



Indicator of The Risk of Water Contamination by Nitrogen

Agri-Environmental Indicators Report

The Environmental Sustainability of Canadian Agriculture

Census Year 2021



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Indicator of The Risk of Water Contamination by Nitrogen
Agri-Environmental Indicators Report, Census Year 2021

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The issue and why it matters

Inorganic nitrogen fertilizers, manures and legume crops (biological nitrogen fixation) provide nitrogen (N), an essential nutrient for crop production. However, when excess rain occurs during the growing season, nitrate in the soil can be lost to water through leaching below the crop root zone or through tile drainage which can result in an environmental risk when nitrate concentrations or loads in surface or ground water exceed environmental or drinking water guidelines. Nitrate losses can occur all year long, however the majority of water and nitrate losses typically occurs during the non-growing season when a portion of the residual soil nitrate that is present in the soil after harvest is leached through the soil profile following precipitation or snowmelt. High concentrations and/or loads of nitrates in fresh water can be toxic to aquatic insects and/or fish (Camargo et al., 2005). Algae and other aquatic plants use N and phosphorus (P) as nutrient sources which can accelerate eutrophication, deplete oxygen levels in water and negatively impact aquatic life (Camargo et al., 2005; Cooper et al., 2015; Sevda et al., 2018). Eutrophication also heightens other important social and economic issues, including but not limited to declining fisheries, raising public trust issues, and increasing regulatory burden among others. For example, the Lake Erie water basin provides drinking water to over 11 million consumers in addition to supporting local economies in tourism, shipping and fishing industries (Watson et al., 2016). High nitrate levels in drinking water can also be harmful to human health if it exceeds the drinking water guideline ($\geq 10 \text{ mg N L}^{-1}$ which is similar to the World Health Organization (WHO) guideline of $50 \text{ mg NO}_3 \text{ L}^{-1}$) (Ward et al., 2018).

Humid regions that have precipitation occurring in excess of evapotranspiration (such as central or eastern Canada or southern British Columbia) could result in high N leaching losses, whereas farmland in the more arid agricultural regions in the Prairie provinces may have negligible losses where there is insufficient precipitation or snow melt for water and nitrate to infiltrate very deeply into the soil profile. Soil type can also impact nitrate leaching as soil texture and soil organic carbon can influence the saturated hydraulic conductivity (drainage) of a soil. Furthermore, crop type (annual versus perennial, legume vs non-legume, high vs low N requiring crop) and N uptake can also affect the concentration of nitrate remaining in the soil, which in turn influences the extent of leaching losses.

The indicator

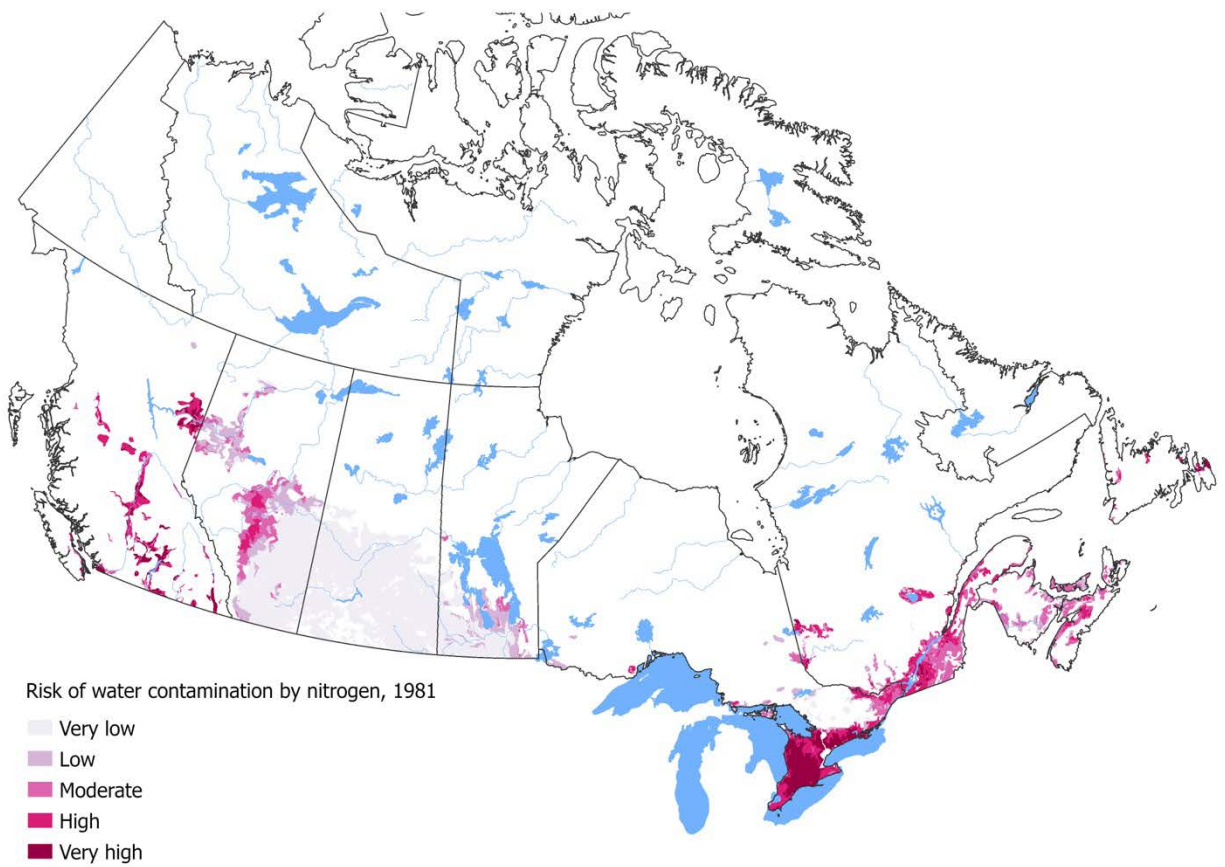
The Indicator of Risk of Water Contamination by Nitrogen (IROWC-N) provides estimates of the risk of high nitrate concentrations and losses across soil and climatic regions in Canada from 1981 to 2021. The risk levels are determined using a

classification system defined in Table 1 and range from very low (level 1) to very high (level 5), with low (level 2), moderate (level 3) and high (level 4) as intermediate risk categories (Figure 1). The IROWC-N indicator uses the Residual Soil N (RSN) indicator data as well as the climatic data, soil and landscape properties as model inputs (De Jong et al., 2007, 2009; Yang et al., 2007, 2013, 2023, 2024; Drury et al. 2007, 2010, 2016).

