CANB v4.0: A Model for Simulating Residual Soil Nitrogen and Nitrogen Leaching in Canadian Regional Scale

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Abstract: A Canadian Agricultural Nitrogen Budget model (CANB v4.0) was developed to calculate two Agri-environmental Indicators; Residual Soil Nitrogen (RSN) and the Indicator of Risk of Water Contamination by Nitrogen (IROWC-N) at 1:1M Soil Landscape of Canada scale for all Canadian farmland. The RSN (kg N ha^{-1}) is the amount of inorganic N which remains in the soil at the end of the growing season and it is calculated as the difference between the total inputs of N and removal of N by the crop and atmospheric losses. The IROWC-N provides an estimate of the concentration and amount of the RSN which can be lost due to surface and groundwater via leaching. Both the growing season and non-growing season N leaching losses were simulated by a daily N leaching model. The outputs are displayed using EasyGrapher software and mapped using Arc-GIS software. The Ecoregion maps and graphs of the RSN, N lost and IROWCN from the CANB v4.0 model were displayed and the results were interpreted. The results indicate that there is an increasing risk of water contamination over time in Canadian farmland. The model can also be used for policy scenario analysis or integrated into a GIS framework at watershed scales.

1 INTRODUCTION

Nitrogen losses to air and water from agricultural practices are important issues affecting global environmental health. For example, N_2O emissions from agricultural systems account for 50% of global greenhouse gases (Rochette et al., 2008) and NH_3 emissions from the soil are involved in the formation of the PM2.5 (Sheppard et al., 2010). NO_3, on the other hand, is easily removed with run off and leaching water to surface and groundwater bodies, affecting human and animal health (Drury et al., 2007). To reduce NOx emissions and leaching losses in agricultural production systems, we need to understand and manage the annual nitrogen cycle as shown in Figure 1. N input to farmland is mainly from inorganic N fertilizers, manures, legume N_2 fixation and atmosphere N deposition. N output from farmland is mainly by N removal in harvested crops, from ammonia volatilization, from denitrificaiton (N_2, N_2O, NO), as well as from NO_3-N leaching (Figure 1). Field research or field modeling on these processes has been conducted for decades, but regional and national estimates of the nitrogen cycle in agricultural systems is still a challenge due to incomplete data sets and the requirement for developing a larger scale model.

Models of the nitrogen cycle in a larger agricultural system have been made during last two decades using survey or census database. For example, the Organization of Economic Cooperation and Development (OECD) developed a series of environmental indicators (OECD 2008), including the residual soil N indicator. These larger scale indicators/models show increasing importance in assessing environmental health as affected by the agricultural N cycle.

In Canada, a nationwide Agro-environmental indicator program has been carried out over the last 15 years to develop regional and national water quality policies (Eilers et al., 2010). For this reason, a Canadian Agricultural Nitrogen Budget (CANB)

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model has been developed to estimate two nitrogen indicators; (1) the residual soil nitrogen (RSN) and (2) the indicator of risk of water contamination by nitrogen (IROWC-N), at the Soil and Landscapes of Canada (SLC) 1:1M scale.

During the last 10 years, the CANB model has been updated on a regular basis as new information and data have become available. The CANB v1.0 to v3.0 models were integrated with a Canadian Regional Agricultural Model for policy scenario analysis (Yang et al., 2007ab; 2011; 2013). A graphic interface program, EasyGrapher, was also developed to support visualization of the CANB outputs (Yang et al., 2014).

Recently, the CANB v4.0 model have just been updated (methods, parameters) with new databases of 2011 agricultural census data, N deposition, N_2O emission rates and 10 by 10 grid daily weather data at various scales, representing the state-of-the-art of larger scale soil N model in Canada. Although the CANB (v1.0-v3.0) model's results have been reported at the SLC, province and Canada scales (De Jong et al., 2009; Yang et al., 2010, 2013), they were never reported in ecoregional scales (ecodistrict, ecoregion and ecozone). The objective of this paper focuses on reporting the CANB v4.0 model's design, I/O structure, scaling up and data visualization methods. The temporal changes of RSN and N leaching during 1985-2010 will be illustrated at the Ecoregion- an inter-mediate scale in Canada's ecological classification framework.

