years

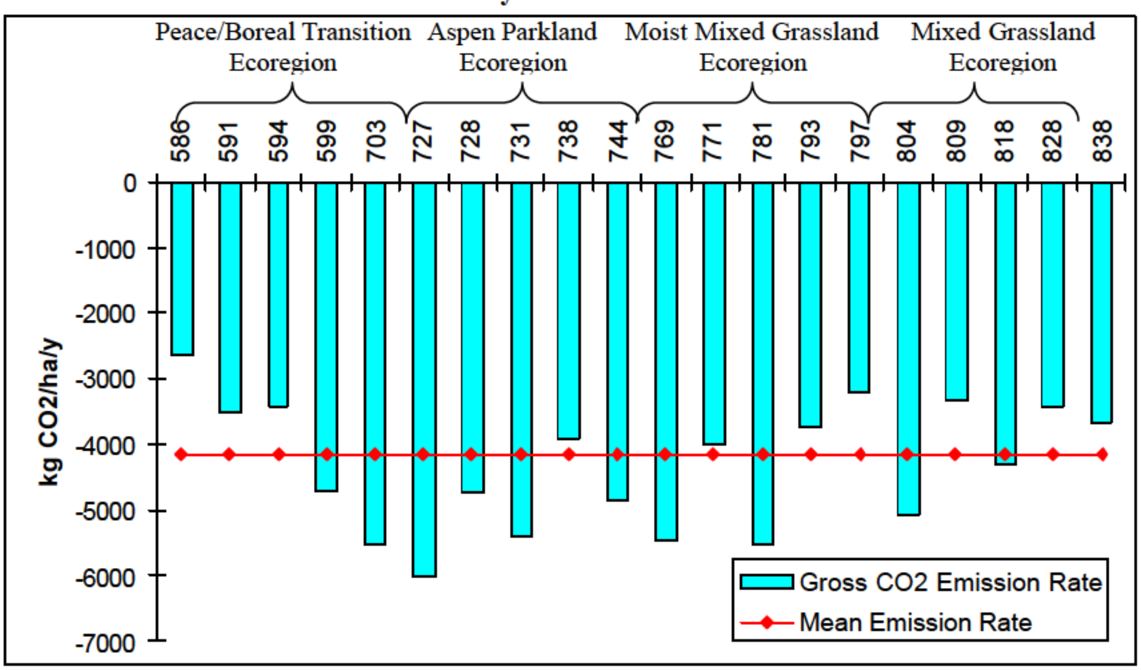

Figure 9: Gross CO_2 emission rates (kg CO_2 ha^{-1} y^{-1}) for conventional till systems for selected Ecodistricts in Alberta

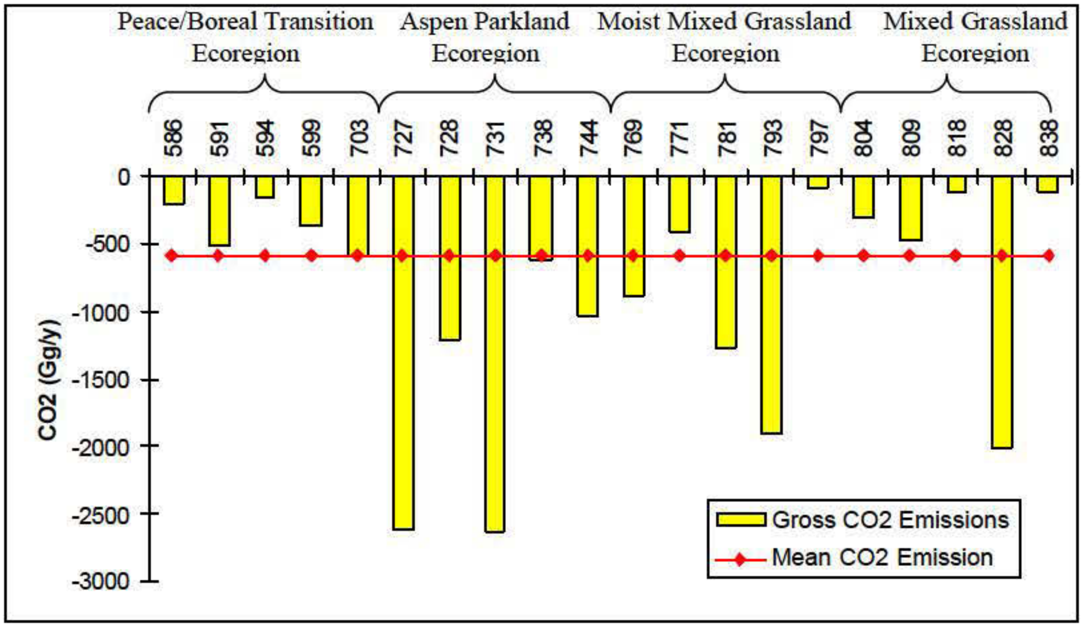

Figure 10: Gross CO_2 emissions (Gg CO_2 y^{-1}) for selected Ecodistricts in Alberta

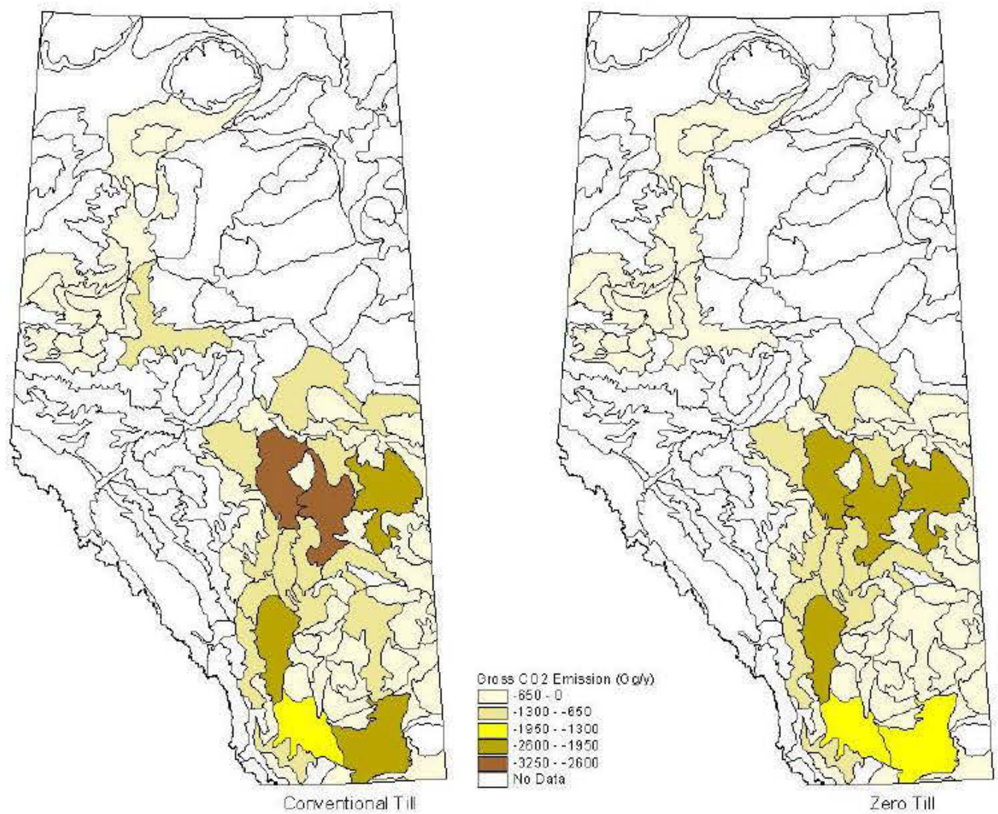

Figure 11: Comparison of gross CO_2 emissions (Gg CO_2 y^{-1}) between CT and ZT systems

4.1.3 Preliminary Estimates

The gross emission of CO_2 from agricultural soils in Alberta can be calculated using the gross CO_2 emission rates and cultivated area of each Ecodistrict. Depending on the tillage system used, Alberta's agricultural soils have a gross emission between -38 000 and -43 000 Gg CO_2 y^{-1}. However, using the C sequestration rates, and if Kyoto accepts C sinks in the emission inventory for agriculture, the agricultural sector in Alberta would have a net C sequestration potential between 4700 and 9000 Gg CO_2 y^{-1}.