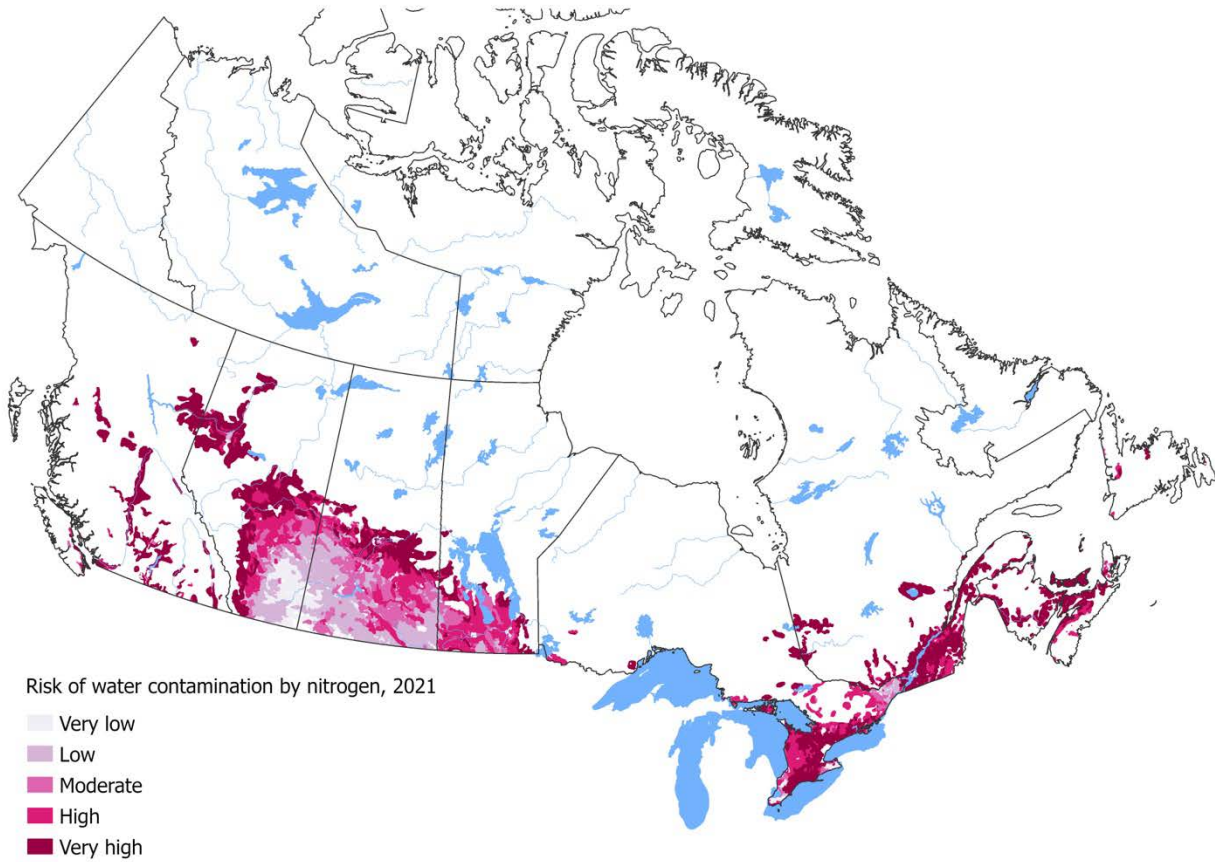
Table 1: IROWC-N classification based on the annual N lost and annual N concentration in the water.

Annual N lost (kg N/ha)	Annual N concentration (mg N/L)		
	0-4.9	5-9.9	≥10.0
0-4.9			
5-9.9			
10.0-19.9			
≥20.0			

Legend	Very High	High	Moderate	Low	Very Low
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(A)



(B)

Figure 1: Risk of water contamination by nitrogen on Canadian farmland in (A) 1981 and (B) 2021.

Updates to both N inputs and N outputs have been incorporated into the recent version of the Canadian Agricultural Nitrogen Budget for Reactive N (CANBNr) model. The N input updates include : 1) provincial fertilizer N sales from 2016 to 2021 with eight fertilizer sources so that the entire data set extends from 1981 to 2021; 2) manure N estimates based upon livestock diets (Sheppard et al., 2010, 2011; Yang et al., 2023); 3) the application of manure N to priority crops; and 4) the harmonization of fertilizer N rates to better account for N in applied manure. The N output updates include: 1) alfalfa, improved and unimproved pasture yield estimates using the EPIC model for 1981–2021 (Wang et al., 2021); and 2) gaseous nitrogen emissions through denitrification (N_2O , N_2)

and ammonia volatilization (NH_3) for 1981–2021 (see Greenhouse Gas emission and Ammonia emission chapters for details).

The IROWC-N water balance was updated using DeNitrification-DeComposition (DNDC) model simulations. In each year, the DNDC model generates monthly drainage estimates from 20 annual crops at the Soil Landscape of Canada (SLC) scale (improved pasture, unimproved pasture, forage, hay, fruit and vegetable crops were excluded). The crop area weighted average of DNDC water balance at each SLC was then used for each of the 27 crops in the CANBNr model. The IROWC-N module uses these weighted drainage values and the RSN as inputs to calculate nitrate-N leaching loss and N concentration in the leaching water (De Jong et al., 2009, Yang et al., 2014, 2023, 2024; Drury et al., 2016). Nitrate concentration and leaching losses were calculated in both the non-growing season (NGS), which includes the months from October to April, and the growing season (GS), which includes May to September. Both N loss and N concentration were used to estimate the IROWC-N risk classes, as described in the next section.

The IROWC-N module in the CANBNr model provides critical information from both a crop productivity and a soil N leaching perspective. For example, insufficient water can limit crop growth, nutrient uptake and yields, whereas excess water can result in nitrous oxide emissions, nitrate leaching losses and negatively impact nutrient uptake and yields. The IROWC-N module does not account for N loss in surface runoff as N losses through runoff are generally believed to be small compared to N losses through tile drainage and deep percolation (De Jong et al., 2009; Drury et al., 1996, 2010, 2014, Woodley et al., 2018). Nitrate loss through tile drainage impacts surface water quality, whereas nitrate loss through deep percolation negatively impacts ground water quality.

