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BC Agricultural Research Data Protocol Workshop

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Nitrous Oxide Estimates and Farm Nitrogen Budgets

Shabtai Bittman and Derek Hunt and

Agassiz Research and Development Centre, Agassiz, BC

Canada

Why is Nitrogen important

- Nitrogen is the most abundant of the essential nutrients in plants (1-5% of dry matter and 16% of protein), forming the foundation of all protein.
- So N uptake from soil is necessary for plant growth and plant protein is needed for humans and livestock.

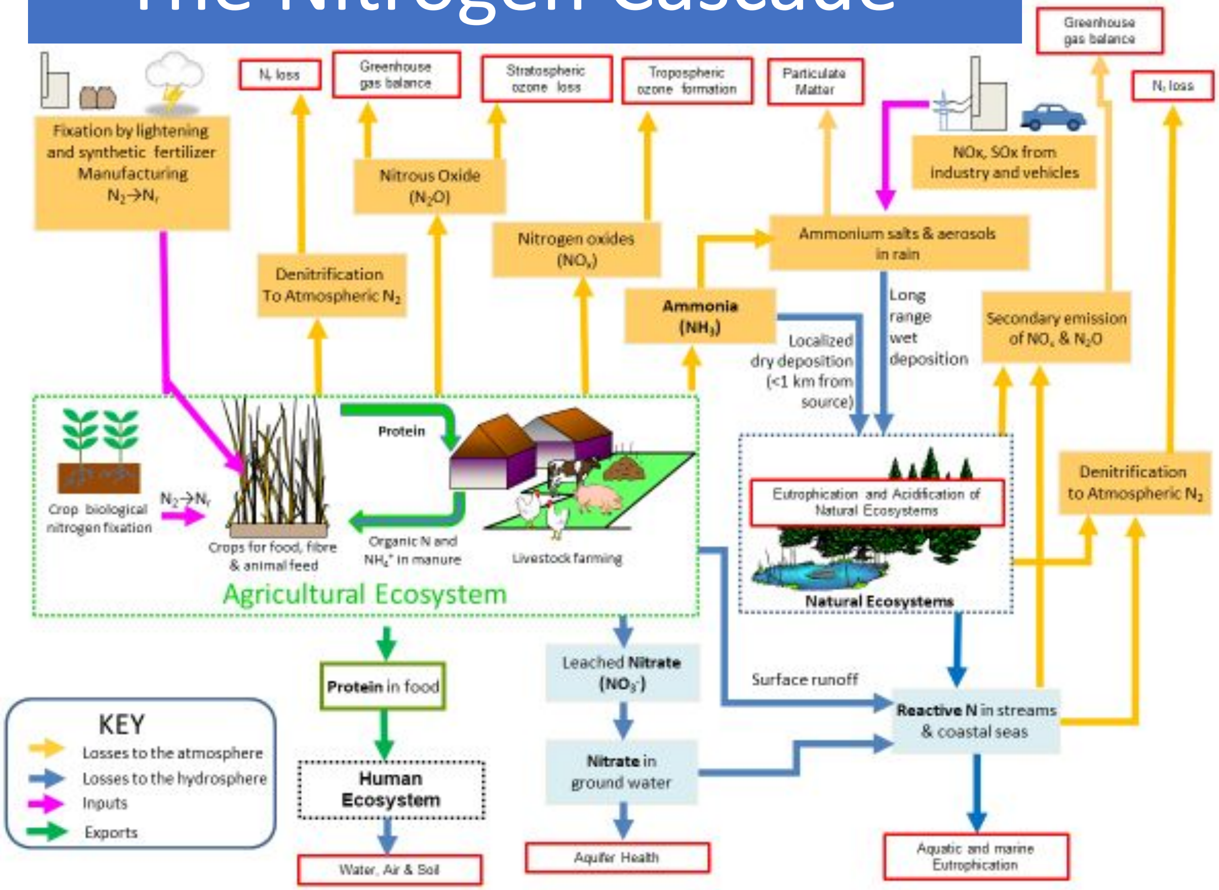
But there are concerns about N inputs in agriculture

- Inputs of N and other nutrients must be carefully balanced with outputs. If inputs are too high there will be environmental losses, if too low there will be soil mining.