Provincial estimates of GHG emissions by Environment Canada (Neitzert et al. 1999) for Alberta in 1996 were -199 000 Gg CO_2 equivalent (all gases and all sectors). The net emission (all gases) from the agricultural sector in Alberta was -21 000 Gg CO_2 equivalent, -2000 Gg CO_2 was from agricultural soils. In comparison, provincial estimates by the National Climate Change Process (McIlveen 1999) projected that Alberta's total GHG emission in the year 2000 would be -205 000 Gg CO_2 equivalent (all gases and all sectors). There was no breakdown for each sector in Alberta. However, by the year 2000, they projected that the agricultural sector would have a net emission of 0 Gg CO_2.

There is growing interest in providing incentives for C sequestration. One method is to establish C trading and pay for C sequestration. The range of valuation of C emissions permit/trading is between $5 (Sinks Table Options Paper 1999) to $50 (Subak 2000) per tonne (C equivalent). If 50% of Alberta's farmers practice ZT (pers. comm. P. Gamache), then Alberta could have an economic gain of $9.5 to $95 million per year (6850 Gg CO_2 y^{-1} would be sequestered). It should be mentioned that the ability of the soil to store C is not infinite and that these numbers should be used with caution for any long-term predictions. True commitment to long-term reduction of GHG emissions requires other means of reducing GHG emissions.

4.2 Nitrogen Model

4.2.1 Gross Nitrous Oxide Emissions

Gross N_2O emissions were calculated, for each Ecodistrict in Alberta's agriculture area (Appendix 8). Gross emissions ranged from -0.03 to -0.91 Gg N_2O y^{-1} from soil module; -0.19 to -1.41 Gg N_2O y^{-1} from crop residue module; and 0.002 to -0.46 Gg N_2O y^{-1} from fertilizer module (Table 18). On average, 41% of the N_2O emission were from the soil module, 51% from crop residue module and 8% were from fertilizer module (Figure 12).

Table 18: Range of gross N_2O emissions (Gg N_2O y^{-1}) from each module

	Mean	Minimum	Maximum
Soil Module	-0.23	-0.034	-0.91
Crop Residue Module	-0.35	-0.019	-1.42
Fertilizer Module	-0.05	0.002	-0.46

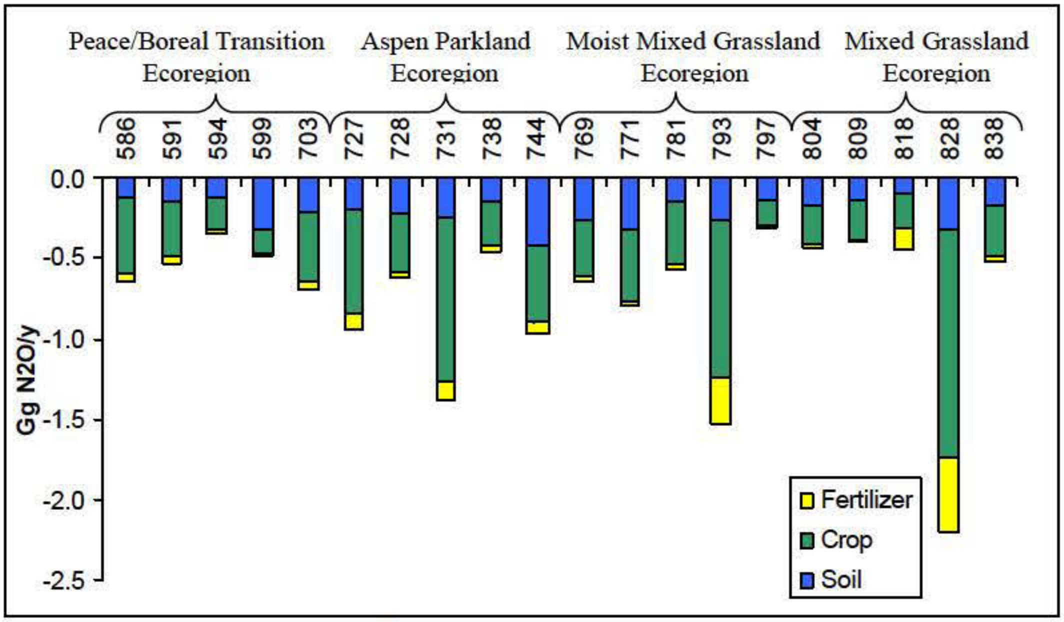

Figure 12: Gross N_2O emission (Gg y^{-1}) from the soil, crop and fertilizer for selected Ecodistricts in Alberta

Gross N_2O emissions were highest from Ecodistricts 793, 730 and 828 (-1.53, -1.62, and -2.19 Gg N_2O y^{-1} respectively). Ecodistricts 731, 798, 678, 739, and 684 had the next highest gross N_2O emissions (Figure 13).

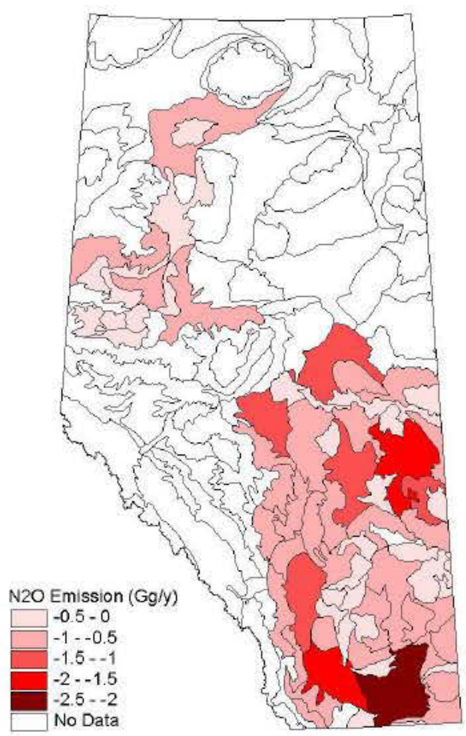

Figure 13: Emission of N_2O (Gg y^{-1}) from each Ecodistrict in Alberta

Further investigation of these Ecodistricts indicates that the majority of N_2O emissions emitted are from the decomposition of crop residue (Table 19). This may have implication for an overall GHG budget because in order to sequester C farmers are encouraged to retain crop residue, however this may have negative results due to the high emissions of N_2O from the decomposition of crop residue compared to the soil and fertilizer modules.

Table 19: Gross N_2O emissions (Gg N_2O y^{-1}) from selected Ecodistricts in Alberta

Ecodistrict	Gross N_2O Emission (Gg N_2O y^{-1})	Proportion of N_2O from Soil	Proportion of N_2O from Crop Residue	Proportion of N_2O from Fertilizer
678	-1.31	0.249	0.660	0.090
684	-1.27	0.271	0.656	0.073
730	-1.62	0.289	0.637	0.074
731	-1.39	0.179	0.732	0.089
739	-1.30	0.693	0.275	0.032
793	-1.53	0.173	0.638	0.189
798	-1.38	0.297	0.624	0.079
828	-2.19	0.146	0.646	0.208

4.2.2 Preliminary Estimates

Nitrous oxide has a long atmospheric lifetime and its unique absorption bands give N_2O a large global warming potential, approximately 310 times more effective (molar basis) than CO_2 over 100 years. The summation of the gross N_2O emission for each Ecodistrict provides a gross N_2O emission estimate for all of Alberta. The model predicted that the gross emission of N_2O from Alberta was -14 212 Gg CO_2 equivalent y^{-1} (Table 20). Environment Canada (Neitzert et al. 1999) estimated that gross N_2O emission was -10 000 Gg CO_2 equivalent y^{-1} from agricultural soils in Alberta. In addition, the National Climate Change Process (McIlveen 1999) projected that in the year 2000, N_2O emissions would be -6100 Gg CO_2 equivalent y^{-1} from the agricultural sector in Alberta. The amount of N_2O emission from synthetic fertilizer predicted here was -1200 Gg CO_2 equivalent y^{-1}, which is comparable to the -1600 Gg CO_2 equivalent y^{-1} estimated by Environment Canada (Jaques et al. 1997). Whereas Monteverde et al. (1997) estimated 2700 Gg CO_2 equivalent y^{-1} would be emitted from fertilizer as N_2O. Monteverde et al. (1997) also estimated 2600 Gg CO_2 equivalent y^{-1} would be emitted from crop residues as N_2O. This amount is less than half of what was predicted from this model.

Gross CO_2 emissions from agricultural soils are approximately three times greater than gross N_2O emissions from agricultural soils in Alberta. However, if Kyoto accepts 7100 Gg CO_2 y^{-1} are sequestered in agricultural soils, there is still a net loss of GHG emissions from Alberta's agricultural sector (-6900 Gg CO_2 equivalent y^{-1}).