IROWC-N risk classes

The amount of nitrate-N loss and the concentration of nitrate-N in drainage water are two parameters that are used to assess the IROWC-N classes, as they both relate to the potential environmental impacts of N losses. There are 4 N-loss categories (0 to 4.9 kg N ha⁻¹; 5 to 9.9 kg N ha⁻¹; 10 to 19.9 kg N ha⁻¹; and ≥ 20.0 kg N ha⁻¹) and 3 N-concentration categories (<5.0 mg N L⁻¹; 5-9.9 mg N L⁻¹ and ≥ 10.0 mg N L⁻¹) as depicted in the IROWC-N risk classification matrix (Table 1). Nitrate concentrations of < 5.0 mg N L⁻¹ in drainage water complies with the water quality guideline for aquatic life in fresh waters (4.7 mg NO₃-N L⁻¹), and the 5.0–9.9 mg N L⁻¹ approaches the Canadian drinking water guideline of 10 mg N L⁻¹ (Guy, 2008). The higher risk levels of ≥ 10 mg N L⁻¹ represents nitrate concentrations that have reached or exceeded the Canadian drinking water guideline.

Limitations

The methodology used to calculate IROWC-N is based on the following three primary approximations that enable reporting for large spatial units at a coarse temporal scale: 1) The RSN is calculated as a nitrogen budget at harvest each year when soil organic nitrogen is assumed to be at an equilibrium level; 2) The N loss is estimated during the 7-month non-growing season period (October 1 to April 30) as well as during the 5-month growing season (May 1 to September 30) as most annual crops are planted in May and reach maturity by the end of September, even though some crops such as soybean or corn may be harvested in October and November; 3) A crop area-weighted water balance was used for 27 crops in each SLC polygon, as deriving water balances for each individual crop and in each of the 3487 SLC polygons is unfeasible. These assumptions should be considered when interpreting the results.

Although there are published water quality studies at field or watershed scales, there is insufficient data available to validate the results for every crop and polygon across the country. Nevertheless, comparisons across different ecoregions, provinces and nationally as well as over time can be made to identify hot spots. In addition, positive or negative trends in the indicator data over time can be assessed. In particular, policymakers or consultants could use these indicator results to identify areas that are at high risk for potential RSN accumulation and N leaching. The results should, however, be confirmed by field testing, particularly in areas presenting a high level of risk.

Results and interpretation

National trend

The majority of farmland in Canada in 1981 was in the very low risk class of water contamination by nitrogen especially in the Prairie provinces and much of the farmland in northern regions in Ontario (Figure 1A). The Timiskaming district in Ontario and some areas in Quebec and the Atlantic provinces fell into the moderate to high risk categories in 1981. Southern Ontario and British Columbia had pockets of farmland in the very high risk class in 1981. In 2021, the farmland area in the very low risk class decreased substantially in the Prairie provinces and was distributed mainly in agricultural areas in southern Alberta and southern Saskatchewan. In Ontario, North Bay changed from the very low risk class in 1981 to moderate risk class in 2021 (Figure 1A and B). There was a noticeable increase in the high and very high risk classes in British Columbia, western Alberta and northern regions of the Prairies, eastern Manitoba, southern and northern

Ontario, Quebec and the Atlantic provinces in 2021 (Figure 1B). On a national scale, the proportion of farmland in the very low risk class decreased gradually from 69% in 1981 to 13% in 2021, while the proportion in the low risk class increased from 9% to 28%, the moderate class increased from 8% to 16%, the high risk class increased from 8% to 21%, and the very high risk class increased from 6% to 20% (Table 2). The change from 2016 to 2021 was aggravated by drought conditions in 2021 which resulted in reduce yields and N uptake and increased RSN after harvest as was discussed in the RSN chapter.

The changes in the risk classes for farmland between 1981 and 2021 (Figure 2) identify regions where the risk of nitrate contamination of water have increased, remained stable or improved over time. The risk of water contamination by N remained stable in southern Alberta, southwestern Saskatchewan and southern Ontario, but increased by one or two risk classes in the northern regions of British Columbia, northern Alberta, northern Saskatchewan, most of Manitoba, northern Ontario, northern Quebec as well as New Brunswick and Prince Edward Island. There were increases of one risk class in some areas in all the provinces. In contrast, southern Ontario and Nova Scotia had some regions which had a decreased risk by one to two risk classes. Changes in the national IROWC-N classes were primarily impacted by the Prairie provinces because they account for the majority of farmland area in Canada. In most census years, the low precipitation in most of Alberta and Saskatchewan resulted in lower drainage volumes and nitrate losses which resulted in a lower risk of water contamination by nitrogen compared to all other provinces.

