Residual Soil Nitrogen

Agri-Environmental Indicators Report

The Environmental Sustainability of Canadian Agriculture

Census Year 2021




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Residual Soil Nitrogen
Agri-Environmental Indicators Report, Census Year 2021

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The issue and why it matters

There has been increasing awareness of the environmental impacts associated with inorganic nitrogen (N) losses including ammonia volatilization, nitrous oxide and dinitrogen emissions, and nitrate leaching from agricultural soils and the need to mitigate these impacts while ensuring food security. Nitrogen is an essential nutrient required for crop production (crops can use either ammonium (NH_4^+) or nitrate (NO_3^-)), and nitrogen can be added to soils by using synthetic nitrogen fertilizers, manures or by growing legume crops that can fix nitrogen from the air making it plant available. However, nitrogen use and transformations in soils for field crop production is by nature very “leaky” as external factors including weather can result in nitrogen (nitrate) leaching through the soil profile and out of the crop root zone when excess rains or snowmelt occurs (Woodley et al. 2018). Nitrogen can also be lost to the air through ammonia volatilization following N application if nitrogen from urea-based fertilizers or manure are not incorporated into the soil (e.g., injection) or if the fertilizers are not used in combination with an enhanced efficiency product that can reduce ammonia volatilization losses (Drury et al. 2017; Woodley et al. 2020, Drury et al., 2024). Nitrate, a form of inorganic nitrogen available to plants, can also be lost in gaseous forms (nitrous oxide and dinitrogen) if the soil becomes very wet following large rain events and the soil oxygen levels decrease. When these conditions occur, a microbial process called denitrification can convert plant-available nitrate to nitrous oxide (N_2O), one of the greenhouse gases (GHG) and dinitrogen (N_2) which can escape into the air and be an economic loss and N_2O emissions negatively impacts our environment. Nitrous oxide can deplete the ozone layer in the upper stratosphere and contribute to climate variability and climate change. The diagram of the nitrogen cycle pertaining to field crop production was illustrated in the Agri-Environmental Indicator Report 4 (Drury et al., 2016). Climate change and climate variability could also contribute to losses if excess rain or drought conditions interfere with crop nitrogen uptake. Canada was one of 195 countries that signed an agreement in 2015 to fight climate change and implement strategies that will help reduce temperature increases to less than 2°C (Environment and Climate Change Canada, 2016). The residual soil nitrogen (RSN) indicator can help identify potential regions where nutrient management practiced should be deployed to improve nitrogen balances in Canadian soils.

The RSN indicator was developed to get a better idea of the risk of losing nitrogen from agricultural soils by estimating the amount of N remaining in the soil at the end of the growing season (Drury et al., 2007). We used a mass balance approach (N input = N output + RSN) using census information (annual crop and livestock databases), crop yields, soil properties and a Canadian Agricultural Nitrogen Budget – Reactive N (CANBNr) model to account for all of the N inputs (fertilizers, manures, N fixation by legume crops and atmospheric deposition) as well as N outputs (crop nitrogen uptake, ammonia volatilization and growing season nitrous oxide emissions) to determine how much nitrogen is left over at the end of the cropping season that could potentially be lost before the next crop is planted. We estimated annual N inputs and N outputs on a regional, provincial and national basis from 1981 to 2021. This information will help us identify which regions have a high risk of having residual inorganic nitrogen remaining in the soil after crops are harvested and which regions have a low risk so that appropriate beneficial management practices (BMP) can be targeted especially in the high and very high risk areas. The RSN indicator also has temporal and spatial components, and we can examine changes and potentially identify trends to this indicator over time (over 40 years) on a regional, provincial or national basis. For example, RSN can be used to see if changes in soil and crop management practices have led to improvements in N utilization with lower risk over time, or conversely if changes in cropping systems and/or climate have led to increases in risk and potential losses over time.

The RSN indicator

The RSN indicator provides an estimate of the leftover inorganic nitrogen remaining in the soil at the end of the cropping season, and it could therefore be considered a nitrogen use efficiency indicator. Ideally, nitrogen application would match crop N uptake and negligible losses would then occur during the growing season with very little N left in the soil after crop harvest. However, this rarely occurs for multiple reasons including climate variability (for example, frequency and intensity of rainfall during the growing season) and soil factors that may limit nitrogen uptake by crops. If nitrogen is applied through fertilizers, manure or the decomposition of a previous legume and a heavy rain occurs before plants can take up the inorganic N from the soil, then N could be lost due to leaching and/or denitrification. Furthermore, if the nitrogen source added to the soil is urea or a urea-ammonium nitrate solution, then during the hydrolysis of the urea to ammonium in soils, some of the N may be lost due to ammonia volatilization into the air (Drury et al., 2017; Woodley et al., 2020). This chemical transformation occurs when the pH surrounding the fertilizer is above a pH of 7, and the loss can be exacerbated if the urea-based fertilizer is impacted by hot and windy conditions. In addition, some N sources may not be fully taken into consideration when adding the manure and/or nitrogen fertilizer to the soil or over-application occurs to account for the aforementioned losses. Nitrogen inputs can carry over from the previous growing season (particularly if the winter/spring period was dry with minimal nitrate leaching or N_2O losses such as in the drier regions of Canada including Saskatchewan and Alberta), so the contribution from a previous summer legume crop or overwinter cover crop may be an additional N input that should be taken into consideration when deciding the crop N requirements. Hence, more N may be available to the crop in excess of the crop’s requirements, which may result in excess RSN at the end of the growing season.

Even if we carefully account for all N inputs, if uncontrollable factors impact crop growth and nitrogen uptake (such as droughts, floods, pests, pathogens, weeds, etc.,) then the crop may not achieve the desired yield potential, which could also result in excess inorganic N remaining in the soil at the end of the growing season.