Table 20: Gross emissions of N_2O (Gg y^{-1}) and the CO_2 equivalent* from agricultural soils in Alberta

	Total	Soil	Crop	Fertilizer
Gross N_2O Gg y^{-1}	-46	-17	-25	-4
Gross CO_2 equiv. Gg y^{-1}	-14212	-5198	-7841	-1174

* Multilply gross N_2O emission by 310 for CO_2 equivalent

5.0 Conclusions

This report predicts the gross CO_2 emission rates from agricultural soils for each Ecodistrict in Alberta's agricultural area. Gross emissions of CO_2 were highest from Ecodistricts within the Aspen Parkland Ecoregion and are most likely a result of higher soil organic C contents. Conventionally tilled systems appeared to lose more C than ZT systems. In addition, ZT systems appeared to sequester more C. Suggesting a change from CT to ZT may reduce GHG emissions of CO_2.

There is general agreement among the soil science community that C sequestration occurs in soils. However, it is dependent on climate, soil type, cropping system and tillage management. Net increases in soil C are the result of greater inputs into the system than C emitted by decomposition. The cereal cropping systems under ZT was predicted as having the greatest net change of C after five years. The fallow systems under CT were predicted as having the lowest net change of C. Carbon sequestration potential appeared to be greatest in Ecodistricts within the Peace Lowland and Boreal Transition Ecoregion. The total C sequestration potential for Alberta was 7100 Gg CO_2 y^{-1}. However, the ability of the soil to store C is not infinite and these numbers should be used with caution for any long-term predictions. True commitment to long-term reduction in GHG emissions requires other means of reducing GHG emissions. Nevertheless, if C trading is permitted, it could have an economic benefit between $9.5 million and $95 million per year for Alberta.

There is a belief that C sequestration may also increase the emissions of N_2O from soil. Unfortunately, it was not possible to link the C model and the N model to see if this relationship could be modeled. However, it was apparent that the majority of the N_2O emissions were from the soil and crop residue modules and not from the fertilizer module. This may have implication for an overall GHG budget because in order to sequester C farmers are encouraged to retain crop residue, however this may have negative results due to the higher emissions of N_2O from the decomposition of crop residue.

It was predicted that gross emissions of CO_2 were between -38 000 and -43 000 Gg y^{-1} and gross N_2O emissions were -14 000 Gg CO_2 equivalent y^{-1} from agricultural soils in Alberta. If Kyoto accepts C sinks of agricultural soils in the emission inventory, and all other things remain equal, the amount of C sequester by soils in Alberta is still not enough to offset the N_2O emission.

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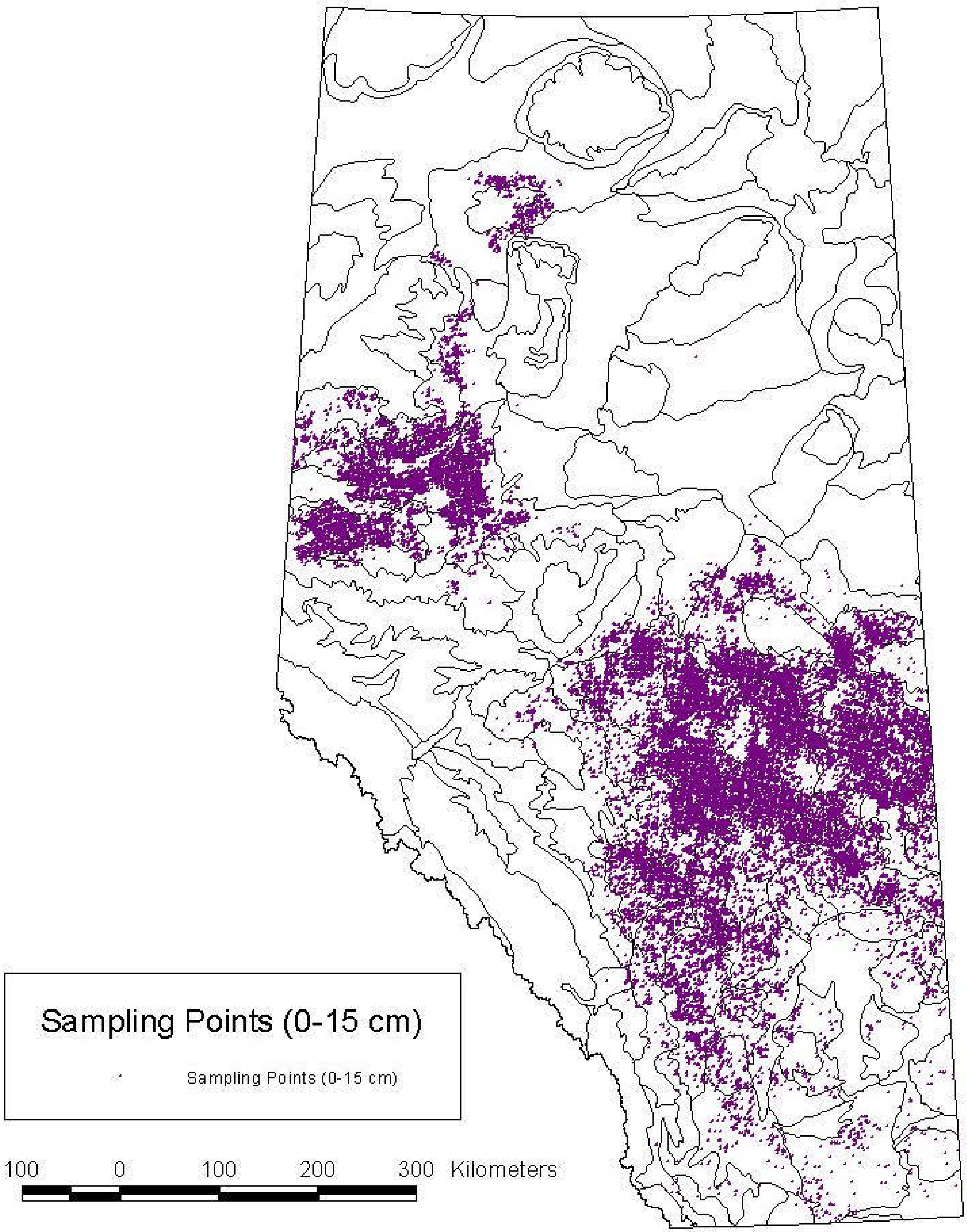
Appendix 1: Soil sampling points from Norwest Labs Ltd. data 1993-1997 in Alberta's agricultural area (0 to 15 cm)



Appendix 2: Descriptive statistics of organic matter values (%) for each Ecodistrict in Alberta's agricultural area from Norwest Labs Ltd. data 1993-1997

Ecodistrict	N	Mean	Std Dev	Min	Max	CV	Skewness
586	217	3.92	1.57	1.60	13.50	40.05	2.60
587	43	3.26	1.58	1.10	7.10	48.36	1.09
588	147	5.18	1.62	1.70	11.80	31.37	0.63
590	258	4.82	1.49	2.10	13.70	30.96	2.03
591	152	6.09	1.93	3.30	13.70	31.67	1.21
592	481	6.93	2.88	1.90	21.10	41.56	1.25
593	1074	5.90	1.70	1.00	16.30	28.78	0.59
594	259	4.53	1.31	1.80	9.60	29.00	1.21
595	191	5.27	1.58	1.10	10.80	29.95	0.89
596	738	4.72	1.34	1.00	19.30	28.31	2.31
597	196	4.76	1.96	1.60	17.50	41.14	1.82
598	391	5.82	1.58	2.90	14.50	27.17	1.15
599	418	7.09	1.32	2.70	13.30	18.62	-0.12
600	76	5.09	2.35	1.90	12.20	46.20	1.00
610	135	5.85	2.53	2.00	20.50	43.25	2.63
615	20	3.96	0.89	2.70	5.60	22.44	0.33
616	231	4.20	2.14	1.00	15.40	50.86	1.71
617	215	5.40	3.18	1.10	19.50	58.86	1.69
618	66	5.29	2.05	3.00	17.70	38.86	3.68
622	106	5.49	2.27	1.90	13.70	41.24	1.34
623	209	6.04	3.24	1.40	20.60	53.61	1.73
629	45	6.80	2.41	1.30	12.80	35.49	0.25
630	51	5.67	1.42	2.90	10.40	24.98	0.86
678	1212	6.02	2.61	1.10	20.70	43.30	1.45
679	22	4.25	2.07	1.00	9.50	48.86	0.81
680	1365	5.51	2.40	1.00	21.60	43.50	1.37
681	1028	5.60	2.32	1.60	21.90	41.51	2.14
683	325	5.01	2.19	1.00	21.40	43.76	2.23
684	1618	5.68	2.46	1.00	21.50	43.27	1.61
686	148	4.88	2.53	1.40	20.60	51.92	2.09
687	1369	5.53	2.03	1.20	21.60	36.78	1.21
688	433	4.60	1.57	1.00	9.30	34.11	0.44
692	259	5.53	2.23	2.10	19.20	40.34	1.87
703	265	5.48	2.60	2.10	20.20	47.35	1.67
708	450	6.73	2.79	2.10	19.00	41.47	1.29
727	7707	7.58	2.29	1.00	21.70	30.17	0.27
728	2447	5.98	1.43	1.10	15.50	23.96	0.08
729	817	5.74	1.47	1.30	11.10	25.62	-0.05
730	4063	5.33	1.50	1.00	17.60	28.11	0.79
731	2288	6.36	1.42	1.00	18.40	22.31	0.43
732	119	6.10	2.17	2.20	14.80	35.50	0.87
737	707	7.71	2.30	2.60	20.30	29.87	0.42
738	352	4.47	1.18	1.10	8.70	26.49	0.07
739	470	4.69	1.55	1.60	13.00	33.06	0.81
740	533	6.22	1.79	1.30	14.20	28.76	0.32