2 PROGRAM DESIGN

The CANB model is written using Intel Fortran compiler. The graphic support software, EasyGrapher, is written using MS Visual Studio NET which is linked with MS Excel (Yang et al., 2014). Arc GIS v10 is used for mapping the model outputs. The CANB program can be run under various computer Windows systems. The following sections describe the CANB input/output data and structure.

2.1 Soil Landscapes of Canada (SLC)

The SLCs are a series of GIS coverage at a 1:1 million scale organized by a uniform national soil and landscape criteria based on permanent natural attributes for the whole SLC polygons (http://sis.agr.gc.ca/cansis) (Soil Landscapes of Canada Working Group, 2005). In Canadian ecosystem framework, the SLC v3.x polygons are the most detailed spatial entities within the ecological framework (http://sis.agr.gc.ca/cansis/nsdb/ecostrat/index.html), including a nested hierarchy of 15 Ecozones (i.e., each color represent an ecozone in Figure 2), 194 Ecoregions (i.e., curved lines are boundaries of ecoregions within ecozones in Figure 2), 1027 Ecodistricts (nested within Ecoregions) and 12353 SLC polygons (nested within Ecordistrict) (Table 1).

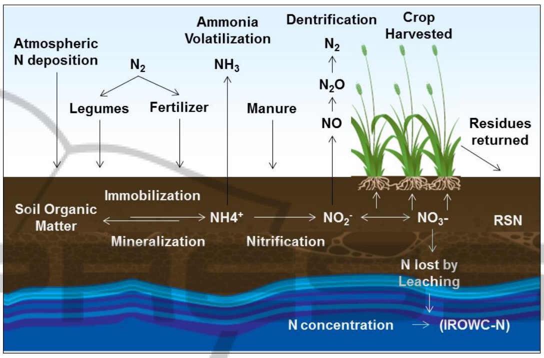

Figure 1: Conceptual view of the nitrogen cycle in agricultural soils. Residual soil nitrogen (RSN) is the amount of inorganic N remaining in the soil after harvest. IROWC-N is the estimate of the amount of RSN which leaches from the agricultural soils.

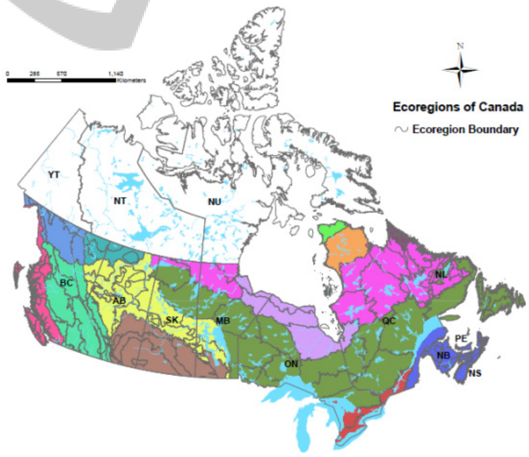

Figure 2: Canada Ecoregions - subdivisions of the ecozones characterized by distinctive regional ecological factors, including climate, physiography, vegetation, soil. Water, fauna and land use.

The names of Canada province (Figure 2) in this paper were coded as follows: BC: British Columbia, AB: Alberta, SK: Saskatchewan, MB: Manitoba, ON: Ontario, QC: Quebec, NB: New Brunswick, NS: Nova Scotia, PE: Prince Edward Island, NL: Newfoundland and Labrador. NT: Northwest Territories, YT: Yukon Territory and NU: Nunavut.

Over the last 15 years, the SLC v3.x has also compiled with agricultural census database (every five year) and national climate data (every year) for use by the National Agri-Environmental Health Analysis and Reporting Program (Eilers et al., 2010), the National Carbon and Greenhouse Gas Emission Accounting and Verification System and other related national programs.