- Each N atom in the environment can be incorporated into a succession of N molecules that have potential environmental consequences.

- N lost to the environment enters a *cascade* of transformations and transports.

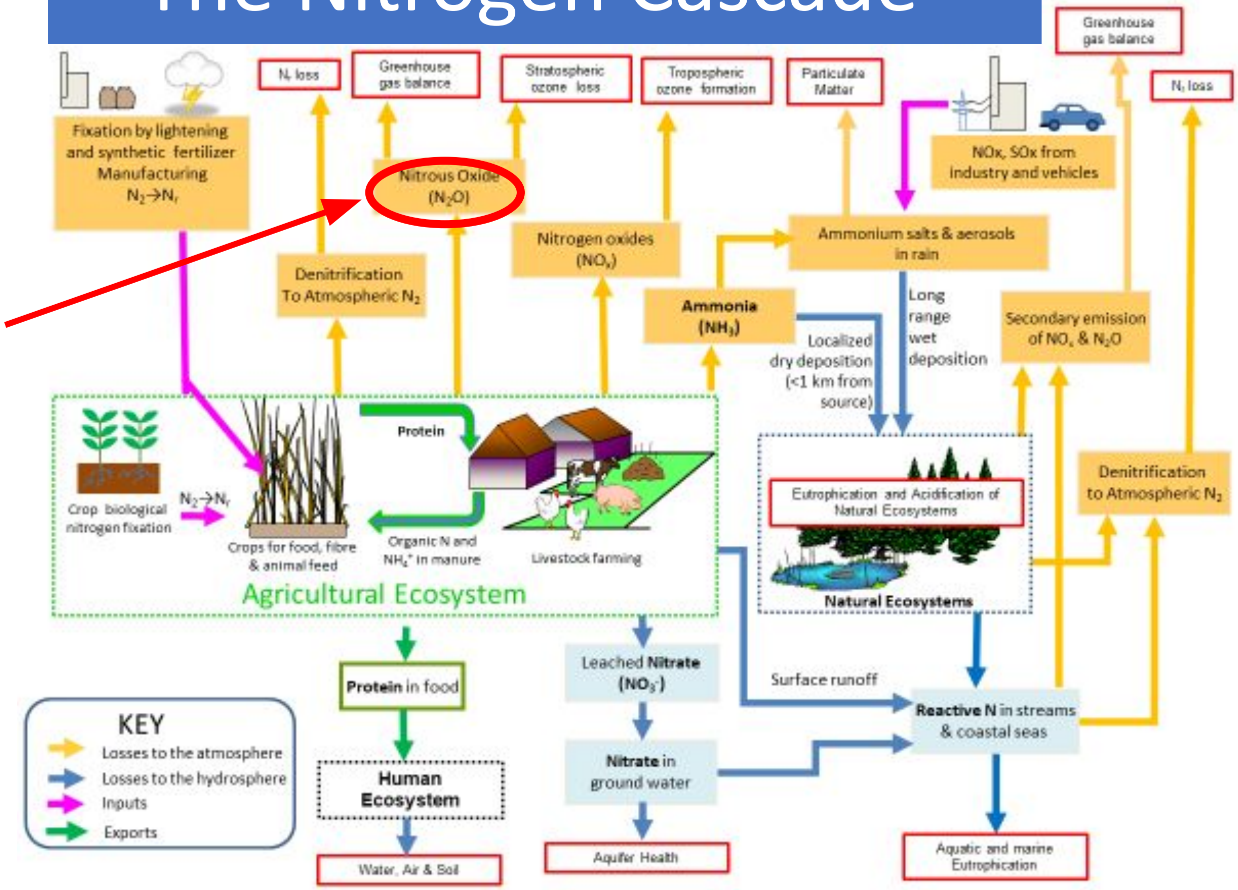
The Nitrogen Cascade-



Based on James Galloway, U. Virg.