Appendix 2 continued

Ecodistrict	N	Mean	Std Dev	Min	Max	CV	Skewness
743	96	3.84	1.15	1.40	6.40	29.97	0.12
744	875	6.02	1.51	1.00	13.90	25.15	0.44
746	449	8.82	2.02	1.40	14.30	22.94	-0.51
750	184	8.44	2.20	5.50	17.30	26.10	0.79
769	122	4.28	0.95	1.90	7.20	22.26	0.48
771	130	3.09	0.96	1.00	5.60	31.04	0.20
779	61	3.67	1.10	1.90	7.20	29.91	1.06
781	483	5.95	1.33	1.50	9.70	22.39	-0.55
786	79	4.03	1.32	1.90	12.80	32.75	3.96
787	79	3.51	0.91	1.60	5.50	26.01	0.15
788	197	3.65	0.99	1.30	7.60	27.09	0.74
790	81	3.74	1.23	2.00	7.30	32.97	1.08
791	166	3.69	1.02	2.10	9.40	27.57	1.39
793	247	2.57	0.74	1.00	8.70	28.64	3.09
798	1623	5.60	1.48	2.00	13.20	26.37	0.61
804	36	3.49	1.20	1.00	6.20	34.29	0.24
806	29	2.80	1.81	1.90	12.10	64.80	5.17
809	76	2.26	0.82	0.90	5.00	36.19	0.88
811	25	4.22	2.27	1.00	9.90	53.70	1.36
812	71	2.44	0.52	1.40	4.40	21.44	0.98
814	30	2.37	0.80	1.40	5.50	33.61	2.19
818	31	2.83	0.51	1.80	4.40	18.15	0.46
823	39	3.06	2.52	1.70	17.60	82.44	5.36
828	241	2.10	0.56	1.00	5.50	26.80	2.40
833	15	2.93	1.22	1.80	5.70	41.70	1.28
838	19	2.88	1.58	1.50	6.80	54.78	1.67
1016	37	9.68	1.75	6.00	12.50	18.08	-0.22

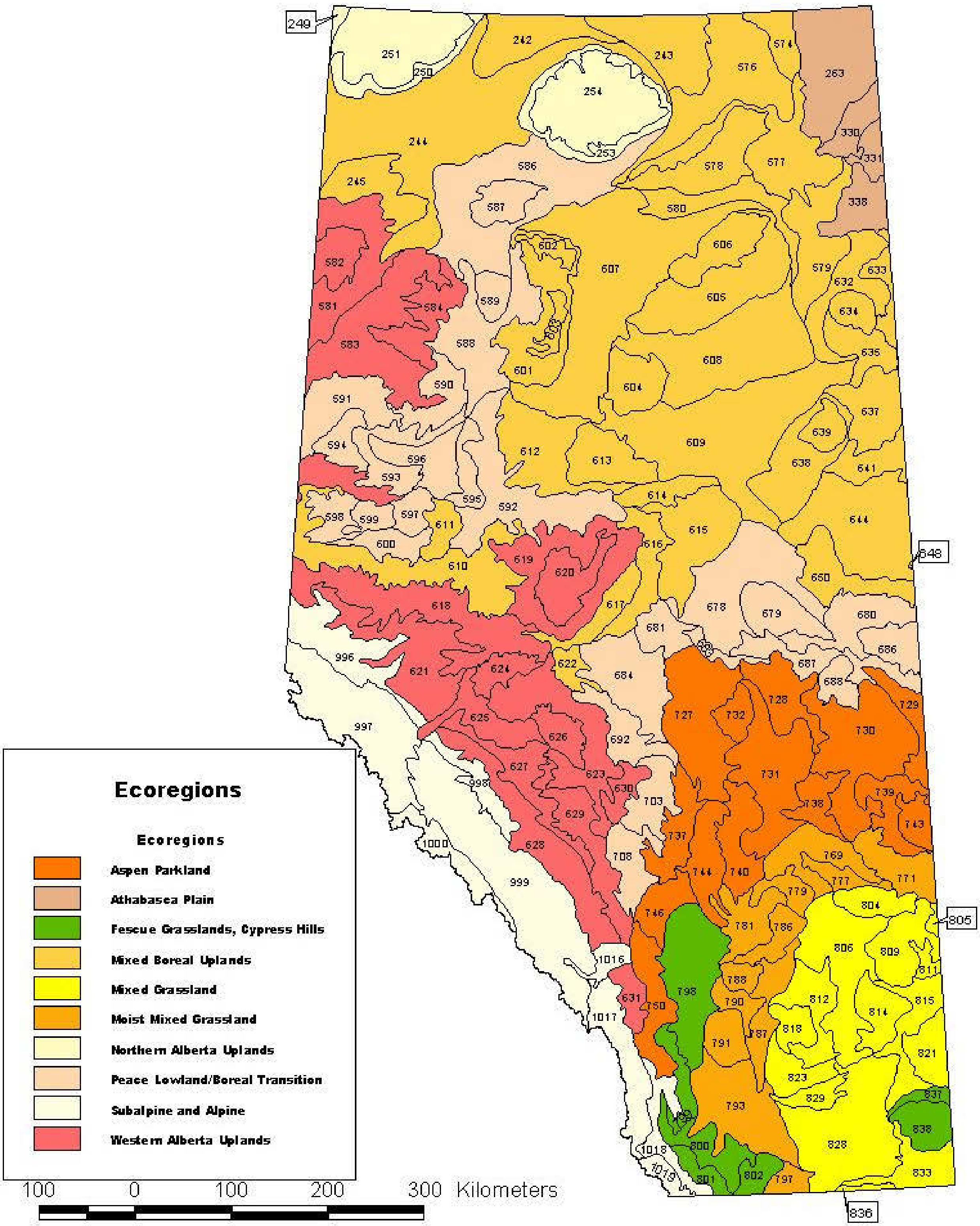
Appendix 3: Descriptive statistics for fertilizer (kg N ha^{-1} y^{-1}) use for each Ecodistrict in Alberta's agricultural area from the Farm Fertilizer Protection Program