2.2 Input Data and Collection

The CANB program requires input data from various scales. (1) The SLC scale datasets that are geographically located in 3247-3345 Soil Landscapes of Canada 1:1M polygons (Soil Landscapes of Canada Working Group, 2005). These include crop area, animal numbers and crop managements that come from the census of agriculture every five years (Table 1). Canadian Soil Information Service (http://sis.agr.gc.ca/cansis) provides the SLC v3.2 mapping framework, soil classification, and profile data. (2) Daily weather data (1980-2012) were obtained from Canadian weather framework, and was allocated to each SLC to drive the water balance model to estimate soil N loss over both growing and non-growing seasons (De Jong et al., 2009). (3) Data that are collected at the provincial scale include industrial fertilizer sales (CFI, 2006), annual crop yields from Statistics Canada (2003), fertilizer N application rates from provincial agronomic recommendations and manure storage and management methods from Farm survey (Yang et al., 2011). (4) Data from the Canada scale include average N fixation rates and animal N excretion rates (Yang et al., 2007a).

2.3 CANB Model Structure

The CANB v4.0 model's data are structured into data folders as illustrated in Figure 3. First the model reads input data from their files and folders. Then the CANB calculates the RSN and N lost to leaching at the SLC polygon level from 1981 to 2011. The outputs are either saved as text files or scaled-up from the SLC level to the eco-regional scale (Figure 3). The output data are displayed either graphically or as data sheets. The required maps for the CANB output are mapped by the Are GIS software. The detailed module links and I/O data flow in the CANB model can be seen from Figure 3.

2.4 RSN Module

Residual Soil Nitrogen (kg N ha^{-1}) is calculated as the difference between the total N input into soil (N_{input}) minus the total N output (N_{output}) for each hectare of farmland (Farmarea) at the end of the growing season. Detailed descriptions on N input and N output equations were given in our previous publications (De Jong et al., 2009; Yang et al., 2007a, 2010; 2011; 2013) In this paper, for easy illustration purpose, we present following basic equations 1-3 as below. For each of the 3247 to 3345 soil polygons from 1981 to 2011, the RSN is calculated by:

$$RSN = (N_{input} - N_{output})/Farmarea \tag{1}$$

$$N_{input} = N_{fert} + N_{man} + N_{fix} + N_{depo} \tag{2}$$

$$N_{output} = N_{crop} + N_2O + NH_3 \tag{3}$$

where all N components in Eqs (2) and (3) are expressed as kg N SLC^{-1}. N_{fert} is the total amount of inorganic N from fertilizer applied; N_{man} is the amount of available inorganic N from manure applied to crops and pasture after N losses, plus the amount of N mineralized from the organic manure that was applied in the previous 3 years; N_{fix} is the amount of N fixed by leguminous crops after subtracting legume residue N being carried over to the next year, plus the amount of N mineralized from legume residue and roots remaining from the previous 3 years; N_{depo} is the amount of wet and dry deposition of atmospheric N;. N_{crop} is the amount of N removed in the harvested portion of crops and pasture, N_2O is the amounts of greenhouse gas lost to the atmosphere and NH_3 is the amounts of ammonia N gas lost to the atmosphere.

2.5 IROWC-N Module

The IROWC-N module calculates N lost by leaching and N concentration in the leached water based on salt leaching concepts (De Jong et al., 2009). The IROWC-N module first takes the RSN from the CANB model as an input. The amount of N leaching from the soil in the drainage water during the non-growing season $N_{lostNGS}$ and growing season N_{lostGS} (kg N ha^{-1}) was simulated as shown in Figure 4.

The N concentration in the non-growing season ($N_{concNGS}$) (mg N L^{-1}) and growing season (N_{concGS}) (mg N L^{-1}) were then calculated using the cumulative drainage water volumes in the growing and non-growing seasons. These were simulated using a modified daily Versatile Soil Moisture Budget model (Baier et al., 1979) which was integrated into the IROWC-N module using daily weather datasets across Canadian farmland (De Jong et al., 2009).

Table 1: List of CANB v4.0 Inputs, output datasets, variables and numbers of locations from 1981 to 2011.