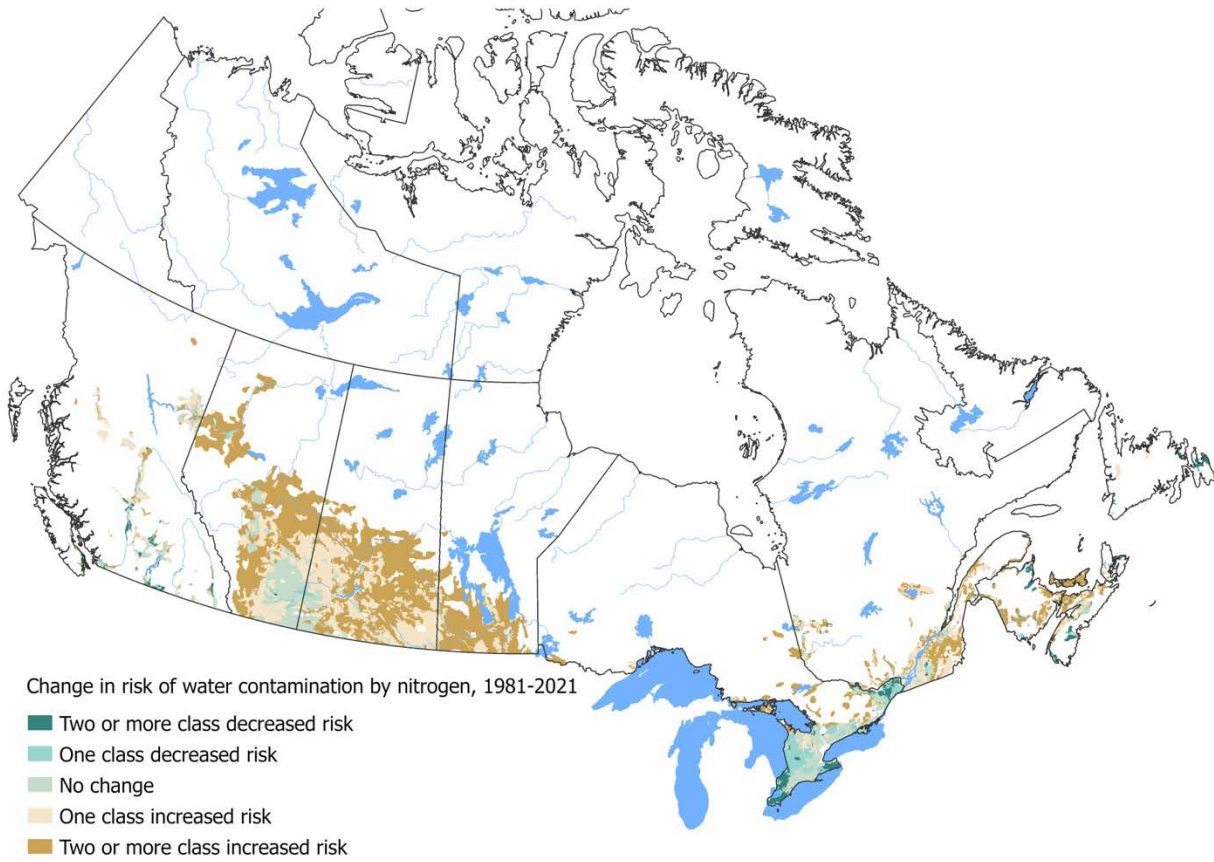


Figure 2: Change in the risk of water contamination by nitrogen on farmland in Canada, 1981 to 2021.

Provincial and time trend

There were significant differences in the IROWC-N classes between provinces from 1981 to 2021 (Figure 1). For example, in 1981, the majority (83–100%) of the farmland in the Prairie provinces was in the very low and low risk categories due in part to a large proportion of agricultural land being under summerfallow and receiving minimal N inputs as well as lower precipitation which contributes to lower volumes of drainage water compared to the rest of Canada (Table 2, 3 and 4). However, the proportion of land in these two risk classes dropped substantially to 41% in Alberta, 57% in Saskatchewan and only 16% in Manitoba in 2021 (Table 2). In contrast to the decreases in the very low and low risk classes in the Prairie provinces, there were dramatic increases in the from 0–3% of the agriculture land in 1981 to 24–46% in the high and very high risk classes in 2021. Agricultural land in the moderate risk class increased in Saskatchewan and

Manitoba over the 41 years and generally decreased in all other provinces except Alberta where it remained fairly constant (Table 2).

Table 2: Percentage (%) of farmland in the various IROWC-N risk classes from 1981 to 2021.

Class	Very low									Low									Moderate								
	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	2	0	2	2	1	0	1	4	7	5	8	3	4	3	3	6	3	3	14	12	14	7	7	11	7	16	4
Alberta	64	84	68	46	36	43	42	48	20	19	9	16	20	33	10	16	17	21	13	5	11	13	10	22	16	14	12
Saskatchewan	100	100	100	96	53	59	54	56	12	0	0	0	3	37	21	8	20	45	0	0	0	1	8	17	23	10	18
Manitoba	77	16	14	16	0	6	4	17	1	19	25	52	16	7	15	2	3	15	4	46	29	41	8	11	13	12	38
Ontario	2	2	4	7	0	14	12	28	16	6	2	9	8	1	10	10	15	8	9	10	9	10	2	14	12	33	13
Quebec	0	0	0	0	0	0	0	1	1	5	5	1	2	0	0	1	2	1	35	17	14	16	1	18	9	8	1
New Brunswick	2	0	0	2	0	0	1	0	0	30	33	4	12	4	2	4	2	1	59	23	53	41	2	34	61	4	0
Nova Scotia	0	0	0	2	0	0	1	1	0	11	7	6	13	1	1	6	0	1	53	23	9	59	1	19	36	17	7
Prince Edward Island	0	0	0	0	0	0	0	0	0	30	45	0	0	0	0	0	0	0	70	10	6	20	0	0	56	0	0
Newfoundland and Labrador	0	0	0	12	0	2	2	0	0	0	0	0	0	0	0	0	0	2	27	1	7	15	3	1	7	4	5
Canada	69	70	65	57	34	40	37	43	13	9	6	11	10	27	15	10	15	28	8	8	8	11	8	17	18	13	17

Class	High									Very High								
	1981	1986	1991	1996	2001	2006	2011	2016	2021	1981	1986	1991	1996	2001	2006	2011	2016	2021
British Columbia	38	34	34	27	11	15	17	14	8	40	45	46	59	77	69	67	61	76
Alberta	3	1	4	17	13	19	18	16	20	0	0	0	2	6	4	8	5	26
Saskatchewan	0	0	0	0	2	3	9	12	15	0	0	0	0	0	0	5	2	10
Manitoba	0	12	5	26	46	50	10	36	35	0	0	0	1	39	18	71	31	11
Ontario	33	35	37	24	18	45	33	14	40	50	50	42	52	80	17	33	10	24
Quebec	54	49	50	46	50	67	68	47	27	5	28	34	36	49	14	21	41	69
New Brunswick	10	33	41	37	60	53	33	48	27	0	10	2	7	33	10	0	45	62
Nova Scotia	34	68	79	25	76	76	50	63	48	1	2	5	0	19	2	3	15	34
Prince Edward Island	0	45	72	58	25	75	44	55	24	0	0	22	23	75	25	0	46	76
Newfoundland and Labrador	24	34	33	25	50	31	31	25	34	35	57	42	48	47	56	54	64	14
Canada	8	8	8	13	14	20	17	18	21	6	7	6	8	17	7	17	10	20

¹ Total numbers across the five classes are ≤100 (%) due to not assessed area of the farmland (%) in each provinces. Not assessed areas accounted for 1–6% in British Columbia, <1% in Prairie provinces, <3% in New Brunswick, 3–7% in Nova Scotia and up to 29% in Newfoundland and Labrador due to lack of water balance data. In 1981, 21% of the agricultural land in British Columbia was in the very low, low and moderate risk classes and 78% was in the high and very high risk classes. Between 1% and 3% of the farmland area in British Columbia could not be assessed due to a lack of drainage data. By 2021, however, the area in the high and very high risk classes more than doubled, to cover 84% of the farmland area (Table 2).