Ecodistrict	N	Mean	Min	Max	Range	Std
586	254	15.89	1.70	40.55	38.85	7.84
587	65	15.47	3.14	31.98	28.84	6.20
588	256	17.13	2.41	39.75	37.34	8.24
590	176	16.15	2.14	44.75	42.61	8.44
591	334	17.56	1.81	108.12	106.31	9.82
592	318	16.61	0.59	53.03	52.44	8.62
593	474	16.66	1.13	42.01	40.88	8.18
594	137	16.41	2.24	40.44	38.20	7.81
595	258	17.90	0.63	42.02	41.39	8.48
596	260	19.21	1.98	47.02	45.04	9.24
597	110	17.31	1.00	41.82	40.82	8.73
598	346	18.12	1.97	46.34	44.37	8.17
599	229	18.85	2.35	45.35	43.00	9.31
600	38	17.61	3.07	33.33	30.27	8.98
607	20	13.87	6.00	27.85	21.85	5.64
610	115	15.41	1.44	39.33	37.89	8.87
611	14	17.90	6.74	36.80	30.06	8.28
612	13	12.55	2.07	22.81	20.73	6.23
615	53	16.17	1.80	39.19	37.39	7.99
616	80	16.87	1.86	38.20	36.34	8.06
617	33	18.00	5.99	33.93	27.95	6.41
618	40	15.30	1.82	49.90	48.08	10.16
622	48	15.64	1.74	51.74	50.00	8.80
623	157	14.97	1.47	42.60	41.13	7.74
629	58	14.22	2.72	30.13	27.41	6.32
630	47	12.54	2.47	44.36	41.89	6.96
631	46	19.50	1.59	35.31	33.71	7.64
678	694	16.81	0.74	48.04	47.30	8.42
679	48	16.00	2.02	46.15	44.13	8.68
680	452	16.22	0.93	42.46	41.53	7.74
681	480	20.90	1.87	46.29	44.42	8.63
683	140	17.32	0.76	42.25	41.49	8.25
684	640	15.87	0.60	42.85	42.25	8.25
686	30	13.66	3.17	29.75	26.58	6.29
687	485	17.29	1.18	50.70	49.52	8.37
688	206	14.93	1.03	38.08	37.05	7.71
692	235	13.85	1.05	38.29	37.24	7.42
703	425	17.23	1.39	41.47	40.07	8.32
708	503	15.51	1.07	49.53	48.46	7.45
727	1710	19.37	0.00	59.67	59.67	8.88
728	821	16.18	1.05	46.08	45.04	8.00
729	337	14.33	0.56	39.44	38.88	6.46
730	1284	14.50	1.06	45.90	44.85	7.18
731	1404	16.49	0.00	48.52	48.52	7.70
732	109	16.02	1.89	41.61	39.72	7.46
737	682	19.15	0.36	205.60	205.24	10.73

Appendix 3 continued

Ecodistrict	N	Mean	Min	Max	Range	Std
738	312	17.24	1.09	39.83	38.74	6.83
739	148	13.23	1.44	37.33	35.89	6.81
740	486	16.55	0.62	38.23	37.62	8.40
743	169	10.74	0.24	44.76	44.52	6.54
744	702	18.32	0.43	39.63	39.20	7.48
746	574	18.65	0.96	56.60	55.64	8.23
750	313	17.27	0.74	54.09	53.35	7.65
769	262	10.50	0.88	41.11	40.23	5.82
771	113	10.16	1.03	26.47	25.44	5.65
777	34	8.10	2.25	15.95	13.70	3.38
779	93	6.78	1.09	30.40	29.31	5.22
781	423	13.21	0.32	52.04	51.71	7.36
786	127	9.95	1.44	30.41	28.98	6.29
787	95	18.01	0.99	508.31	507.33	58.25
788	144	16.83	1.59	54.62	53.03	10.11
790	79	21.36	1.70	170.74	169.04	27.84
791	226	10.91	0.97	125.60	124.63	9.47
793	601	36.01	0.83	1145.84	1145.02	84.24
797	37	15.26	3.10	26.20	23.09	5.50
798	1061	18.47	0.64	165.42	164.78	13.52
799	104	13.80	0.97	28.28	27.32	6.55
800	223	21.41	1.08	159.93	158.84	19.12
801	114	15.79	1.68	102.36	100.69	10.65
802	54	17.30	2.67	39.58	36.92	7.45
804	25	8.75	1.08	35.67	34.59	7.27
806	32	10.74	0.00	29.76	29.76	8.15
809	34	6.30	0.43	28.39	27.97	6.24
811	12	3.62	1.44	6.48	5.04	1.85
812	30	82.89	1.38	1199.84	1198.46	211.79
815	28	29.09	1.38	206.16	204.78	46.21
821	31	7.08	1.45	21.50	20.04	5.29
823	53	57.51	1.46	936.73	935.28	137.58
828	528	46.49	0.80	1657.02	1656.21	128.71
829	12	88.16	0.67	216.16	215.49	78.19
833	16	13.23	1.84	21.52	19.68	6.06
837	48	10.27	2.44	29.38	26.93	6.03
838	41	13.36	1.73	37.84	36.11	7.93
1018	36	17.79	3.26	71.20	67.94	14.86

Appendix 4: Ecoregions and Ecodistricts of Alberta



Appendix 5: Carbon sequestration rates for each cropping system for each Ecodistrict in Alberta's agricultural area

Ecoregion	Ecodistrict	Crop type	Conventional Tillage		Zero Tillage	
			kg C ha^{-1} 5y^{-1}	kg C ha^{-1} y^{-1}	kg C ha^{-1} 5y^{-1}	kg C ha^{-1} y^{-1}
Peace	586	cereal	4047	809	4564	913
Peace	586	fallow	-1954	-391	-1653	-331
Peace	586	forage	3289	658	3796	759
Peace	586	oilseed	1579	316	2016	403
Peace	587	cereal	3974	795	4502	900
Peace	587	fallow	-1481	-296	-1253	-251
Peace	587	oilseed	1726	345	2141	428
Peace	588	cereal	2908	582	3601	720
Peace	588	fallow	-2514	-503	-2127	-425
Peace	588	forage	2389	478	3035	607
Peace	588	oilseed	224	45	870	174
Peace	590	cereal	2546	509	3294	659
Peace	590	fallow	-3795	-759	-3211	-642
Peace	590	forage	1755	351	2499	500
Peace	590	oilseed	97	19	763	153
Peace	591	cereal	2906	581	3599	720
Peace	591	fallow	-3452	-690	-2921	-584
Peace	591	forage	2384	477	3030	606
Peace	591	oilseed	264	53	904	181
Peace	592	cereal	2275	455	3065	613
Peace	592	fallow	-3798	-760	-3213	-643
Peace	592	forage	996	199	1857	371
Peace	592	oilseed	17	3	695	139
Peace	593	cereal	3719	744	4287	857
Peace	593	fallow	-2361	-472	-1997	-399
Peace	593	forage	3199	640	3720	744
Peace	593	oilseed	1243	249	1733	347
Peace	594	cereal	3032	606	3705	741
Peace	594	fallow	-3013	-603	-2549	-510
Peace	594	forage	2449	490	3086	617
Peace	594	oilseed	509	102	1111	222
Peace	595	cereal	3166	633	3819	764
Peace	595	fallow	-3028	-606	-2562	-512
Peace	595	forage	2343	469	2996	599
Peace	595	oilseed	561	112	1156	231
Peace	596	cereal	2726	545	3447	689
Peace	596	fallow	-3385	-677	-2864	-573
Peace	596	forage	2003	401	2708	542
Peace	596	oilseed	197	39	847	169
Peace	597	cereal	607	121	1654	331
Peace	597	fallow	-4442	-888	-3758	-752
Peace	597	forage	-649	-130	464	93
Peace	597	oilseed	-1853	-371	-887	-177
Peace	598	cereal	2738	548	3457	691
Peace	598	fallow	-3160	-632	-2674	-535
Peace	598	forage	1681	336	2436	487

Appendix 5 continued

Ecoregion	Ecodistrict	Crop type	Conventional Tillage		Zero Tillage	
			kg C ha^{-1} 5y^{-1}	kg C ha^{-1} y^{-1}	kg C ha^{-1} 5y^{-1}	kg C ha^{-1} y^{-1}
Peace	598	oilseed	241	48	884	177
Peace	599	cereal	1256	251	2203	441
Peace	599	fallow	-4723	-945	-3996	-799
Peace	599	forage	566	113	1493	299
Peace	599	oilseed	-1250	-250	-376	-75
Peace	600	cereal	2998	600	3677	735
Peace	600	fallow	-3502	-700	-2963	-593
Peace	600	forage	3114	623	3648	730
Peace	600	oilseed	771	154	1333	267
Peace	678	cereal	1578	316	2476	495
Peace	678	fallow	-4053	-811	-3429	-686
Peace	678	forage	853	171	1735	347
Peace	678	oilseed	-967	-193	-137	-27
Peace	679	cereal	3426	685	4039	808
Peace	679	fallow	-2392	-478	-2024	-405
Peace	679	forage	3382	676	3875	775
Peace	679	oilseed	1475	295	1929	386
Peace	680	cereal	2070	414	2891	578
Peace	680	fallow	-3759	-752	-3180	-636
Peace	680	forage	1418	284	2214	443
Peace	680	oilseed	-462	-92	290	58
Peace	681	cereal	2613	523	3351	670
Peace	681	fallow	-3810	-762	-3224	-645
Peace	681	forage	1733	347	2480	496
Peace	681	oilseed	123	25	785	157
Peace	683	cereal	2902	580	3596	719
Peace	683	fallow	-2849	-570	-2410	-482
Peace	683	forage	2292	458	2953	591
Peace	683	oilseed	477	95	1084	217
Peace	684	cereal	1941	388	2782	556
Peace	684	fallow	-4480	-896	-3790	-758
Peace	684	forage	977	195	1840	368
Peace	684	oilseed	-299	-60	428	86
Peace	686	cereal	3366	673	3988	798
Peace	686	fallow	-3617	-723	-3060	-612
Peace	686	forage	3572	714	4035	807
Peace	686	oilseed	407	81	1025	205
Peace	687	cereal	2779	556	3491	698
Peace	687	fallow	-3051	-610	-2581	-516
Peace	687	forage	2176	435	2855	571
Peace	687	oilseed	376	75	999	200
Peace	688	cereal	2810	562	3518	704
Peace	688	fallow	-2987	-597	-2527	-505
Peace	688	forage	2454	491	3090	618
Peace	688	oilseed	596	119	1185	237
Peace	692	cereal	1830	366	2689	538
Peace	692	fallow	-3074	-615	-2601	-520