CANB I/O data	Variable	No. of agricultural polygons
Inputs		
Crop area for 27 crop types	27	3247-3345
Animal numbers for 21 animal types	21	3247-3345
Fertilizer N for 27 crop types	27	3247-3345
Manure N for 27 crop types	27	3247-3345
N fixation for 27 crop types	27	3247-3345
Atmosphere wet and dry N deposition	3	3247-3345
N mineralization from legumes and manure	4	3247-3345
Crop yield for 27 crop types	27	3247-3345
N uptake for 27 crop types	27	3247-3345
N2O, N2, NH3-N emissions	3	3247-3345
Outputs		
RSN and N components	15	3247-3345
N lost (summer, winter & annual)	3	2780
N concentration in leached water	3	2780
Drainage (summer, winter & annual)	3	2780
Scale up output		
SLC (total of 12353)	>20	3247-3345
Eco-district (total of 1027)	>20	377
Eco-region (total of 194)	>20	68
Eco-zone (total of 15)	>20	8
Province	>20	10
Canada	>20	1

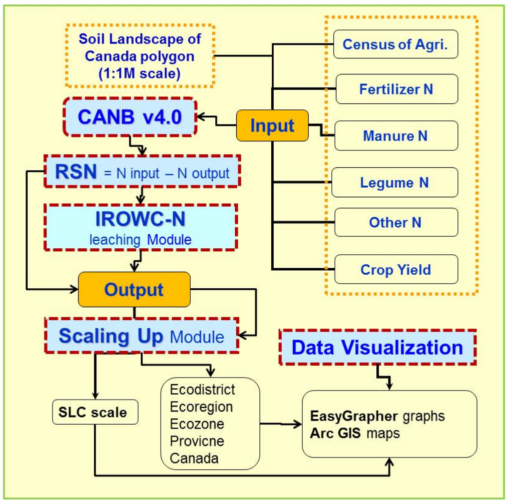

Figure 3: Flow chart of the Canadian Agricultural Nitrogen Budget (CANB) v4.0 model.

2.6 RSN and IROWC-N class

For mapping and result interpretation purposes, the RSN result is grouped into 5 classes; 0-9.9 (very low), 10-19.9 (low), 20-29.9 (medium), 30-39.9 (high) and ≥40 (very high) in kg N ha^{-1} farmland. The water contamination indicator, IROWC-N, is classified to 5 risk classes based on combination of N lost and N concentration (Table 2) (De Jong et al 2007).

Table 2: The IROWC-N classification.

Annual N lost (kg N/ha)	Annual N concentration (mg of N/L)		
	0-4.9	5.0-9.9	≥10.0
0-4.9	Very low	Very low	low
5.0-9.9	Very low	low	moderate
10.0-19.9	low	moderate	high
≥20.0	Moderate	high	very high

2.7 Scaling up Module

The RSN, N lost (N_{lostGS} and $N_{lostNGS}$) and N concentration (N_{concGS} and $N_{concNGS}$) values were scaled up from the SLC 1:1M scale to the Ecodistrict, Ecoregion, Ecozone, provincial and national scales using the farmland area weighted averages developed as Yang et al. (2007a).

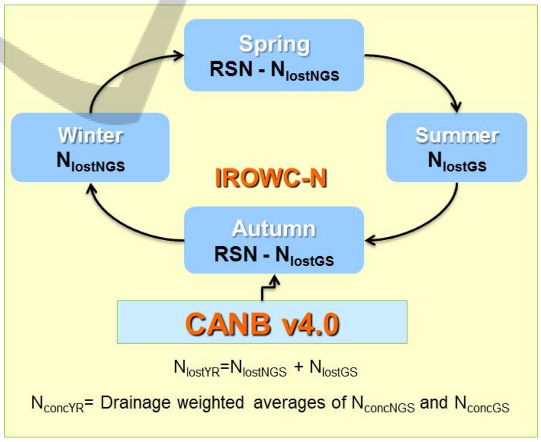

Figure 4: Data flow for N lost and N concentration in the leached water over the non-growing, growing seasons.