It should be noted that the methods used to estimate the N input and N output were slightly different in this report as compared to the previous RSN Agri-Environmental Indicator Report (Drury et al., 2016). In the previous report, we considered all N inputs and N outputs to the soil, such as the amount of fertilizer and/or manure-nitrogen that was applied to the soil. Hence, in this scenario, if there were losses of N from ammonia volatilization or denitrification during the storage of the manure, then these were not considered as an input to the soil, and their losses were also not considered as a direct N output. The new version of the model includes additional steps in the process. The manure N produced by all livestock is now considered as an input and N losses during manure storage is now considered in the N output category (Yang et al., 2023, 2024). Therefore, in general, the N inputs and N outputs in this report are greater in number than what was previously reported. Furthermore, there is more information available pertaining to alfalfa as well as improved and unimproved pasture yields than in previous reports. This data, combined with the usage of the Environmental Policy Integrated Climate model (EPIC) model, has provided us with improved estimates of yields and N inputs from alfalfa, improved pastures and unimproved pastures than before (Wang et al., 2021).

The CANBNr model was updated from previous versions of the CANB v4.0 model (Yang et al., 2014; Drury et al., 2016; Yang et al., 2023, 2024). The CANBNr model calculates the amount of RSN remaining in the soil using multiple databases including the Census of Agriculture (COA), the Canadian soil information system (CanSIS), additional N inputs (fertilizer sales), N outputs (crop N uptake, ammonia and nitrous oxide emissions) and N coefficients (for example, N content of various crops and manures). The COA database includes crop types, acreages and yields, as well as livestock types and numbers. The Soil Landscapes of Canada (SLC) v3.2 in the CanSIS database contains information on soil types and landscape properties. The RSN indicator is calculated for each of the 3,487 agricultural Soil Landscape of Canada (SLC) polygons (Soil Landscape of Canada Working Group, 2010). The CANBNr model calculates the RSN for each SLC polygon as follows:

$$N_{input} = N_{fertilizer} + N_{manure} + N_{fixation} + N_{deposition} \quad [1]$$

$$N_{output} = N_{food} + N_{feed} + N_{N2O} + N_{NH3} \quad [2]$$

$$RSN = N_{input} - N_{output} \quad [3]$$

Where $N_{fertilizer}$ is the total amount of fertilizer N applied to crops; N_{manure} is the total amount of manure N produced by livestock; $N_{fixation}$ is the total amount of N fixed by leguminous crops; and $N_{deposition}$ is the amount of wet and dry deposition of atmospheric N. For the N output equation, N_{food} and N_{feed} is the amount of N removed in the harvested portion of crops and pasture; N_{N2O} is the nitrate lost from soil or stored manure as nitrous oxide; and N_{NH3} is the ammonia volatilization losses from fertilizers and manure. Additional model details are reported by Yang et al. (2023, 2024). The N_{N2O} and N_{NH3} losses were obtained from the respective N_2O and NH_3 indicator teams and the losses are described in greater detail in their own chapters and associated technical reports.

An RSN value is considered very low if it falls between 0–9.9 kg N ha^{-1}, low if between 10–19.9 kg N ha^{-1}, moderate if between 20–29.9 kg N ha^{-1}, high if between 30–39.9 kg N ha^{-1} and very high if RSN ≥ 40.0 kg N ha^{-1}.

Limitations

The RSN indicator provides estimates for the amount of inorganic N in the soil after harvest in different soils, regions and climates across Canada. The RSN values were not directly measured as this is not practical on a regional, provincial or national scale. Instead, the data used to predict the amount of RSN in soil is based upon fertilizer nitrogen application to crops and nitrogen sales data, livestock numbers and their typical excretion rates, biological N fixation by leguminous and non-leguminous crop types, and acreages harvested and their corresponding yields. In addition, a comprehensive database that contains the soil and landscape properties associated with agricultural land in Canada was used. Activity data including conservation and nutrient management practices which may reduce NH_3, N_2O, N_2 or NO_3^- leaching losses is not available on regional, provincial or national scales and could not be considered in this report. Nevertheless, the RSN does provide us with information about regions which could be at high risk or at low risk, as well as how the RSN in these regions may have changed over time.

Results and interpretations

Nitrogen inputs varied by province and by time for the census years (every five years) from 1981 to 2021 (Table 1). In 1981, Saskatchewan had the lowest N inputs of all provinces at 23.0 kg N ha^{-1}, which was likely due to the low crop N requirements as many regions were fairly dry, as well as the number of acres that would not have received N as a result of being under fallow (this practice was used in the past as a means of conserving soil moisture). The two other Prairie provinces, Alberta and Manitoba, also had fairly low N inputs of 52.5 and 61.5 kg N ha^{-1}, respectively when compared to British Columbia (107.0 kg N ha^{-1}) as well as the Central and Maritime provinces, which had N inputs ranging from 98.8 to 177.6 kg N ha^{-1} in 1981.

Table 1: N inputs, N outputs and residual soil nitrogen (kg N ha^{-1}) from 1981 to 2021 by census year (every five years).