Appendix 5 continued

Ecoregion	Ecodistrict	Crop type	Conventional Tillage		Zero Tillage	
			kg C ha^{-1} 5y^{-1}	kg C ha^{-1} y^{-1}	kg C ha^{-1} 5y^{-1}	kg C ha^{-1} y^{-1}
Peace	692	forage	1036	207	1891	378
Peace	692	oilseed	-365	-73	372	74
Peace	703	cereal	1303	261	2243	449
Peace	703	fallow	-4154	-831	-3514	-703
Peace	703	forage	697	139	1604	321
Peace	703	oilseed	-398	-80	344	69
Peace	708	cereal	1939	388	2781	556
Peace	708	fallow	-5096	-1019	-4311	-862
Peace	708	forage	900	180	1775	355
Peace	708	oilseed	-805	-161	0	0
Aspen	727	cereal	172	34	695	139
Aspen	727	fallow	-4970	-994	-4601	-920
Aspen	727	forage	-1749	-350	-1269	-254
Aspen	727	oilseed	-1755	-351	-1263	-253
Aspen	728	cereal	991	198	1453	291
Aspen	728	fallow	-4321	-864	-4000	-800
Aspen	728	forage	-1037	-207	-610	-122
Aspen	728	oilseed	-916	-183	-485	-97
Aspen	729	cereal	1160	232	1609	322
Aspen	729	fallow	-3708	-742	-3432	-686
Aspen	729	forage	-695	-139	-293	-59
Aspen	729	oilseed	-587	-117	-181	-36
Aspen	730	cereal	1468	294	1895	379
Aspen	730	fallow	-4056	-811	-3755	-751
Aspen	730	forage	-515	-103	-126	-25
Aspen	730	oilseed	-380	-76	11	2
Aspen	731	cereal	266	53	782	156
Aspen	731	fallow	-4715	-943	-4365	-873
Aspen	731	forage	-1822	-364	-1337	-267
Aspen	731	oilseed	-1654	-331	-1169	-234
Aspen	732	cereal	969	194	1433	287
Aspen	732	fallow	-4329	-866	-4008	-802
Aspen	732	forage	-378	-76	1	0
Aspen	732	oilseed	-648	-130	-238	-48
Aspen	737	cereal	594	119	1086	217
Aspen	737	fallow	-5026	-1005	-4652	-930
Aspen	737	forage	-1097	-219	-665	-133
Aspen	737	oilseed	-915	-183	-485	-97
Aspen	738	cereal	2015	403	2401	480
Aspen	738	fallow	-3079	-616	-2850	-570
Aspen	738	forage	-447	-89	-64	-13
Aspen	738	oilseed	152	30	503	101
Aspen	739	cereal	2152	430	2528	506
Aspen	739	fallow	-2893	-579	-2678	-536
Aspen	739	forage	1034	207	1307	261
Aspen	739	oilseed	332	66	670	134
Aspen	740	cereal	1484	297	1909	382

Appendix 5 continued

Ecoregion	Ecodistrict	Crop type	Conventional Tillage		Zero Tillage	
			kg C ha^{-1} $5y^{-1}$	kg C ha^{-1} y^{-1}	kg C ha^{-1} $5y^{-1}$	kg C ha^{-1} y^{-1}
Aspen	740	fallow	-3274	-655	-3031	-606
Aspen	740	forage	-547	-109	-156	-31
Aspen	740	oilseed	-348	-70	40	8
Aspen	743	cereal	3211	642	3509	702
Aspen	743	fallow	-2519	-504	-2332	-466
Aspen	743	forage	662	132	963	193
Aspen	743	oilseed	717	143	1026	205
Aspen	744	cereal	1249	250	1692	338
Aspen	744	fallow	-4489	-898	-4156	-831
Aspen	744	forage	-869	-174	-455	-91
Aspen	744	oilseed	-529	-106	-127	-25
Aspen	746	cereal	-36	-7	503	101
Aspen	746	fallow	-5282	-1056	-4890	-978
Aspen	746	forage	-2420	-484	-1890	-378
Aspen	746	oilseed	-1998	-400	-1487	-297
Aspen	750	cereal	-294	-59	264	53
Aspen	750	fallow	-6815	-1363	-6309	-1262
Aspen	750	forage	-2956	-591	-2386	-477
Aspen	750	oilseed	-3036	-607	-2448	-490
Moist Mix	769	cereal	1431	286	2260	452
Moist Mix	769	fallow	-4164	-833	-3636	-727
Moist Mix	769	forage	-547	-109	425	85
Moist Mix	769	oilseed	-631	-126	137	27
Moist Mix	771	cereal	2813	563	3466	693
Moist Mix	771	fallow	-2571	-514	-2245	-449
Moist Mix	771	forage	2939	588	3468	694
Moist Mix	771	oilseed	1053	211	1608	322
Moist Mix	779	cereal	2327	465	3042	608
Moist Mix	779	fallow	-3188	-638	-2783	-557
Moist Mix	779	forage	1307	261	2043	409
Moist Mix	779	oilseed	934	187	1503	301
Moist Mix	781	cereal	398	80	1358	272
Moist Mix	781	fallow	-5502	-1100	-4804	-961
Moist Mix	781	forage	-217	-43	713	143
Moist Mix	781	oilseed	-1433	-287	-564	-113
Moist Mix	786	cereal	2172	434	2907	581
Moist Mix	786	fallow	-3284	-657	-2867	-573
Moist Mix	786	forage	2372	474	2973	595
Moist Mix	786	oilseed	-333	-67	397	79
Moist Mix	787	cereal	2716	543	3382	676
Moist Mix	787	fallow	-2653	-531	-2317	-463
Moist Mix	787	forage	2926	585	3457	691
Moist Mix	787	oilseed	956	191	1523	305
Moist Mix	788	cereal	2500	500	3193	639
Moist Mix	788	fallow	-3296	-659	-2878	-576
Moist Mix	788	forage	-1831	-366	-696	-139
Moist Mix	788	oilseed	523	105	1145	229