3 DATA VISUALIZATION

3.1 Maps at the Ecoregional Scales

Maps of the CANB outputs are produced using Arc GIS Map software and can be made at any ecological scales of SLC, Ecodistrict, Ecoregion and Ecozone. As examples, the RSN class in 1985 and 2010 and the IROWC-N risk classes for the same years are mapped in Figure 5 and Figure 6.

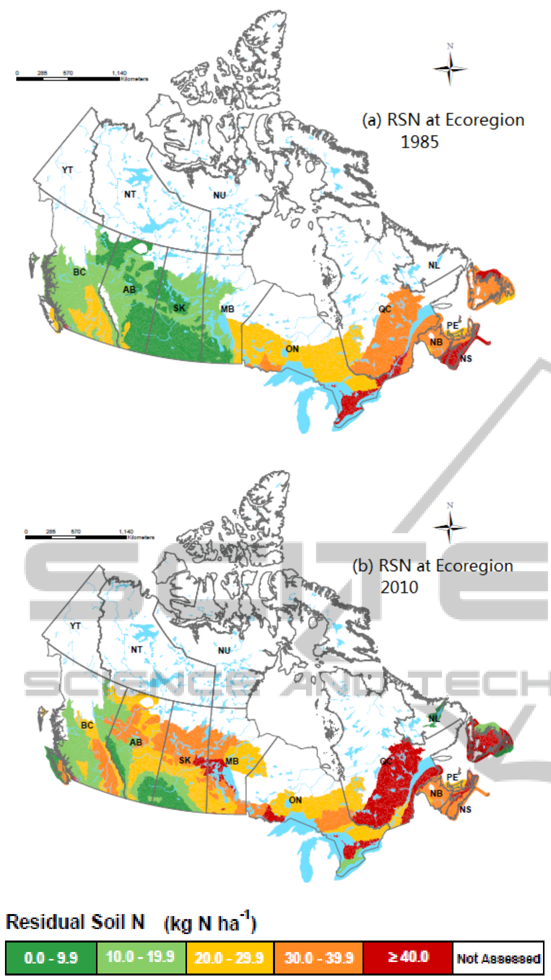

Figure 5: Residual Soil N (RSN) levels on Canadian Ecoregion in 1985 (a), and 2010 (b).

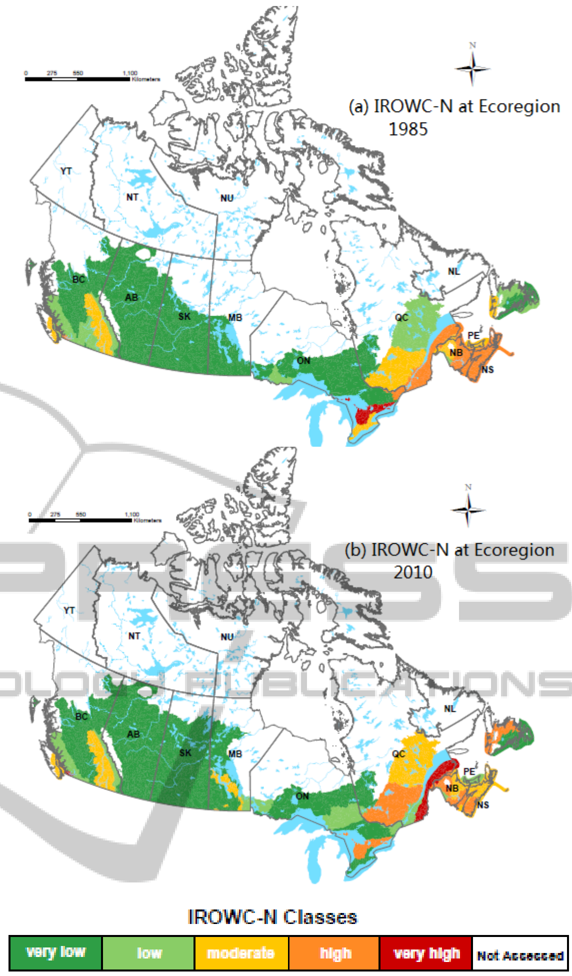

Figure 6: Indicator of Risk of Water Contamination by Nitrogen (IROWC-N) risk class on Canadian Ecoregion in 1985 (a), and 2010 (b).