Class	N input									N output									RSN								
Year	**1981**	**1986**	**1991**	**1996**	**2001**	**2006**	**2011**	**2016**	**2021**	**1981**	**1986**	**1991**	**1996**	**2001**	**2006**	**2011**	**2016**	**2021**	**1981**	**1986**	**1991**	**1996**	**2001**	**2006**	**2011**	**2016**	**2021**
British Columbia	107,0	103,9	104,8	116,8	123,0	121,8	119,7	133,0	149,0	61,4	57,2	58,3	61,7	54,2	63,4	62,5	76,0	58,6	45,7	46,8	46,4	55,0	68,8	58,4	57,2	57,0	90,4
Alberta	52,5	49,6	55,0	65,3	72,6	74,7	82,1	87,8	86,8	43,4	45,5	46,5	48,5	46,9	57,3	61,1	73,2	50,9	9,1	4,1	8,6	16,8	25,7	17,4	21,0	14,6	35,9
Saskatchewan	23,0	27,1	26,2	43,8	51,0	58,4	67,1	81,2	85,9	28,4	34,0	34,5	40,1	34,5	45,3	51,3	64,3	42,7	-5,4	-7,0	-8,4	3,7	16,5	13,1	15,8	16,9	43,1
Manitoba	61,5	79,9	87,4	98,8	107,6	108,1	114,3	138,4	138,0	50,8	59,1	60,4	65,7	62,9	73,9	70,0	98,2	79,7	10,7	20,8	27,1	33,1	44,6	34,2	44,3	40,2	58,3
Ontario	147,5	155,0	152,8	161,3	165,7	169,9	170,3	160,0	183,4	104,8	107,0	110,9	117,0	104,9	137,5	136,1	139,4	150,4	42,8	48,0	42,0	44,3	60,8	32,4	34,3	20,6	33,1
Quebec	139,3	154,5	154,1	166,9	175,0	172,6	180,5	200,4	211,3	98,5	103,5	99,2	116,7	108,2	116,8	120,9	140,5	136,6	40,7	51,0	55,0	50,2	66,8	55,7	59,7	59,9	74,7
New Brunswick	98,8	107,2	111,3	117,9	134,3	134,7	118,2	144,3	168,0	72,3	74,3	71,5	82,1	83,2	83,3	81,1	82,8	85,7	26,5	32,9	39,8	35,8	51,1	51,4	37,2	61,4	82,3
Nova Scotia	109,8	118,5	119,0	137,7	132,3	133,6	121,6	132,1	152,6	76,6	79,5	74,6	99,7	74,9	80,1	79,4	77,9	85,1	33,2	39,0	44,5	38,0	57,4	53,5	42,2	54,1	67,5
Prince Edward Island	102,8	112,7	121,4	140,1	146,5	156,2	130,0	174,3	206,2	75,6	81,1	77,0	94,3	78,6	90,5	95,8	99,5	105,9	27,2	31,6	44,4	45,8	67,9	65,7	34,3	74,8	100,3
Newfoundland and Labrador	177,5	204,0	206,8	219,2	186,6	222,2	209,0	224,1	359,1	95,5	109,3	110,2	137,2	101,2	116,1	113,7	134,0	156,8	82,1	94,7	96,6	82,0	85,4	106,2	95,3	90,1	202,3
Canada	56,3	59,1	60,4	73,9	81,1	85,4	92,2	102,6	107,2	47,3	50,7	51,1	56,2	51,4	63,8	67,3	80,6	63,0	9,1	8,4	9,3	17,7	29,7	21,6	25,0	22,0	44,2

There was an overall near linear increase in N input over time in Canada (Figure 1), although the increase varied by province, with the maximum N inputs occurring in 2021 where they ranged from 85.9 kg N ha^{-1} in Saskatchewan to 359.1 kg N ha^{-1} in Newfoundland and Labrador (Table 1). Nitrogen inputs in Manitoba, Prince Edward Island and Newfoundland and Labrador in 2021 doubled from 1981 to 2021, while N input in Saskatchewan increased by over three times in the 40-year period (from 23.0 in 1981 to 85.9 kg N ha^{-1} in 2021). For all cropland in Canada, average N inputs almost doubled from 56.3 kg N ha^{-1} in 1981 to 107.2 kg N ha^{-1} in 2021. The increases in N inputs over time were due to multiple factors, including: 1) increased nitrogen fertilization in part due to the use of newer higher-yielding varieties with increased crop N requirements; 2) changes in the types of N fertilizers applied (currently the majority of N fertilizers applied in Canada are either granular urea or liquid urea ammonium nitrate, (UAN)); 3) reduced acreages of land under summerfallow in Western Canada; 4) increased acreages and N inputs from legume crops; and 5) changes in the choice of crops grown.