Ontario had the opposite trend as British Columbia and the Prairie provinces, showing an overall improvement and reduction in the high and very high risk classes over time. Ontario's agricultural land area in the very low and low risk classes ranged from 1–15% in the five census years between 1981 and 2001, and increased to 26–35% in the 2016 and 2021 census years (Table 2). In contrast, agricultural land area in Ontario in the high and very high classes ranged 76–98% during the five census years between 1981 and 2001 and it decreased to 24–64% in the 2016 and 2021 census years. The moderate risk class falls within 9–15% in most census years except for 2001 and 2016, when the proportion was 2% and 32%, respectively (Table 2). The higher crop yields and greater N uptake in southwestern Ontario was partially responsible for the increased area in the very low, low and moderate risk classes over time. There was however a reversal in 2021 due to drought conditions. In Quebec, in 1981 less than 5% of cropland area was in the very low and low risk classes, while the land area in the moderate class was 35%. In 2021, only 3% of the land area in Quebec was in the three lowest risk categories and 27% was in the high risk while 69% was in the very high risk categories.

The proportion of cropland area in the very low risk class was very small in all four Atlantic provinces (0–12%) in all census years (Table 2). Both New Brunswick and PEI had 30% of the land in the low risk category in 1981 and by 2021, there was only 1% of the land in this risk class in New Brunswick and 0% in PEI. In 1981, a majority of the land in New Brunswick, Nova Scotia and PEI was in the moderate risk category (52–70%) and there were dramatic decreases over time resulting in 7% or less by 2021 in the Atlantic provinces. The proportion of land in the high and very high risk classes increased over time in New Brunswick, Nova Scotia and PEI with there being 83–100% of the agricultural land in these two highest risk classes by 2021 whereas Newfoundland and Labrador had 59% in these two classes in 1981 and 48% in 2021.

Nitrate leaching loss

As expected, the Canadian N loss during the seven-month non-growing season (NGS) was consistently greater than that during the five-month growing season (GS) in part because of the lower evapotranspiration losses during the non-growing season and the longer time period (Table 3A). In 1981, for example, the national N loss was 5.3 kg N ha⁻¹ during the NGS whereas it was 1.6 kg N ha⁻¹ during the GS. Similarly, in 2021, the N losses were greater during the NGS (8.1 kg N ha⁻¹) than during the GS (6.3 kg N ha⁻¹) due to increases in tile drain observed in the NGS.

The N losses during the non-growing season were consistently lower in the three Prairie provinces due to low drainage volumes resulting in these more arid regions compared to all other provinces in both 1981 (range 0–2.5 kg N ha⁻¹) and in 2021 (2.6–6.6 kg N ha⁻¹) (Table 3, 4). In contrast, all other provinces had N losses ranging from 20.1 kg N ha⁻¹ in New Brunswick to 60.0 kg N ha⁻¹ in Newfoundland and Labrador in 1981. The N losses over the 2021 NGS in the provinces outside the Prairies ranged from 19.2 kg N ha⁻¹ in Ontario to 75.8 kg N ha⁻¹ in PEI. The pattern of lower N losses in the Prairies and higher N losses in all other provinces during the NGS was also apparent in the GS across all years (Table 3A).

The total annual loss in Canada generally increased from 6.9 kg N ha⁻¹ in 1981 to 14.3 kg N ha⁻¹ in 2021 although it should be noted that in 2016, the lower RSN values contributed to lower leaching losses (9.6 kg N ha⁻¹) (Table 3A). The annual N losses were significantly lower in the Prairie provinces in 1981 (0–4.0 kg N ha⁻¹) as well as in 2021 (7.5–11.9 kg N ha⁻¹). In contrast, the N losses in the other provinces were considerably greater than the Prairie provinces and ranged from 23.6 to 68.8 kg N ha⁻¹ in 1981 and from 21.9 to 86.8 kg N ha⁻¹ in the rest of Canada in 2021 (Table 3A). The relatively low annual N leaching loss (0.0–11.9 kg N ha⁻¹) in Alberta and Saskatchewan over the 40-year period (Table 3A) was due primarily to low annual drainage volumes ranging from 15 to 124 millimetres (Table 4). The higher annual drainage in Manitoba (39 to 179 mm) resulted in greater estimates of N leaching loss (3.9–25.7 kg N ha⁻¹) over the 40-year period (Table 3A). Drainage water loss was considerably greater in

Atlantic Canada in most years (411–868 mm) compared to other provinces, although relatively high drainage losses were also observed in Ontario, Quebec and British Columbia (226–716 mm) (Table 4).

Table 3: N loss (Nlost, kg N ha⁻¹) and N concentration (Nconc, mg N L⁻¹) in the non-growing season (NGS), the growing season (GS) and on an annual basis, 1981 to 2021.