The Nitrogen Cascade-

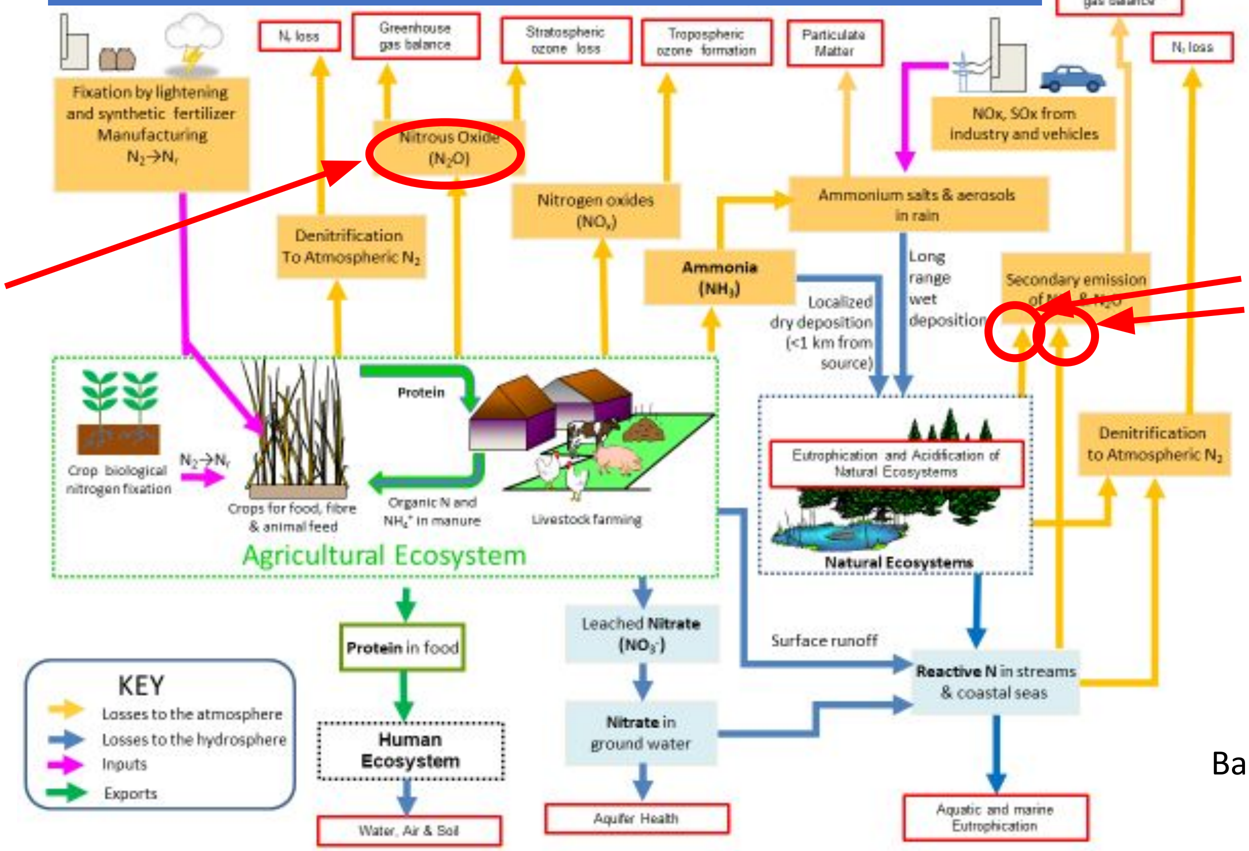
Primary Emissions



Based on James Galloway, U. Virg.

The Nitrogen Cascade-

Primary Emissions



Secondary Emissions

Based on James Galloway, U. Virg.