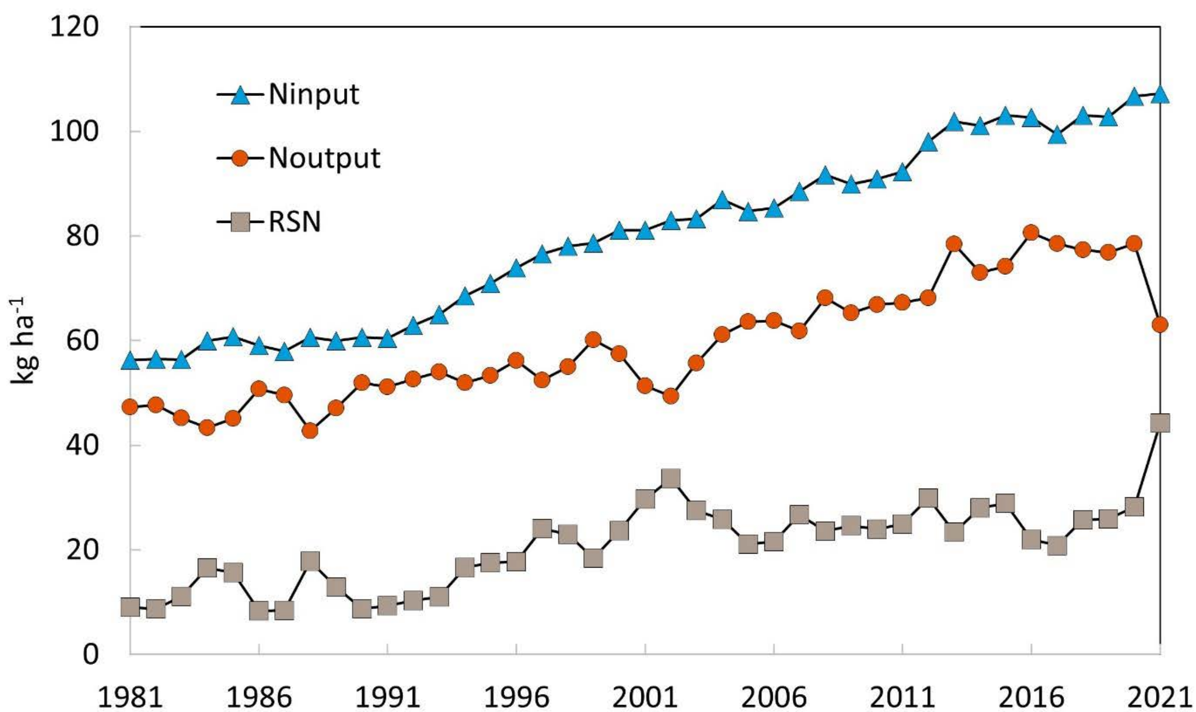


Figure 1: The estimated N input, N output and residual soil N in Canadian soils, 1981 to 2021.

The N outputs in 1981 also varied across provinces and over time, with the lowest N outputs in the Prairie provinces (28.4–50.8 kg N ha^{-1}), intermediate levels in British Columbia (61.4 kg N ha^{-1}) and Atlantic Canada (72.3–95.5 kg N ha^{-1}), and the greatest N outputs were estimated to be in Ontario (104.8 kg N ha^{-1}) and Quebec (98.5 kg N ha^{-1}) (Table 1). Similar to N inputs, the N outputs also increased over time in Canada but the differences between N inputs and N outputs generally increased over time (Figure 1). In 2021, Saskatchewan and Alberta had the lowest N outputs at 42.7 and 50.9 kg N ha^{-1} respectively, whereas Ontario, Quebec and Newfoundland and Labrador had the greatest N outputs at 136.6–156.8 kg N ha^{-1}. In the Prairie provinces, Quebec and British Columbia, the highest N outputs occurred in the 2016 census year, while in other provinces the highest N outputs occurred in 2021, except for Nova Scotia, in which the greatest N output occurred in 1996 (Table 1). The overall N output for Canada increased over time, with 47.3 kg N ha^{-1} in 1981 and the highest N output of 80.6 kg N ha^{-1} in 2016: an increase of 72%, although N outputs decreased to 63.0 kg N ha^{-1} in 2021 due to drought-induced yield decreases in many regions across Canada. The higher N outputs are primarily due to increased crop yields and N uptake as a result of improved farming practices (for example, higher-yielding crop varieties, changes in crop types and distribution, reduced acreages of summerfallow in the Prairies, etc.).

The RSN values are the differences between N inputs and N outputs. Since N inputs increased at a greater rate than N outputs, RSN also increased over time (Figure 1, Table 1). In 1981, the RSN values ranged from 9.1 to 45.7 kg N ha^{-1} in most provinces except Saskatchewan and Newfoundland and Labrador. The RSN in Saskatchewan showed negative values in 1981 to 1991, increased from 3.7 kg N ha^{-1} in 1996 to 16.9 kg N in 2016, and then more than doubled between 2016 and 2021 (43.1 kg N ha^{-1}). In contrast, the RSN in Newfoundland and Labrador remained relatively constant from 1981 (82.1 kg N ha^{-1}) to 2016 (90.2 kg N ha^{-1}) and then doubled to 202.3 kg N ha^{-1} in 2021. The RSN values in 2021 ranged from 33.1 kg N ha^{-1} to 202.3 kg N ha^{-1} and 2021 had the highest RSN values over the 40 years except for Ontario which had the highest RSN values (60.8 kg N ha^{-1}) in 2001, another drought year.

The average RSN in Canada increased from 9.1 kg N ha^{-1} in 1981 to 22.0 kg N ha^{-1} in 2016, and then doubled to 44.2 kg N ha^{-1} in 2021. The doubling of RSN from 2016 until 2021 was due primarily to drought conditions in 2021 that resulted in reduced yields. For example, the precipitation for the June to August period for Alberta in 2021 (145 mm) was 31% less than the 41-year average (208 mm) whereas 2016 (237 mm) had 14% more precipitation than average (Table S1). Similarly, the June to August precipitation was 29% less than average in British Columbia, 24% less than average in Quebec and 14% less than the 41-year average in Ontario whereas all Prairie provinces and British Columbia had more precipitation than average in 2016. The impact of the drought conditions in census years 2001 and 2021 reduced average yields and N uptake (Figure S1). For example, in 2016, the Canadian average N uptake was 73.8 kg N ha^{-1} whereas the N uptake in 2021 was 55.8 kg N ha^{-1} (Figure S1). The difference in N uptake between 2016 and 2021 (18 kg N ha^{-1}) accounts for 81% of the increase in RSN (that is, the difference in N uptake between 2021 is 22.2 kg N ha^{-1}) over these two census years. Spikes in RSN resulting from drought conditions and reduced crop N uptake were also apparent in the 2001 census year as well (Table 1, S1, Figure S1).

Table S1: Average June to August precipitation in the census year and change to 41-year average in 2001, 2016 and 2021 in the provinces of Canada.