3.2 Data Handling

The CANBv4.0 input and output files (more than 500) are saved as text files at various scales (Figure 3). To analyze these data efficiently, we have developed two supporting programs to handle and visualize the CANB outputs: EasyFormatter and EasyGrapher, using the MS Visual Basic NET. The EasyFormatter was designed to transfer the CANB output files to Microsoft Excel, then save as the Excel data file. For example, there are 31 files named 1981RSN.out to 2011RSN.out, dealing with yearly data for the ~3400 SLC polygons. Each file has a data matrix of >3000 records and up to 50 variables. The program can transfer these 31 files to a single MS Excel file with different sheets within seconds. This way, the data can be viewed and analyzed with MS Excel and Access easily.

3.3 Graph

Similarly, the EasyGrapher software was designed to automatically graph the CANB's outputs (Yang et al., 2014). It first transfers CANB's output into MS Excel sheets, and then automatically performs a series of graphical tasks. The bar graphs are generated for all output variables within 30 seconds for each CANB output file. The trend and variation of each variable (Y axis) against their ecoregions (X axis) are displayed in the output graphs. EasyGrapher can plot graphs on CANB output at all scales listed in Table 1. Examples of graphs at the Ecoregion are shown in Figures 7-9. Detailed descriptions on EasyGrapher software can be read from our previous publications (Yang and Huffman, 2004, Yang et al., 2014))

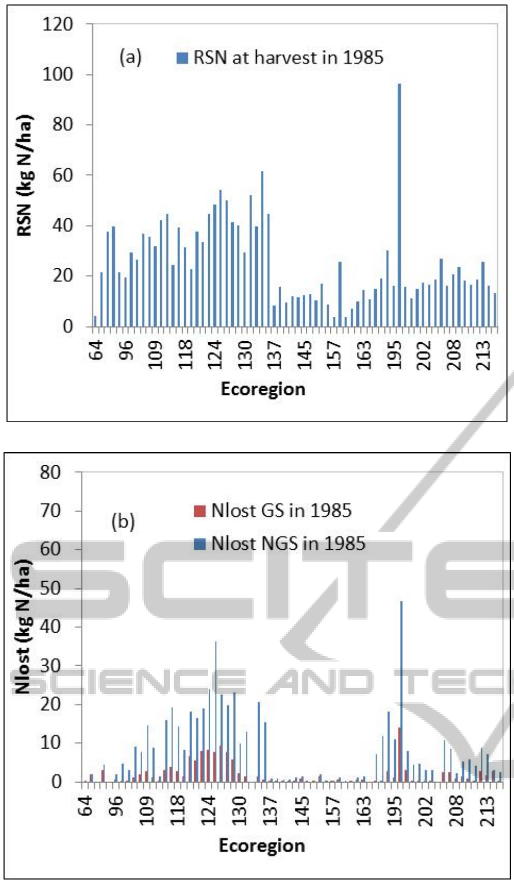

Figure 7: RSN at harvest (a), growing and non-growing season N lost (b) and drainage (c) at the Canada Ecoregion in 1985.

4 RESULTS INTERPRETATION

This section is to show how the map and figures are interpreted but not a completed results and discussion.

4.1 RSN and IROWC-N Risk Classes at Ecoregion

The RSN distribution maps at the Ecoregion (Figures 5) showed significant regional differences in RSN. In 1985, the RSN level was lower in the Western provinces (British Columbia, Alberta, Saskatchewan and Manitoba) but it was high in Central (Ontario, Quebec) and Eastern Canada (Figure 5a). It was also observed that RSN risk classes generally increased from low to high risk classes over a 25 year time especially in Manitoba, Ontario, Quebec and Eastern Canada (Figure 5b).