Appendix 5 continued

Ecoregion	Ecodistrict	Crop type	Conventional Tillage		Zero Tillage	
			kg C ha^{-1} $5y^{-1}$	kg C ha^{-1} y^{-1}	kg C ha^{-1} $5y^{-1}$	kg C ha^{-1} y^{-1}
Moist Mix	790	cereal	194	39	1180	236
Moist Mix	790	fallow	-5062	-1012	-4420	-884
Moist Mix	790	oilseed	-861	-172	-64	-13
Moist Mix	791	cereal	2339	468	3052	610
Moist Mix	791	fallow	-2888	-578	-2522	-504
Moist Mix	791	forage	1482	296	2196	439
Moist Mix	791	oilseed	408	82	1044	209
Moist Mix	793	cereal	3247	649	3846	769
Moist Mix	793	fallow	-2174	-435	-1898	-380
Moist Mix	793	forage	2480	496	3067	613
Moist Mix	793	oilseed	1616	323	2099	420
Moist Mix	797	cereal	3719	744	4258	852
Moist Mix	797	forage	2646	529	3212	642
Moist Mix	797	oilseed	2027	405	2457	491
Fescue	798	cereal	2086	417	2521	504
Fescue	798	fallow	-3936	-787	-3643	-729
Fescue	798	forage	1469	294	1899	380
Fescue	798	oilseed	267	53	666	133
Fescue	799	cereal	3229	646	3579	716
Fescue	799	forage	1281	256	1725	345
Fescue	800	cereal	2554	511	2953	591
Fescue	800	fallow	-7477	-1495	-6922	-1384
Fescue	800	forage	3232	646	3531	706
Fescue	800	oilseed	-1017	-203	-522	-104
Fescue	801	forage	1037	207	1500	300
Mixed	804	cereal	1525	305	2230	446
Mixed	804	fallow	-3968	-794	-3485	-697
Mixed	804	forage	-1326	-265	-227	-45
Mixed	804	oilseed	63	13	893	179
Mixed	805	cereal	3313	663	3801	760
Mixed	805	fallow	-2141	-428	-1880	-376
Mixed	805	oilseed	3284	657	3722	744
Mixed	806	cereal	1719	344	2401	480
Mixed	806	fallow	-3101	-620	-2723	-545
Mixed	806	forage	-10436	-2087	-8229	-1646
Mixed	806	oilseed	1858	372	2469	494
Mixed	809	cereal	2262	452	2878	576
Mixed	809	fallow	-2970	-594	-2608	-522
Mixed	809	oilseed	704	141	1456	291
Mixed	811	cereal	2128	426	2760	552
Mixed	811	fallow	-2705	-541	-2376	-475
Mixed	811	forage	2191	438	2861	572
Mixed	811	oilseed	2370	474	2919	584
Mixed	812	cereal	2812	562	3361	672
Mixed	812	fallow	-2043	-409	-1795	-359
Mixed	812	forage	3005	601	3576	715
Mixed	812	oilseed	2359	472	2909	582

Appendix 5 continued

Ecoregion	Ecodistrict	Crop type	Conventional Tillage		Zero Tillage	
			kg C ha^{-1} 5y^{-1}	kg C ha^{-1} y^{-1}	kg C ha^{-1} 5y^{-1}	kg C ha^{-1} y^{-1}
Mixed	814	cereal	2559	512	3139	628
Mixed	814	fallow	-1997	-399	-1754	-351
Mixed	815	cereal	626	125	1440	288
Mixed	815	fallow	-3602	-720	-3164	-633
Mixed	815	forage	2659	532	3272	654
Mixed	815	oilseed	-5670	-1134	-4142	-828
Mixed	818	cereal	2558	512	3137	627
Mixed	818	fallow	-2835	-567	-2490	-498
Mixed	818	forage	2463	493	3100	620
Mixed	818	oilseed	2073	415	2658	532
Mixed	821	cereal	2535	507	3117	623
Mixed	821	forage	3541	708	4047	809
Mixed	821	oilseed	-830	-166	108	22
Mixed	823	cereal	2087	417	2724	545
Mixed	823	forage	2572	514	3196	639
Mixed	823	oilseed	2137	427	2714	543
Mixed	828	cereal	2619	524	3191	638
Mixed	828	fallow	-2930	-586	-2573	-515
Mixed	828	forage	2664	533	3277	655
Mixed	828	oilseed	2312	462	2867	573
Mixed	829	cereal	1851	370	2516	503
Mixed	829	forage	2155	431	2830	566
Mixed	833	cereal	2368	474	2971	594
Mixed	833	fallow	-2054	-411	-1804	-361
Mixed	833	forage	-85	-17	862	172
Mixed	836	fallow	-1802	-360	-1583	-317
Mixed	836	oilseed	2289	458	2848	570
Fescue	837	cereal	4500	900	4755	951
Fescue	837	fallow	-1461	-292	-1352	-270
Fescue	838	cereal	3725	745	4038	808
Fescue	838	fallow	-1493	-299	-1382	-276
Fescue	838	forage	1022	204	1485	297
Fescue	838	oilseed	2725	545	2942	588

Appendix 6: Ecodistrict area, and proportion of Ecodistrict cultivated to each crop type for each Ecodistrict in Alberta's agricultural area

Ecoregion	Ecodistrict	Area*	Proportion of area in crop type			
			Cereal	Fallow	Forage	Oilseed
Peace/Boreal Transition	586	77711	0.364	0.134	0.143	0.417
Peace/Boreal Transition	587	22746	0.364	0.149	0.168	0.438
Peace/Boreal Transition	588	94131	0.437	0.148	0.159	0.302
Peace/Boreal Transition	590	78028	0.375	0.096	0.323	0.396
Peace/Boreal Transition	591	144628	0.384	0.120	0.228	0.326
Peace/Boreal Transition	592	174153	0.386	0.097	0.339	0.302
Peace/Boreal Transition	593	208480	0.476	0.082	0.164	0.316
Peace/Boreal Transition	594	48466	0.466	0.122	0.293	0.181
Peace/Boreal Transition	595	126790	0.472	0.059	0.188	0.375
Peace/Boreal Transition	596	109769	0.475	0.067	0.222	0.337
Peace/Boreal Transition	597	47807	0.391	0.058	0.364	0.336
Peace/Boreal Transition	598	116322	0.438	0.107	0.240	0.290
Peace/Boreal Transition	599	79563	0.528	0.088	0.136	0.279
Peace/Boreal Transition	600	11218	0.361	0.061	0.466	0.368
Peace/Boreal Transition	678	226769	0.425	0.081	0.402	0.328
Peace/Boreal Transition	679	24523	0.273	0.091	0.607	0.479
Peace/Boreal Transition	680	139611	0.417	0.080	0.413	0.385
Peace/Boreal Transition	681	141912	0.580	0.044	0.258	0.272
Peace/Boreal Transition	683	31569	0.513	0.090	0.272	0.284
Peace/Boreal Transition	684	195775	0.400	0.042	0.521	0.373
Peace/Boreal Transition	686	16125	0.406	0.064	0.453	0.458
Peace/Boreal Transition	687	140254	0.534	0.080	0.229	0.303
Peace/Boreal Transition	688	58590	0.510	0.105	0.234	0.306
Peace/Boreal Transition	692	80908	0.338	0.044	0.586	0.258
Peace/Boreal Transition	703	106615	0.416	0.024	0.517	0.291
Peace/Boreal Transition	708	114496	0.366	0.032	0.570	0.334
Aspen Parkland	727	434302	0.558	0.043	0.239	0.311
Aspen Parkland	728	254289	0.632	0.072	0.079	0.230
Aspen Parkland	729	136085	0.633	0.116	0.068	0.207
Aspen Parkland	730	511637	0.639	0.107	0.080	0.207
Aspen Parkland	731	486775	0.603	0.073	0.115	0.255
Aspen Parkland	732	35711	0.459	0.051	0.413	0.357
Aspen Parkland	737	197626	0.621	0.023	0.265	0.250
Aspen Parkland	738	159734	0.661	0.089	0.031	0.216
Aspen Parkland	739	68021	0.618	0.114	0.182	0.223
Aspen Parkland	740	171708	0.610	0.057	0.164	0.281
Aspen Parkland	743	104000	0.573	0.251	0.072	0.158
Aspen Parkland	744	211215	0.657	0.053	0.142	0.229
Aspen Parkland	746	155674	0.649	0.043	0.214	0.217
Aspen Parkland	750	103823	0.429	0.134	0.397	0.246
Moist Mixed Grass	769	161280	0.544	0.166	0.149	0.236
Moist Mixed Grass	771	103919	0.608	0.194	0.120	0.160
Moist Mixed Grass	779	62649	0.489	0.266	0.150	0.214
Moist Mixed Grass	781	228287	0.622	0.215	0.022	0.137
Moist Mixed Grass	786	88816	0.541	0.241	0.064	0.193

Appendix 6 continued

Ecoregion	Ecodistrict	Area*	Proportion of area in crop type			
			Cereal	Fallow	Forage	Oilseed
Moist Mixed Grass	787	140949	0.535	0.366	0.014	0.088
Moist Mixed Grass	788	71923	0.626	0.204	0.028	0.155
Moist Mixed Grass	790	46476	0.628	0.217	0.064	0.132
Moist Mixed Grass	791	166003	0.553	0.306	0.027	0.123
Moist Mixed Grass	793	507591	0.671	0.113	0.082	0.171
Moist Mixed Grass	797	27504	0.625	0.180	0.124	0.147
Fescue	798	472213	0.695	0.081	0.094	0.185
Fescue	799	32854	0.626	0.057	0.279	0.223
Fescue	800	155934	0.727	0.048	0.104	0.194
Fescue	801	38173	0.457	0.058	0.429	0.398
Mixed Grassland	804	58514	0.494	0.323	0.129	0.151
Mixed Grassland	805	16773	0.513	0.378	0.053	0.089
Mixed Grassland	806	118028	0.459	0.317	0.186	0.166
Mixed Grassland	809	141611	0.487	0.408	0.064	0.073
Mixed Grassland	811	48569	0.503	0.446	0.008	0.024
Mixed Grassland	812	98055	0.487	0.112	0.279	0.269
Mixed Grassland	814	19407	0.498	0.397	0.090	0.028
Mixed Grassland	815	64508	0.496	0.309	0.113	0.128
Mixed Grassland	818	25953	0.547	0.181	0.229	0.169
Mixed Grassland	821	77135	0.527	0.402	0.034	0.031
Mixed Grassland	823	118866	0.571	0.251	0.072	0.101
Mixed Grassland	828	586949	0.567	0.274	0.037	0.102
Mixed Grassland	829	35447	0.504	0.122	0.129	0.154
Mixed Grassland	833	18450	0.503	0.385	0.062	0.059
Mixed Grassland	836	10931	0.504	0.214	0.143	0.226
Fescue	837	36289	0.612	0.188	0.113	0.171
Fescue	838	31823	0.461	0.189	0.262	0.223