Province	1981	1986	1991	1996	2001	2006	2011	2016	2021	41-year average	2001	2016	2021
	Average precipitation June–August (mm)										% change to 41 yr average		
British Columbia	169	148	203	171	199	122	201	215	126	176	13	22	-29
Alberta	177	215	224	201	174	173	238	237	145	208	-16	14	-31
Saskatchewan	180	163	215	147	136	158	233	228	159	191	-29	19	-17
Manitoba	238	197	225	181	203	130	211	273	217	224	-10	22	-3
Ontario	255	258	179	209	192	212	210	183	190	222	-13	-18	-15
Quebec	327	369	248	294	285	325	353	297	226	299	-5	-1	-25
New Brunswick	365	322	288	257	212	347	409	298	238	283	-25	5	-16
Nova Scotia	283	264	191	210	181	372	281	218	225	240	-24	-9	-6
Prince Edward Island	342	268	202	203	163	363	317	264	261	254	-36	4	3
Newfoundland and Labrador	389	271	276	304	255	379	304	298	260	302	-16	-2	-14

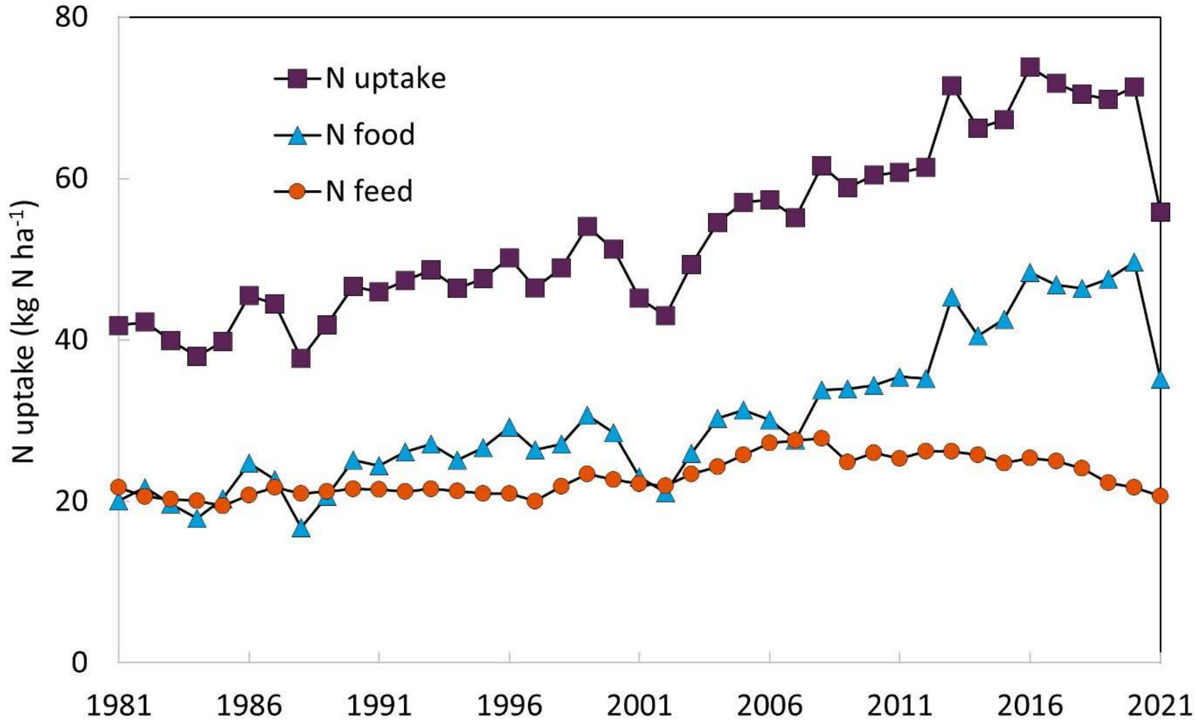
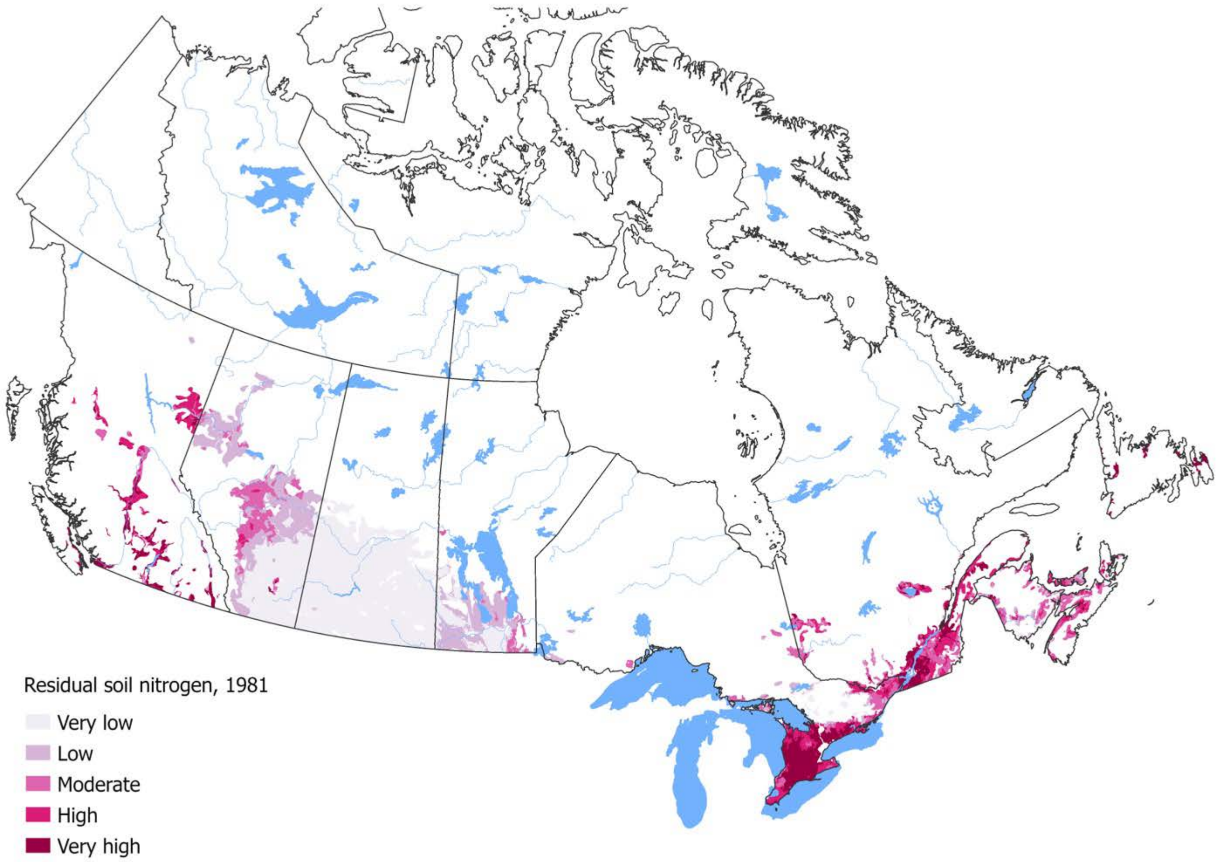