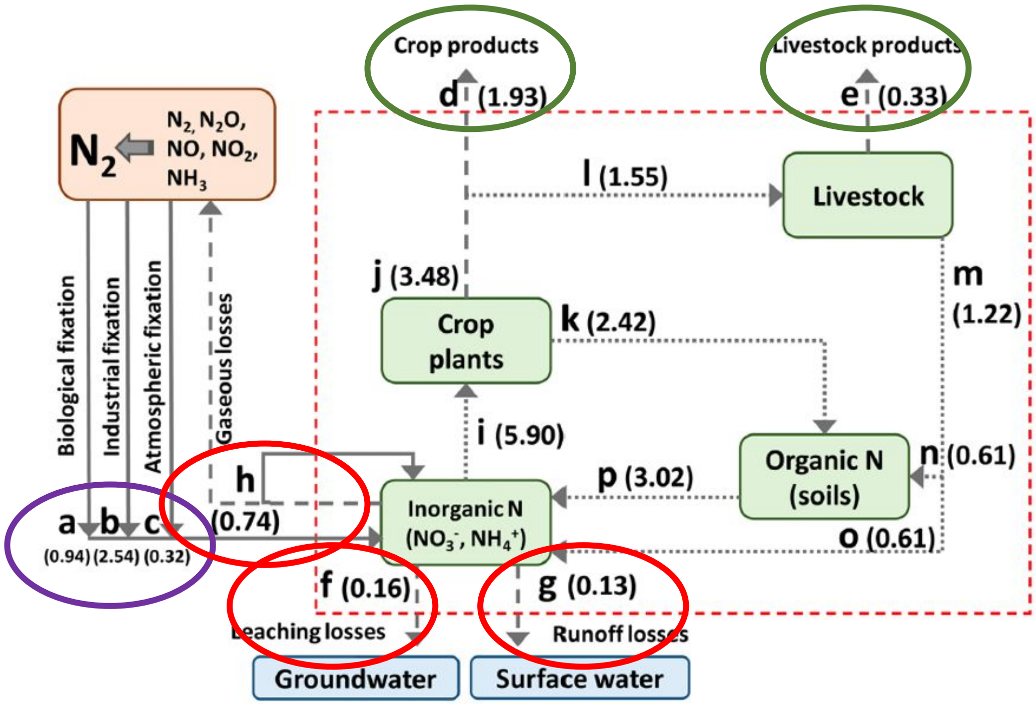
Canada's Agricultural Nitrogen Budget (Tg)

Balance 3.8-2.26=1.54
NUE 59%

Inputs
Fertilizer 2.54
Biological fixation 0.94
Lightening 0.32
Total 3.8

Outputs
Crops 1.93
Livestock 0.33
Total 2.26

Losses
Gaseous (N_2O, NH_3, N_2, NO)= 0.74
Leaching= 0.16
Runoff= 0.13



Karimi et al. (2020). An updated nitrogen budget for Canadian agroecosystems. *Agriculture, Ecosystems & Environment*, **304**, 107046.

Nitrous oxide (N_2O) emissions- why a concern?

- Nitrous oxide is emitted from microbial process when ammonia is oxidized to nitrate (nitrification) and when nitrate is reduced to N_2 (denitrification). The latter is usually greater and occurs in wet but not saturated soils.

- In Canada, agricultural soils accounted for 75% of the national N_2O emissions (increase of 50% since 1990) (ECCC 2018).

- Under the 'strengthened climate plan', Canada committed to setting national GHG reduction targets to 30% below 2020 levels. Obviously, a need to reduce N_2O.

How are N_2O emissions estimated?

Countries report emissions to the Intergovernmental Panel on Climate Change (IPCC)

methodology for quantifying national emissions

- IPCC protocol uses emission factors (Efs) x activity (such as fertilizer use, etc) for national GHGs inventories

- Three T*iers for choosing emission factors* represent level of complexity and data.
  - Tier 1 basic method (default)
  - Tier 2 intermediate and (National specific)
  - Tier 3 Process modelling

Tier 1: Default EF

Most countries use default emission factors
(averaged from many global scientific studies)

Current default: 0.01 kg N_2O-N /kg N applied
2006 IPCC Guidelines (IPCC 2006)

for Direct emissions from

1. applied N as fertilizer,
2. organic amendments and
3. crop residues (incl N fixation)
4. soil mineralization (due to loss of soil C)

Note: IPCC accounts for 'secondary emissions' from lost ammonia volatilization and nitrate leaching

With the exception of reduced N inputs, mitigation measures would not be captured by either the Tier 1 or simple Tier 2 approaches

Canadian (country specific emission factors) under review

Liang, C., MacDonald, D., Thiagarajan, A., Flemming, C., Cerkowniak, D. and Desjardins, R., 2020. Developing a country specific method for estimating nitrous oxide emissions from agricultural soils in Canada. *Nutrient Cycling in Agroecosystems*, *117*, pp.145-167.