* Area is the proportion of the cultivated area analyzed (i.e. upper + middle + lower slope positions; depressional areas are omitted)

Appendix 7: Gross CO_2 emission rate (kg CO_2 ha^{-1} y^{-1}), net change in C, and addition of C for each Ecodistrict in Alberta's agricultural area

	Conventional Tillage (kg CO_2 ha^{-1} y^{-1})			Zero Tillage (kg CO_2 ha^{-1} y^{-1})		
Ecodistrict	**Gross CO_2**	**Net C**	**Addition C**	**Gross CO_2**	**Net C**	**Addition C**
586	-2633	1716	4349	-2237	2071	4309
587	-2138	1454	3592	-1816	1754	3570
588	-3365	987	4352	-2857	1470	4327
590	-4272	875	5147	-3626	1491	5118
591	-3503	977	4480	-2974	1480	4455
592	-4348	624	4972	-3690	1254	4944
593	-2821	1828	4648	-2397	2224	4620
594	-3422	1359	4782	-2906	1847	4754
595	-3510	1443	4953	-2981	1943	4924
596	-3849	1158	5007	-3268	1710	4978
597	-5881	-645	5235	-4989	219	5209
598	-3746	978	4724	-3180	1517	4697
599	-4683	-17	4666	-3974	668	4641
600	-3800	1910	5710	-3228	2448	5676
678	-5335	272	5607	-4528	1049	5577
679	-3758	2551	6309	-3193	3077	6270
680	-5100	711	5811	-4329	1449	5778
681	-4235	1341	5576	-3596	1947	5543
683	-3841	1461	5303	-3262	2010	5272
684	-5502	724	6225	-4670	1521	6191
686	-4051	2153	6204	-3441	2726	6167
687	-3908	1359	5267	-3319	1918	5237
688	-3790	1378	5168	-3219	1919	5138
692	-4862	730	5592	-4125	1464	5589
703	-5508	502	6010	-4675	1303	5977
708	-5563	581	6144	-4721	1389	6110
727	-6021	-794	5226	-5584	-372	5212
728	-4737	16	4753	-4394	345	4739
729	-4528	101	4629	-4200	415	4615
730	-4424	280	4705	-4105	586	4690
731	-5413	-599	4814	-5020	-220	4800
732	-5610	-120	5491	-5204	270	5474
737	-5644	-195	5449	-5236	197	5433
738	-3901	790	4691	-3619	1057	4676
739	-4109	926	5034	-3812	1206	5018
740	-4754	389	5143	-4410	717	5127
743	-3123	1005	4129	-2899	1216	4115
744	-4873	249	5122	-4521	586	5107
746	-6176	-883	5293	-5728	-449	5278
750	-6996	-2173	4823	-6487	-1676	4811
769	-5463	-104	5359	-4795	531	5326
771	-4010	1271	5281	-3524	1720	5244
779	-4415	504	4918	-3877	1009	4886
781	-5519	-831	4687	-4841	-182	4660

Appendix 7 continued

	Conventional Tillage ($kg\ CO_2\ ha^{-1}\ y^{-1}$)			Zero Tillage ($kg\ CO_2\ ha^{-1}\ y^{-1}$)		
Ecodistrict	**Gross CO_2**	**Net C**	**Addition C**	**Gross CO_2**	**Net C**	**Addition C**
786	-4323	345	4668	-3796	842	4638
787	-3444	444	3889	-3025	838	3863
788	-4168	678	4846	-3661	1153	4814
790	-5380	-799	4581	-4720	-166	4554
791	-3862	365	4227	-3391	808	4199
793	-3751	1769	5519	-3298	2182	5480
797	-3202	2163	5365	-2818	2508	5326
798	-4723	967	5690	-4383	1289	5672
799	-3759	1745	5504	-3489	1996	5485
800	-4790	1198	5987	-4445	1523	5968
801	-2121	326	2448	-1968	472	2440
804	-5066	-506	4559	-4472	59	4532
805	-2674	870	3544	-2365	1154	3519
806	-6118	-1339	4779	-5399	-647	4752
809	-3327	-43	3284	-2939	325	3264
811	-3201	-47	3154	-2827	308	3134
812	-4210	1915	6125	-3725	2356	6081
814	-2595	353	2948	-2293	636	2928
815	-5236	-900	4336	-4621	-310	4311
818	-4292	1320	5612	-3795	1778	5573
821	-2463	1048	3511	-2179	1307	3486
823	-3229	1167	4396	-2856	1509	4365
828	-3415	747	4162	-3019	1115	4134
829	-2906	888	3794	-2569	1198	3767
833	-3071	289	3360	-2714	625	3338
836	-1161	96	1257	-1026	223	1249
837	-2008	1820	3828	-1865	1949	3814
838	-3669	1692	5362	-3406	1938	5344

Appendix 8: Gross N_2O (Mg N_2O y^{-1}) emission from each module for each Ecodistrict in Alberta's agricultural area

	N_2O Emission (Mg N_2O y^{-1})			
Ecodistrict	**Soil Module**	**Crop Module**	**Fertilizer Module**	**Total**
586	115	305	0.069	420
587	80	51	0.013	131
588	47	179	0.040	226
590	204	229	0.043	434
591	157	215	0.047	372
592	219	418	0.089	637
593	131	118	0.026	249
594	119	129	0.026	248
595	331	91	0.019	422
596	151	257	0.064	408
597	150	116	0.025	266
598	172	122	0.029	294
599	322	95	0.023	416
600	34	18	0.004	52
678	326	566	0.122	892
679	654	180	0.043	834
680	270	263	0.059	533
681	96	155	0.034	251
683	258	129	0.027	387
684	346	588	0.090	934
686	131	148	0.029	278
687	60	50	0.011	110
688	229	136	0.026	365
692	141	317	0.037	459
703	207	315	0.047	522
708	202	342	0.045	544
727	195	369	0.098	563
728	222	194	0.046	417
729	187	175	0.038	362
730	467	562	0.125	1030
731	248	564	0.133	812
732	264	95	0.020	359
737	249	229	0.057	479
738	137	156	0.039	293
739	905	195	0.038	1100
740	210	273	0.061	484
743	257	73	0.014	330
744	426	266	0.066	692
746	509	183	0.045	692
750	264	288	0.056	553
769	257	188	0.031	445
771	315	232	0.033	548
779	220	66	0.008	287
781	144	198	0.038	341
786	256	40	0.006	296

Appendix 8 continued

Ecodistrict	N_2O Emission (Mg N_2O y^{-1}) Soil Module	Crop Module	Fertilizer Module	Total
787	246	67	0.025	313
788	188	47	0.014	235
790	188	51	0.023	239
791	459	99	0.024	558
793	265	544	0.266	809
797	125	94	0.016	219
798	411	430	0.109	841
799	530	145	0.019	675
800	254	214	0.065	469
801	302	263	0.022	565
804	178	128	0.017	306
805	61	9	0.000	70
806	242	300	0.073	542
809	135	122	0.019	257
811	109	29	0.002	139
812	138	355	0.259	493
814	282	142	0.000	424
815	183	306	0.084	490
818	97	116	0.000	213
821	265	201	0.016	466
823	166	231	0.152	397
828	320	811	0.437	1131
829	144	90	0.074	234
833	138	194	0.039	332
836	127	8	0.000	136
837	143	23	0.004	166
838	183	143	0.033	325
Mean	233	209	0.053	442
Minimum	34	8	0.000	52
Maximum	905	811	0.437	1131
Sum	16767	15038	3.831	31809