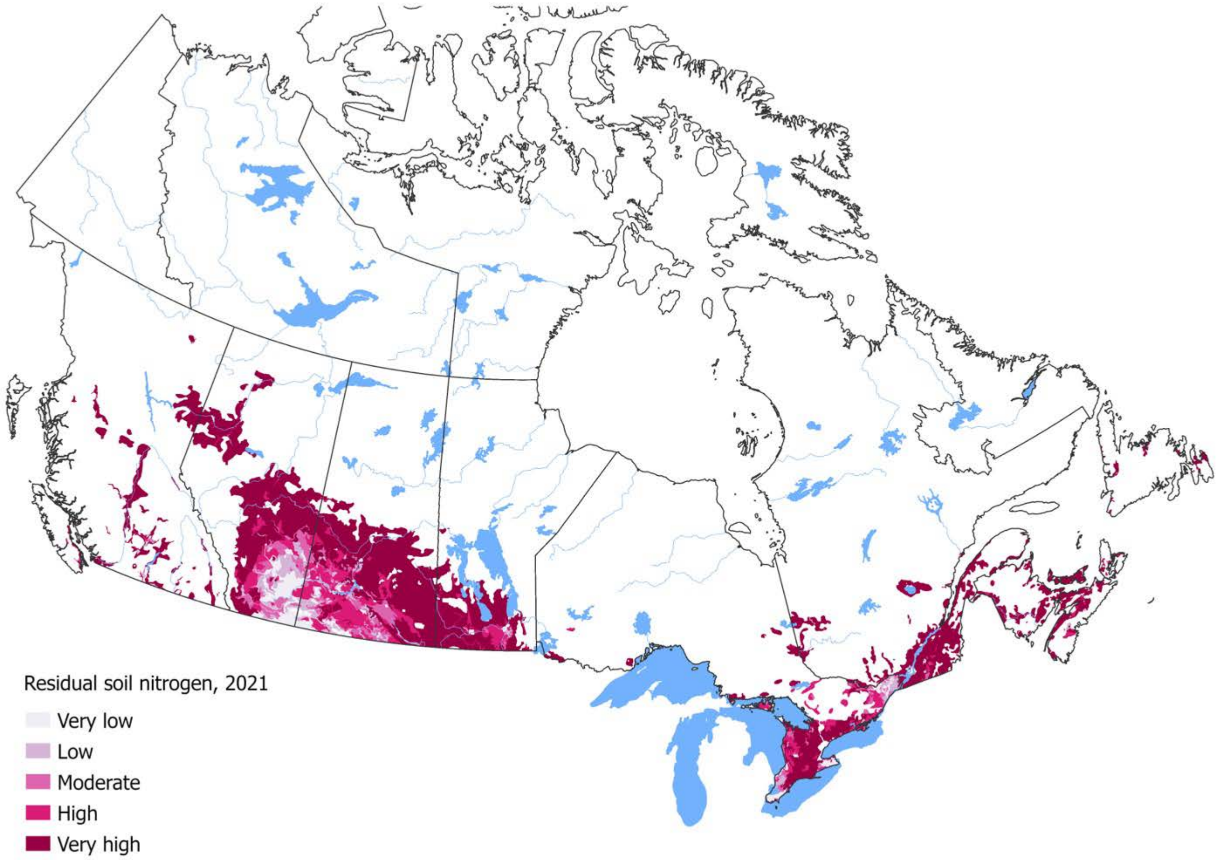
Figure S1: Estimated average N uptake by crops (N food plus N feed) in Canadian soils, 1981 to 2021.

Overall, the RSN increased almost five-fold (35.1 kg N ha^{-1}) over a 40-year period. It should, however, be noted that the RSN in 2021 was significantly higher than that in 2016, and the RSN in 2001 was higher than that 1996, the previous census year. These RSN peaks could be primarily attributed to reduced crop yields and N uptake as a result of drought conditions over the summers of 2001 and 2021.

The RSN maps for both 1981 and 2021 show the varying risk categories for the 3,847 agricultural polygons in Canada (Figure 2). In 1981, a majority of the areas in Saskatchewan, southern Alberta and northern agricultural regions of Ontario had very low to low levels of RSN (Figure 2). Northern Alberta and southern Manitoba had low-moderate risk levels of RSN, whereas central British Columbia, southern Ontario, and many areas of Quebec and the Atlantic provinces had high to very high risk levels of RSN in 1981. In general, considerably more regions in Canada had moderate to very high risk levels of RSN in 2021 than that in 1981. For example, in addition to the very high risk level of RSN in British Columbia and most of the Atlantic provinces, most of the agricultural regions in Manitoba as well as northern Alberta and Saskatchewan also had very high risk levels of RSN in 2021. In contrast in southwestern Ontario, the RSN risk levels were somewhat improved in 2021 compared to 1981, partly due to the higher yields in 2021 resulting from favourable weather in the region.



1981



2021

Figure 2: Residual soil N (RSN) levels on Canadian farmland in 1981 and 2021.