Number	Year	N lost - NGS										N lost - GS										N lost - Annual									
		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			
1	British Columbia	24.8	19.6	23.9	19.6	30.2	28.4	21.7	30.8	38.5	4.5	7.2	5.7	12.0	12.3	5.1	14.9	6.1	19.3	29.3	26.8	29.7	31.6	42.5	33.5	36.6	36.8	57.8			
2	Alberta	2.5	1.2	1.4	1.4	1.8	3.3	2.1	3.5	3.8	1.5	1.6	2.6	3.6	3.0	3.7	5.1	2.7	8.1	4.0	2.8	4.0	5.0	4.7	7.0	7.2	6.2	11.9			
3	Saskatchewan	0.0	0.0	0.0	0.3	1.5	3.4	3.1	2.8	2.6	0.0	0.0	0.0	0.5	0.8	2.6	4.5	1.1	4.9	0.0	0.1	0.0	0.7	2.3	6.1	7.6	3.9	7.5			
4	Manitoba	2.5	5.1	1.3	3.3	11.3	6.7	11.3	10.6	6.6	1.4	3.3	3.2	4.4	6.5	7.0	14.4	5.1	5.2	3.9	8.5	4.5	7.6	17.8	13.8	25.7	15.7	11.9			
5	Ontario	22.4	24.7	20.2	21.5	38.3	18.7	17.9	10.9	19.2	5.6	6.6	2.7	5.1	8.6	1.7	4.5	1.5	2.7	27.9	31.4	22.9	26.6	46.9	20.4	22.4	12.4	21.9			
6	Quebec	28.1	30.5	38.8	32.8	45.8	41.6	41.5	38.4	49.6	6.5	11.9	5.9	7.1	9.5	7.1	9.7	9.8	9.0	34.6	42.4	44.7	39.8	55.3	48.7	51.2	48.2	58.5			
7	New Brunswick	20.1	21.2	29.9	25.7	35.0	39.3	26.7	41.2	52.2	3.5	6.3	4.9	4.0	6.5	6.5	5.8	8.6	10.7	23.6	27.5	34.8	29.7	41.4	45.8	32.4	49.8	62.9			
8	Nova Scotia	23.4	24.7	27.2	23.5	35.3	38.0	28.0	36.3	42.7	3.6	5.1	4.6	4.2	5.8	6.4	4.5	4.2	6.2	27.0	29.8	31.8	27.6	41.1	44.4	32.5	40.6	48.9			
9	Prince Edward Island	21.0	21.5	30.7	33.2	45.8	50.8	25.4	56.3	75.8	3.0	3.0	3.5	4.6	6.9	7.3	4.3	6.2	11.0	24.0	24.5	34.2	37.9	52.7	58.1	29.7	62.5	86.8			
10	Newfoundland and Labrador	60.0	59.1	54.3	55.6	63.7	75.2	65.6	62.4	37.7	8.9	11.6	15.0	10.6	12.3	12.5	14.1	13.4	7.5	68.8	70.7	69.3	66.3	76.1	87.6	79.7	75.8	45.2			
11	Canada	5.3	5.1	4.8	4.8	8.6	7.7	7.2	7.0	8.1	1.6	2.2	1.8	2.8	3.4	3.6	6.1	2.5	6.3	6.9	7.3	6.6	7.6	12.0	11.3	13.3	9.6	14.3			

Number	Year	N lost - NGS										N lost - GS										N lost - Annual									
		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			
1	British Columbia	11.8	15.4	12.5	20.1	22.5	17.3	20.7	14.4	29.7	8.8	10.7	8.8	12.7	14.4	14.0	11.3	10.2	16.7	10.6	12.5	10.9	14.2	17.8	16.2	13.8	12.8	20.8			
2	Alberta	4.9	3.0	5.5	9.4	12.9	9.4	12.4	7.9	19.8	3.9	1.9	3.8	7.7	11.1	7.0	9.1	6.1	15.5	4.3	2.2	4.2	8.1	12.9	7.8	9.7	7.0	16.6			
3	Saskatchewan	0.1	0.1	0.1	2.8	9.0	6.0	8.0	9.1	25.1	0.0	0.1	0.1	2.6	7.0	4.4	5.1	8.3	22.6	0.1	0.1	0.1	2.7	8.8	5.1	5.9	8.8	23.3			
4	Manitoba	5.0	9.6	16.1	18.8	20.7	17.3	20.8	18.8	32.9	4.2	7.6	14.1	15.9	16.7	12.8	11.6	15.4	29.7	4.6	8.6	14.6	16.8	18.9	14.3	14.2	17.2	31.0			
5	Ontario	13.1	14.9	13.7	14.5	14.6	8.8	10.3	6.5	8.6	9.4	10.4	11.8	11.2	8.9	7.6	7.3	5.6	6.9	12.0	13.3	13.4	13.6	12.9	8.6	9.4	6.3	8.1			
6	Quebec	7.6	12.6	9.8	10.6	12.8	8.4	10.7	12.8	15.0	3.4	4.9	6.0	6.0	6.7	3.8	4.4	6.4	9.2	6.0	8.6	8.8	9.0	10.9	7.1	8.3	10.1	12.9			
7	New Brunswick	3.7	7.2	5.9	5.8	9.9	7.4	6.0	11.7	14.5	1.5	3.1	2.7	3.2	5.7	3.2	2.2	6.1	7.5	3.0	5.4	5.0	5.2	8.8	6.2	4.5	9.9	12.2			
8	Nova Scotia	5.1	7.6	8.9	6.4	9.3	7.4	5.9	7.3	9.7	2.8	4.4	5.5	3.8	5.9	3.3	3.1	4.7	5.8	4.6	6.7	8.3	5.7	8.6	6.2	5.2	6.9	8.9			
9	Prince Edward Island	3.9	6.4	8.7	8.1	13.0	9.6	5.6	11.8	16.0	1.9	4.4	6.0	4.9	8.2	4.7	2.8	7.6	8.5	3.4	6.0	8.3	7.4	12.1	8.5	4.9	11.2	14.3			
10	Newfoundland and Labrador	8.8	13.7	15.1	12.3	12.9	14.0	15.1	15.0	7.7	3.1	6.0	5.3	5.5	5.0	6.1	6.4	6.3	2.9	7.1	10.8	9.8	9.9	9.5	11.7	11.9	11.6	5.8			
11	Canada	4.0	4.2	5.3	8.2	12.4	8.8	11.2	9.7	22.4	2.9	2.8	4.2	6.7	9.6	6.5	7.3	8.0	18.9	3.5	3.5	4.7	7.3	11.7	7.5	8.5	9.0	20.0			

Table 4: Drainage water (mm) in the non-growing season (NGS), the growing season (GS) and on an annual basis, 1981 to 2021.