Similar regional differences were found for the IROWC-N class distribution (Figure 6). The IROWC-N classes were in the very low and low classes in Western Canada except a moderate zone in British Columbia. Most farmland in Central and Eastern Canada showed moderate, high and very high IROWC-N classes (Figure 6). In Central and Eastern Canada, IROWC-N classes were shafted from low, moderate in 1985 (Figure 6a) to moderate, high and very high classes in 2010 during a 25 year period (Figure 6b).

4.2 N Lost at the Ecoregion

In 1985 the RSN values were higher (> 20 kg N ha^{-1}) in Ecoregions 64-135 compared with the RSN values (<20 kg N ha^{-1}) in Ecoregions 137-213, except in Ecoregion 196 where the RSN was extremely high (48.5 kg N ha^{-1}) (Figure 7a). The N leaching loss was higher in Ecoregions 109-135 and 180-200 (Figure 7b) because the drainage water was higher in these regions (data not shown).

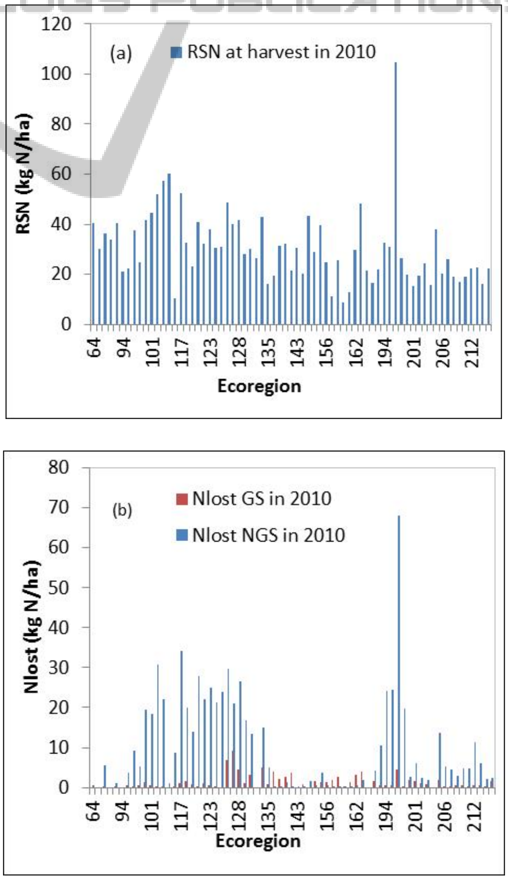

Figure 8: RSN at harvest (a) and growing and non-growing season N lost (b) at the Canada Ecoregion in 2010.

In 2010, the RSN levels were more than 20 kg N ha^{-1} in most of the Ecoregions (Figure 8a) and the N lost levels increased (Figure 8b) compared with 1985, driven by both higher RSN and higher drainage levels in 2010 (data not shown). It was found that N lost in non-growing season was 2-5 times higher than in growing season in both 1985 (Figure 7b) and 2010 (Figure 8b).

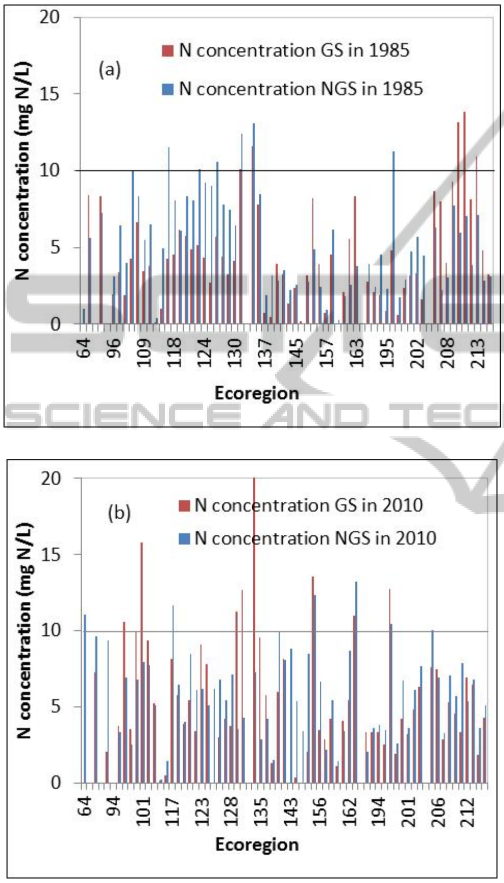

Figure 9: Growing season (GS) and non-growing season (NGS) N concentration at Ecoregion in 1985 (a) and in 2010 (b).