The differences in risk levels over the 40 years (that is, 2021 to 1981) indicated that most of Canadian agricultural land was at least two or more risk classes higher in 2021 than they were in 1981 (Figure 3). There were however some areas in British Columbia, southern Alberta, southern Saskatchewan, southern Ontario and parts of the St Lawrence Lowlands that did not change risk classes. In the case of British Columbia and parts of the St Lawrence Lowlands, the reason why there was no apparent change in the risk levels was because they were already in the highest risk class in 1981.

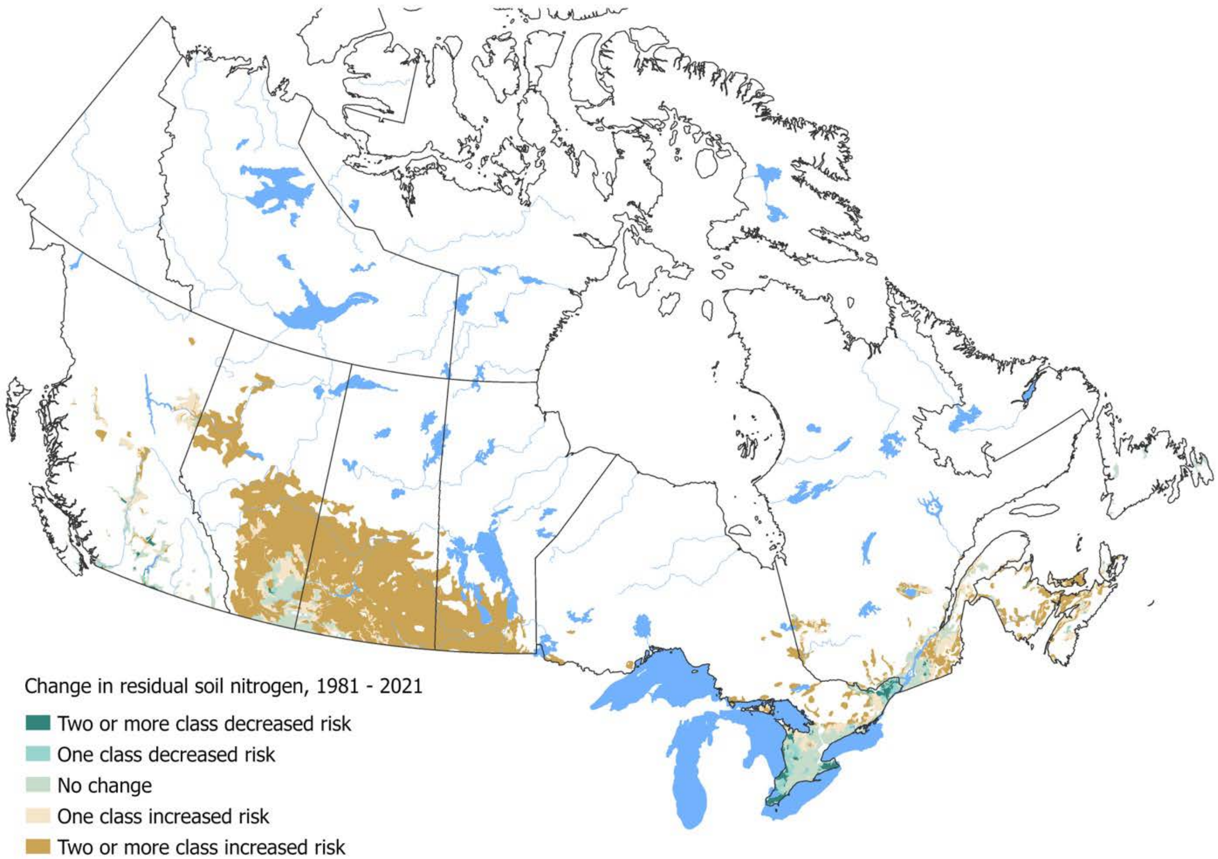


Figure 3: Changes in RSN levels on Canadian farmland, 1981 and 2021.

In 1981, all of Saskatchewan and between 45 to 48% of Manitoba and Alberta were in the very low RSN risk class. In contrast, all other provinces had between 0 and 2% of their land in this very low risk class, which contained less than 9.9 kg N ha^{-1} RSN in soils. Manitoba had 52% of its land in the low risk class (10–19.9 kg N ha^{-1}) in 1981 followed by Alberta with 38% (Table 2). All other provinces had between 0 and 22% of the land in this lowest risk class. New Brunswick, Nova Scotia and Prince Edward Island had between 45 to 49% of their lands in the moderate risk class (20–29.9 kg N ha^{-1}) in 1981. The range for the other provinces was between 0% in Saskatchewan and 23% in Quebec. In 1981, Ontario and Quebec had between 27 and 33% of the agricultural land in the high risk class whereas New Brunswick, Nova Scotia and Prince Edward Island ranged between 25 and 43% of the land and British Columbia had the highest land area

(48%) in this high risk class. There were very small areas in the Prairie provinces (0-1%) and in Newfoundland and Labrador (7%) that were in the high risk class in 1981. In 1981, Newfoundland and Labrador had the largest proportion of agricultural land (92%) in the very high risk RSN category (≥ 40.0 kg N ha^{-1}), followed by Ontario (51%), Quebec (43%) and British Columbia (38%). All other provinces had below 10% of the agricultural land in this risk class.

Table 2: Percentage (%) of farmland in the various residual soil nitrogen (RSN) risk classes from 1981 to 2021. The very low risk class ranges from 0 to 9.9 kg N ha^{-1}, the low risk class ranges from 10.0 to 19.9 kg N ha^{-1}, the moderate risk class ranges from 20.0 to 29.9 kg N ha^{-1}, the high risk class ranges from 30.0 to 39.9 kg N ha^{-1}, whereas the RSN levels in the very high risk class are ≥ 40.0 kg N ha^{-1}.