3B - N conc (mg N L ⁻¹)		NGS-drainage										GS-drainage										Annual-drainage									
Number	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			
1	British Columbia	254	176	232	153	164	190	141	249	214	70	92	80	107	97	46	143	67	119	324	268	313	260	261	237	284	316	333			
2	Alberta	36.3	33	20	11	10	34	17	32	16	42.6	64	59	38	22	55	59	36	51	78,9	97	79	49	32	89	76	67	67			
3	Saskatchewan	12	18	8	6	15	59	31	24	11	4	34	50	17	9	65	81	14	23	15	52	58	23	24	124	112	38	34			
4	Manitoba	55	58	11	21	59	47	57	68	23	37	46	28	30	43	58	123	37	20	93	103	39	51	102	105	179	104	43			
5	Ontario	197	191	191	181	275	254	213	205	265	87	107	34	65	104	42	84	37	63	285	298	226	246	378	296	297	241	328			
6	Quebec	384	258	413	343	364	507	400	340	363	211	262	128	152	154	209	235	168	105	595	520	541	495	518	716	636	508	468			
7	New Brunswick	580	326	512	452	357	532	451	354	330	243	196	186	145	116	206	269	144	137	822	523	698	597	473	738	720	498	466			
8	Nova Scotia	470	332	342	417	377	492	470	486	413	142	137	106	166	98	195	148	87	105	612	469	448	583	475	687	618	573	517			
9	Prince Edward Island	544	342	373	433	357	532	462	491	480	164	69	64	102	86	157	157	84	131	709	411	437	534	443	688	619	575	611			
10	Newfoundland and Labrador	586	426	376	473	546	485	438	409	269	282	192	240	186	250	185	237	204	177	868	618	617	659	796	671	676	613	446			
11	Canada	71	60	54	46	62	94	68	69	58	41	64	54	38	34	66	88	34	41	112	123	108	84	96	160	156	102	99			

Nitrate concentration

The nitrate-N concentration in drainage water was generally higher during NGS than during GS (Table 3B). In 1981, N concentrations in the NGS ranged from 0.1 in Saskatchewan (as a result of virtually no excess drainage) to 13.1 mg N L⁻¹ in Ontario (Table 3B). In 2021, the nitrate-N concentrations in drainage water were considerably greater in all provinces except Ontario and Newfoundland and Labrador in 2021, with a range from 7.7 mg N L⁻¹ in Newfoundland and Labrador to 32.9 mg N L⁻¹ in Manitoba. The N concentration during the GS ranged from 0.0 in Saskatchewan to 9.4 mg N L⁻¹ in Ontario in 1981, but increased to a range from 2.9 mg N L⁻¹ in Newfoundland and Labrador to 29.7 mg N L⁻¹ in Manitoba in 2021. A similar pattern is observed for annual N concentrations, with a range from 0.1 to 12.0 mg N L⁻¹ in 1981 to a range from 5.8 mg N L⁻¹ in Newfoundland and Labrador to 31.0 mg N L⁻¹ in Manitoba in 2021. In 2021, the average N concentration reached or exceeded the 10 mg N L⁻¹ drinking water guideline in seven out of the 10 provinces (Table 3B).

Response options

Large residual soil nitrogen levels in the soil at harvest, soils with low water holding capacity, high precipitation and/or snowmelt rates all contribute to high nitrate-N leaching losses in the soils below the root zone. Nitrate-N moving below the rooting zone has the potential to enter surface waters through tile drainage or the groundwater which could impact aquifers and drinking water wells in rural communities. Nitrate-N can be leached from soil if precipitation is greater than evapotranspiration. The four primary management options to reduce the nitrate concentration and losses in drainage waters are as follows:

1. Reduce the amount of RSN left in the soil after harvest. Management options including 4R nutrient stewardship practices (Right Source, Right Rate, Right Time, Right Place), for example, the use of enhanced efficiency fertilizers such as those containing urease and nitrification inhibitors, improved placement with injection (Drury et al., 2017; Woodley et al., 2020), double slot injection systems (Drury et al., 2024) and in-season diagnostic tests (Zebarth et al., 2009), help mitigate nitrogen losses to the environment.
2. Utilize a cover crop to capture any residual N in the soil. The captured N may then be available to the subsequent crop in the following year if the timing of the residue decomposition and release of N from the cover crop aligns with crop demand. For example, winter wheat grown as a cover crop is shown to reduce the nitrate concentration in tile drainage water by 21–38% and nitrate loss by 14-16% compared to treatments without cover crops (Drury et al., 2014).
3. Utilize conservation agricultural practices, such as improved crop rotations (Agomoh et al. 2021) and/or conservation tillage practices such as zone tillage (Shi et al., 2011) to increase soil organic carbon sequestration, which in turn improves soil structure and water holding capacity.
4. Capture edge of field losses using wetlands and/or vegetative filter strips (Walton et al., 2020).

References

- Agomoh, I.V., Drury, C.F., Yang, X.M., Phillips, L.A. and W. D. Reynolds. 2021. Crop rotation enhances soybean yields and soil health indicators. *Soil Sci. Soc. Am. J.* (in press Feb 2021).
- Camargo, J.A., Alonso, A., Salamanca, A. 2005. Nitrate toxicity to aquatic animals: a review with new data for freshwater invertebrates. *Chemosphere* 58: 1255-1267
- Cooper, M.J., Costello, G.M., Francoeur, S.N., Lamberti, G.A. 2015. Nitrogen limitation of algal biofilms in coastal wetlands of Lakes Michigan and Huron. *Freshw. Sci.* Nov 2015. DOI: 10.1086/684646.
- De Jong, R., C.F. Drury, J.Y. Yang, and C.A. Campbell, 2009. Risk of water contamination by nitrogen in Canada as estimated by the IROWC-N model. *J. Environ. Manage.* 90: 3169-3181.
- De Jong, R., J.Y. Yang, C.F. Drury, E.C. Huffman, V. Kirkwood, and X.M. Yang, 2007. The indicator of risk of water contamination by nitrate-nitrogen. *Can. J. Soil Sci.* 87:179-188.
- Drury, C.F., Agomoh, I., Yang, X.M., Philipps, L.A., Reynolds, W.D. Helmers, M., Calder, W., Hedge, T. (2024). Stacking nitrogen management practices: Combining double-slot fertilizer injection with urease and nitrification inhibitors improves yields and reduces ammonia and nitrous oxide emissions. *Soil Sci. Soc. Am. J.* 1-15. doi.10.1002/saj2.20677
- Drury, C.F., C.S. Tan, J.D. Gaynor, T.O. Oloya and T.W. Welacky. 1996. Influence of controlled drainage subirrigation on surface and tile drainage nitrate loss. *J. Environ. Qual.* 25: 317-324.
- Drury, C.F., C.S. Tan, T.W. Welacky, W.D. Reynolds, T.Q. Zhang, T.O. Oloya, N.B. McLaughlin, and J.D. Gaynor, 2014. Reducing nitrate loss in tile drainage water with cover crops and water table management systems. *J. Environ. Qua.* 43: 587-598.
- Drury, C.F., J.Y. Yang, R. De Jong, T. Huffman, X.M. Yang, and K. Reid, 2010. Residual Soil Nitrogen. In: Eilers, W., R. MacKay, L. Graham, and A. Lefebvre (eds). *Environmental sustainability of Canadian agriculture: Agri-Environmental indicator report series—Report # 3*. Ottawa, ON, Canada: Agriculture and Agri-Food Canada; p. 74-80.
- Drury, C.F., J.Y. Yang, R. De Jong, X.M. Yang, E. Huffman, V. Kirkwood, and K. Reid, 2007. Residual soil nitrogen indicator for Canada. *Can. J. Soil Sci.* 87: 166-177.
- Drury, C.F., Yang, J.Y., and De Jong, R. 2016. "Water Contamination by Nitrogen.", in Clearwater, R.L., Martin, T. and Hoppe, T. (eds.) - *Environmental sustainability of Canadian agriculture: Agri-environmental indicator report series -- Report #4*, Agriculture and Agri-Food Canada, Chapter 11, pp. 121-130.
- Drury, C.F., Yang, X.M., Reynolds, W.D., Calder, W., Oloya, T.O., and Woodley, A.L. 2017. Combining urease and nitrification inhibitors with incorporation reduces ammonia volatilization, nitrous oxide emissions and increases corn yields. *J. Environ. Qual.* 46: 939-949.
- Guy, M. 2008. Ideal performance standards for the nitrate ion. National Agri-Environmental Standards Initiative. Report No. 4–43. Environment Canada, Gatineau, Quebec, Canada.