4.3 N Concentration at the Ecoregion

N concentration increased from 0.5-13.8 mg N L^{-1} in 1985 to 0.8-22.4 mg N L^{-1} in 2010 at Ecoregion (Figure 9), showing significant regional difference among Ecoregions. There was an obvious increasing trend of the N concentration in most Ecoregions in 2010 compared with 1985. For example, 5-7 Ecoregions in 1985 showed that N concentrations were above the drinking water guideline of 10 mg N L^{-1} (i.e., horizontal lines in Figure 9a), while 8-10 Ecoregions were shown that N concentration was greater than 10 mg N L^{-1} in 2010 .

4.4 N Input Changes in Canada

N input increased gradually with time, while N output increased slowly, fluctuating with climate conditions (Yang et al., 2013). This fluctuation resulted in the increase of RSN values of 13.4 kg N ha^{-1} from 1985 to 22.3 kg N ha^{-1} in 2010.

The quick increase of N input was attributed to the increased use of N fertilizer and legume N fixation, while manure N and N deposition were fairly constant over the last 25 year period (Yang et al., 2013).

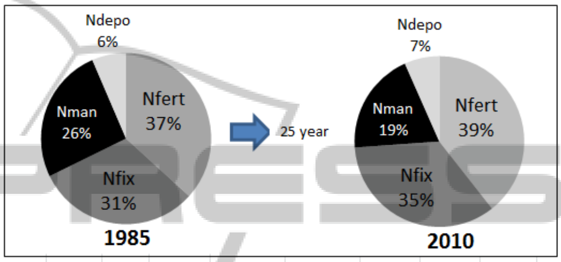

Figure 10: Percentage of fertilizer N (N_{fert}), N fixation (N_{fix}), manure N (N_{man}) and N deposition (N_{depo}) in N input in 1985 and 2010.

In summary, fertilizer N contributed 37-39% of total N input, and N fixation accounted for 31-35%. Manure N (19-26%) and N deposition (6-7%) contributed small percentages of total N input compared with fertilizer N and N fixation (Figure 10).

5 CONCLUSSIONS

RSN and the risk of N loss through leaching were successfully simulated by the Canadian Agricultural Nitrogen Budget model from 1981 to 2011 for Canadian farmland at the Soil Landscapes of Canada 1:1 million scale.

Increasing trends of both the RSN and IROWC-N indicators were significant during a 25 year period in Canadian farmland as shown by Ecoregion maps. We concluded that the Ecoregion maps of N indicators are at a suitable ecological scale for presenting the results to public users, such as citizen and students at school and universities because the detailed SLC map of the RSN and IROWC-N indicators are designed for specialists, consultant, researchers and policy makers, and difficult to interpret. Increases in RSN values were found from Western to Eastern Canada. In Western region except BC, the RSN increased from Southern to

Northern regions.

Graphic display of the RSN and N loss values at Canada Ecoregion provided quantitative visualization of which Ecoregions the RSN and N lost levels were high and we concluded that high N input resulted in high RSN, and high N lost was driven by both high N input and high precipitation and drainage in a given ecoregion. The increased RSN values were mainly due to the continuous increase of N input from fertilizer, manure and biological N fixation compared to moderate increases in N uptake by crop yields. Farm management response options should be established to reduce nitrate N leaching in higher risk regions, such as reducing livestock numbers, matching fertilizer N to crop requirements etc.

The principle of the CANB v4.0 program can be applicable to other regional scales, such as watershed, forestry, urban areas or other countries for estimating the amount of surplus N entering into ecosystem, environment or human food chain.

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