Class	Very low									Low									Moderate								
Year	1981	1986	1991	1996	2001	2006	2011	2016	2021	1981	1986	1991	1996	2001	2006	2011	2016	2021	1981	1986	1991	1996	2001	2006	2011	2016	2021
British Columbia	1	0	0	0	0	0	0	2	3	4	2	3	2	2	3	4	7	6	9	18	8	6	6	6	9	9	3
Alberta	48	71	50	41	23	40	36	42	14	38	24	34	11	20	12	10	17	12	13	5	14	29	10	24	14	20	12
Saskatchewan	100	100	100	79	29	37	43	44	4	0	0	0	18	35	42	19	14	10	0	0	0	2	33	19	23	12	12
Manitoba	45	15	10	13	0	3	2	14	0	52	13	6	5	2	14	5	4	1	4	69	40	2	12	9	13	3	6
Ontario	2	2	1	3	0	10	9	23	15	5	2	9	8	0	8	9	14	9	15	12	6	8	1	14	14	39	13
Quebec	0	0	0	0	0	0	0	1	1	2	2	1	2	0	0	1	2	0	23	14	5	8	0	2	3	5	1
New Brunswick	2	0	0	0	0	0	1	0	1	22	16	3	8	1	1	3	1	1	45	35	26	31	6	8	19	3	0
Nova Scotia	0	0	0	0	1	0	1	1	0	4	3	0	4	1	1	2	0	2	44	25	6	45	1	3	19	11	2
Prince Edward Island	0	0	0	0	0	0	0	0	0	14	0	0	0	0	0	0	0	0	49	59	6	10	0	0	22	0	0
Newfoundland and Labrador	0	0	0	12	0	2	5	4	1	0	0	0	0	0	0	0	1	4	1	1	0	3	0	0	2	3	0
Canada	61	66	59	48	19	29	31	36	8	18	9	12	13	21	24	12	13	9	8	11	9	12	19	18	17	16	11

Class	High									Very High								
Year	1981	1986	1991	1996	2001	2006	2011	2016	2021	1981	1986	1991	1981	1986	1991	1996	2001	2006
British Columbia	48	30	46	16	6	9	9	8	3	38	50	43	48	30	46	16	6	9
Alberta	1	0	2	15	32	20	25	19	12	0	0	0	1	0	2	15	32	20
Saskatchewan	0	0	0	0	4	2	13	24	21	0	0	0	0	0	0	0	4	2
Manitoba	0	2	44	50	9	40	11	21	12	0	0	0	0	2	44	50	9	40
Ontario	27	23	29	19	3	40	33	19	30	51	62	55	27	23	29	19	3	40
Quebec	33	30	20	24	3	9	8	16	5	43	55	75	33	30	20	24	3	9
New Brunswick	25	27	33	31	11	25	42	12	2	6	21	38	25	27	33	31	11	25
Nova Scotia	43	42	49	28	5	16	39	10	10	9	31	46	43	42	49	28	5	16
Prince Edward Island	38	19	43	34	0	0	49	0	0	0	22	51	38	19	43	34	0	0
Newfoundland and Labrador	7	0	4	12	0	8	6	3	3	92	99	96	7	0	4	12	0	8
Canada	6	5	10	13	13	15	19	21	17	8	9	9	6	5	10	13	13	15

[1] Please note that the numbers are rounded and may not always add up to exactly 100%.

There was a dramatic decrease in the very low risk class for RSN in Canada as it decreased from 61% of the land in 1981 to only 8% in 2021, whereas land area in the low risk class only decreased by 50% from 18% in 1981 to 9% in 2021. The land area in Canada in the moderate risk class increased from 8% in 1981 to 19% in 2001 and then decreased to 11% by 2021. The proportion of the high risk class area more than doubled from 1981 (6%) to 2021 (17%), and the proportion of very high risk RSN class increased by sevenfold from 8% of the land area in 1981 to 56% in 2021.

What is especially concerning is that all provinces had over 61% of their land area in the high and very high risk classes, and Manitoba, Quebec and all of the Maritime provinces had more than 93% of their land area in these two highest risk classes in 2021 (Table 2). Although 2021 was found to have the highest RSN over the 40-year period, it is noted that all but three provinces (Alberta, Saskatchewan and Ontario) had a majority (79 to 100%) of their land in the high and very high risk classes in 2016 as well (Figure 1, Table 2).

Response options

These RSN results indicate that RSN levels in soils have been increasing over time in many regions of Canada as a result of increasing N inputs, which have been increasing at greater rates than the N outputs. While N outputs (yields and N uptake) have also increased, the increases are lower than the increases in N outputs. This is certainly an issue in years that have either drought conditions or excess rains that limit crop yields and N uptake as was observed in census years 2001 and 2021, as well as several other mid-census years. These trends of increasing RSN levels over time could be addressed by:

1) Improving N fertilizer use efficiency through the adoption of nutrient management strategies including the use of urease and nitrification inhibitors, improved placement, improved timing of fertilizer application and the right rate (Drury et al.2017; Woodley et al., 2020, Drury et al., 2024).
2) Accounting for the available N from previous manure applications and/or legume crops by using in-season soil and/or plant testing in addition to precision agriculture soil mapping technology (Zebarth et al., 2009).
3) Incorporating manure and organic amendments to minimize N losses to runoff, erosion and ammonia volatilization losses (Mencaroni et al., 2021).
4) Using cover crops to catch any residual N that is left over at the end of the growing season to prevent overwinter N losses (Drury et al., 2014).
5) Using in-season crop sensors to adjust the amount of N applied to crops with a side-dress N application (Zebarth et al., 2009).

6) Exploring management practices such as diverse crop rotations and/or conservation tillage practices that will increase soil health parameters including soil organic carbon and soil structure to help plants be more resilient under adverse weather conditions (for example, drought, excess rain) (Agomoh et al., 2020, 2021; Bowles et al., 2020; Li et al., 2023).

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