- Sevda, S., Sreekishnan, T.R., Pous, N., Puig, S., Pant, D. 2018. Bioelectroremediation of perchlorate and nitrate contaminated water: A review. *Bioresour. Technol.* 255: 331-339.
- Sheppard, S. C., Bittman, S., Swift, M. L. and Tait, J. 2010. Farm practices survey and modelling to estimate monthly NH₃ emissions from swine production in 12 Ecoregions of Canada. *Can. J. Anim. Sci.* 90: 145-158.
- Sheppard, S. C., Bittman, S., Swift, M. L. and Tait, J. 2011. Modelling monthly NH₃ emissions from dairy in 12 Ecoregions of Canada. *Can. J. Anim. Sci.* 91: 649-661.
- Shi, X., Yang, X.M., Drury, C.F., Reynolds, W.D., McLaughlin, N.B., Welacky, T.W., and Zhang, X.D. 2011. Zone tillage impacts on organic carbon of a clay loam in southwestern Ontario. *Soil Sci. Soc. Am. J.* 75:1083-1089.
- Walton, C. R., Zak, D., Audet, J., Petersen, R. J., Lange, J., Oehmke, C., ... & Hoffmann, C. C. (2020). Wetland buffer zones for nitrogen and phosphorus retention: Impacts of soil type, hydrology and vegetation. *Science of the Total Environment*, 727, 138709.
- Wang, Z., Yang, J.Y., Drury, C.F., Jiang, R. 2021. Simulating alfalfa and pasture yields at regional and national scales in Canada from 1981 to 2019, *Agri. Syst.* 19: 103166. <https://doi.org/10.1016/j.agsy.2021.103166>
- Ward, M.H., Jones, R.R., Brender, J.D., de Kok, T.M., Weyer, P.J., Nolan, B.T., Villanueva, C.M. and van Breda, S.G. 2018. Drinking water nitrate and human health: An updated review. *Int. J. Environ. Res. Public Health* 15: 1557, 1-31
- Watson, S. B., Miller, C., Arhonditsis, G., Boyer, G. L., Carmichael, W., Charlton, M. N., ... & Wilhelm, S. W. (2016). The re-eutrophication of Lake Erie: Harmful algal blooms and hypoxia. *Harmful algae*, 56, 44-66.
- Woodley, A.L., Drury, C.F., Reynolds, W.D., Tan, C.S., Yang, X.M., Oloya, T.O. (2018). Long-term cropping effects on partitioning of water flow and nitrate loss between surface runoff and tile drainage. *J. Environ. Qual.* 47:820-829. doi.10.2134/jeq2017.07.0292
- Woodley, A.L., Drury, C.F., Yang, X.M., Phillips, L.A., Reynolds, W.D., Calder, W. and T.O. Oloya. 2020. Ammonia volatilization, N₂O emissions and corn yields as influenced by nitrogen placement and enhanced efficiency fertilizers. *Soil Sci. Soc. Am. J.* 84: 1327-1341.
- Yang J.Y., Drury, C.F., De Jong, R., Huffman, Ted., Yang, X.M. 2014. CANB v4.0: A Model for Simulating Residual Soil Nitrogen and Nitrogen Leaching in Canadian Regional Scale. DOI: 10.5220/0005005005290536
- Yang, J.Y., C.F. Drury, R. De Jong, E.C. Huffman, X.M. Yang, and K. Reid, 2013. Sensitivity analysis for nitrogen inputs, nitrogen outputs, and changes in biofuel crop acreages for predicting residual soil nitrogen and nitrate leaching in Canadian agricultural soils. *Ecol. Model.* 267: 26-38.
- Yang, J.Y., R. De Jong, C.F. Drury, E.C. Huffman, V. Kirkwood, and X.M. Yang, 2007. Development of a Canadian Agricultural Nitrogen Budget (CANB v2.0) model and the evaluation of various policy scenarios. *Can. J. Soil Sci.* 87: 153-165.

- Yang, J.Y., Drury, C.F., Jiang, R., Yang, X.M., Worth, D.E., Bittman, S., Grant, B.B., Smith, W.N., Reid, K., 2023. Simulating nitrogen balance in Canadian agricultural soils from 1981 to 2016. *J. Environ. Manag.* 341, 118015. <https://doi.org/10.1016/j.jenvman.2023.118015>.
- Yang, J.Y., Drury, C.F., Jiang, R., Worth, D.E., Bittman, S., Grant, B.B., Smith, W.N., 2024. Reactive nitrogen losses from Canadian agricultural soils over 36 years. *Ecol. Model.* 495, 110809. <https://doi.org/10.1016/j.ecolmodel.2024.110809>.