Source	Emission factor %
Synthetic Nitrogen	2.1
Organic nitrogen	1.8
Crop residue nitrogen	0.59
Fine soil	3.0
Medium –coarse soil	0.6
Mean of texture	1.2
Annual crops	2.1
Perennial crops	0.4
BC dry	0.2
BC wet and irrigated	1.0
Secondary emissions	
Volatilization of ammonia	(0.5 dry; 1.4 wet)
Leaching	0.75

Average EFs (current and proposed) for fertilizers applied to low topographic areas

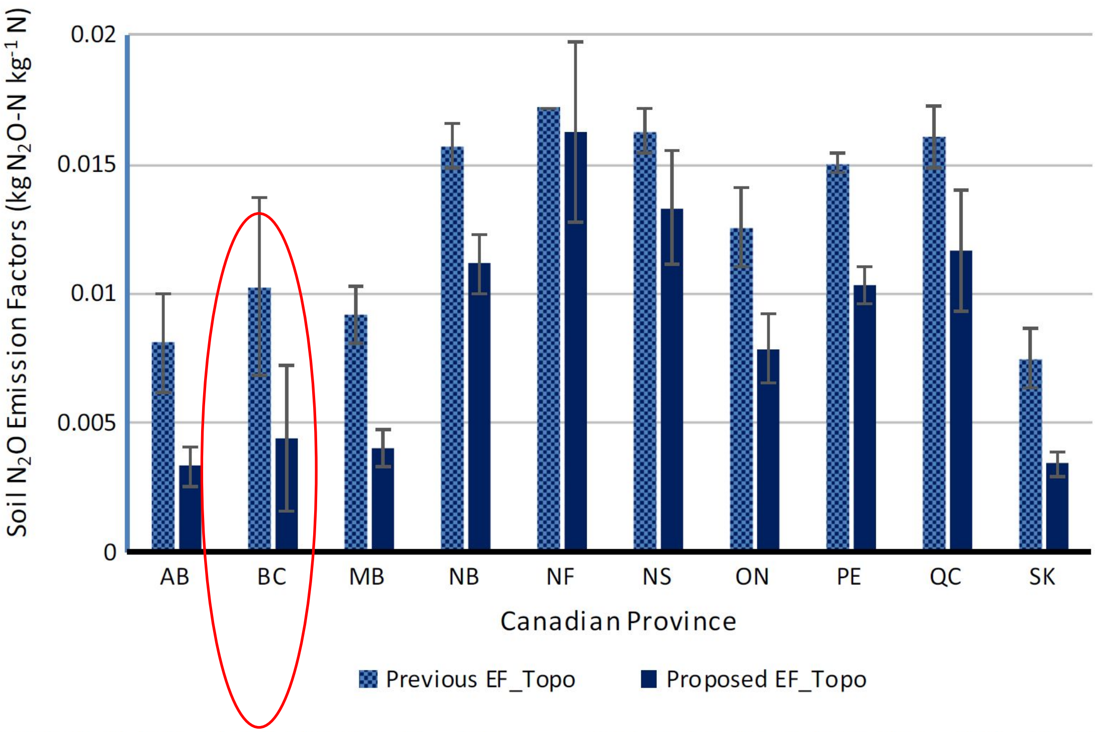


Fig. 4 Average synthetic N-induced soil nitrous oxide emission factors (EF_Topo) adjusted for low landscape position of ecodistricts derived previously through a linear function of growing season precipitation over potential evapotranspiration and an exponential equation with the growing season precipitation for each province of Canada (AB: Alberta; BC: British Columbia; MB: Manitoba; NB: New Brunswick; NF: Newfoundland and Labrador; NS: Nova Scotia; ON: Ontario; PE: Prince Edward Island; QC: Quebec; SK: Saskatchewan)

BC EF's

Direct measurements

N_2O emission factors for manure and fertilizer on grass over 5 full years at Agassiz (2008-2013)

Treatment	Rate application (kg N/ha)	Emission factor
Fertilizer	400	0.84
Whole slurry	400	0.38
Liquid fraction slurry	400	0.63
Whole slurry	600	0.65
Liquid fraction	600	0.65
Mean		0.63

Hunt, D., et al. 2019. Year-round N2O emissions from long-term applications of whole and separated liquid dairy slurry on a perennial grass sward and strategies for mitigation. *Frontiers in Sustainable Food Systems*, *3*, p.86.

BC EF's

Direct measurements

N2O emissions in Summer and Winter from grass receiving whole slurry, separated liquid fraction, and commercial fertilizer

(5 year mean at Agassiz BC)

		Summer	Winter
N Source	N rate kg/ha	N_2O (kg N_2O-N/ha)	
Control	0	0.16	0.07
Fertilizer	400	2.79	0.79
Whole slurry	400	1.27	0.48
Separated liquid slurry	400	2.26	0.52
Whole slurry	600	2.97	1.03
Separated liquid slurry	600	3.12	0.68
Mean		2.10	0.59

RATIO Winter N_2O : year round N_2O = 22%

Hunt et al 2019, Pelster et al 2023

BC EF's
Direct measurements

N_2O emission factors (% of applied N),
Manure on grass and pre-corn at Agassiz, BC

	2001	2002
Pre-corn Early manure	1.16	0.73
Pre-corn Late manure	0.74	1.19
Tall fescue Early manure	0.01	0.07
Tall fescue Late manure	0.13	0.09
Tall fescue Split manure	0.06	0.08

BC EF’s
Direct measurements

Dairy farming systems BMPs (stacked)

Crop	BMP	2016-2018 (EF)	Notes
Corn	Broadcast whole slurry (reference)	0.58	Typical farm
	Injected sludge	0.97	P recovery
Corn +cover crop	Injected sludge + cover crop	1.4	P recovery + increased yield/ reduced leaching
Corn +cover crop	Injected sludge+ cover crop+ Nitrification Inhibitor	0.67	Above +nitrification inhibitor
Grass	Broadcast whole slurry (reference)	0.42	Typical farm
	Banded Sep. liquid banded	0.68	less ammonia/ P loading
	Banded Sep. liquid + lax harvest	0.81	Above +higher yield and N capture
	Banded Sep. liquid + lax harvest Nitrification Inhibitor	0.38	Above + nitrification inhibitor
Mean Corn		0.92	
Mean Grass		0.57	

(Yuechen Li MSc thesis)

How to estimate N_2O emissions and emission reductions using Nitrogen Budgets

N BUDGET: N inputs- N exports= surplus

Two types of N budgets:

- Field budgets:

field inputs *(fert., manure, fixation) –* ***field outputs*** *(crop, harvested residue).*

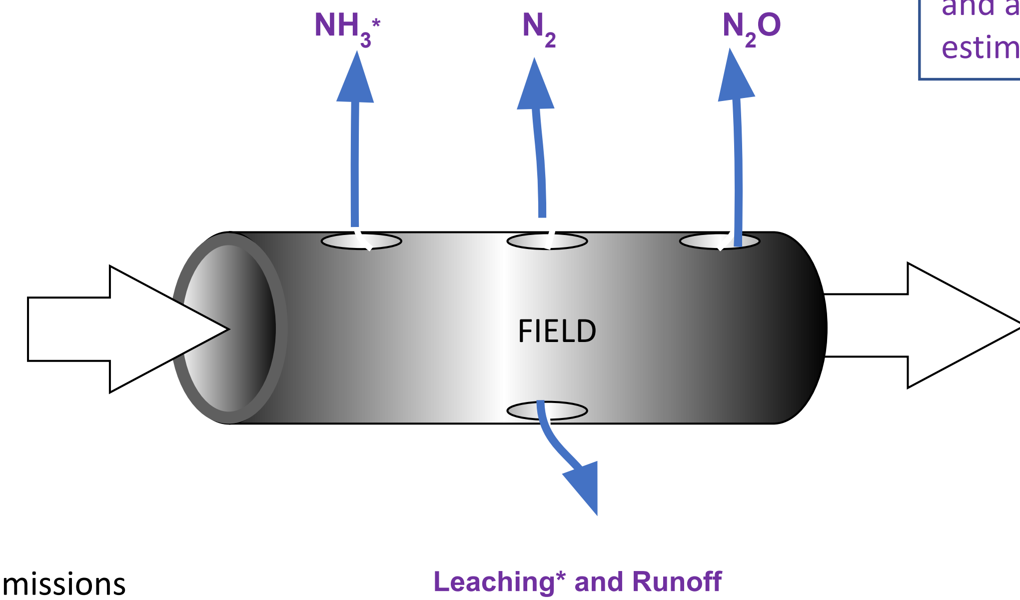
- Farmgate budgets:

farm imports *(fert., feed, animals, fixation…) –* ***farm exports*** *(crop, animals…)*

Field Nitrogen Budget

Some losses from field as gases and as solutes to water, can be estimated (N2 usually unknown)

Field inputs
- Fertilizer*
- manure/ amendments/ AD effluent*
- N fixation*
- Atmospheric deposition



Field outputs
- grain
- hay/ silage
- Cover crop harvested
- removed straw

* Used for N2O emissions

Field Nitrogen Budget

Field Inputs

- Fertilizer***
- Manure/ amendments/ AD effluent***
- *N fixation****
- Crop residue***
- Seed (weight, book value)
- Mulch (amount, book value)
- Atmospheric deposition (factor- optional)

***Used for N2O Emissions

Field outputs

- Grain
- Hay/ silage
- Cover crop harvested
- Removed straw

Field Metrics

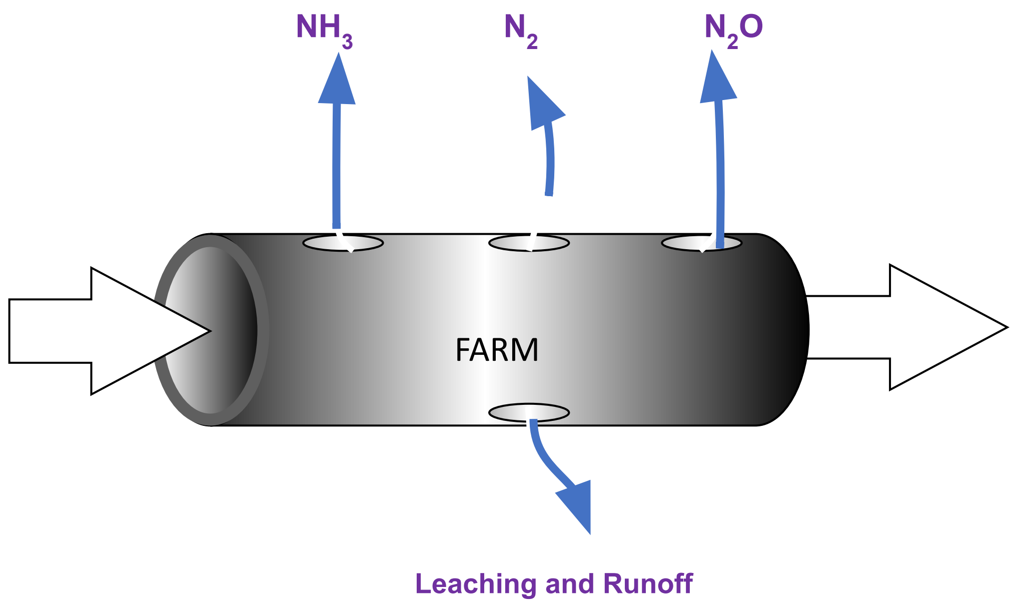
Field Surplus= Losses = (Inputs – Outputs)

Field Nitrogen use efficiency (NUE)= Outputs/Inputs

Farmgate Nitrogen Budget

Farmgate Imports

- Purchased fertilizer
- Purchased feed
- Purchased livestock
- Imported manure/ amendments/ AD effluent
- Purchased bedding/ mulch
- N fixation
- Atmospheric deposition



Farmgate exports

- Sold grain
- Sold hay/ silage
- Sold straw
- Exported manure
- Sold livestock, milk, eggs

- Losses include losses from buildings and storages as well as field
- Manure application and crop consumption by livestock are internal nutrient cycles and not estimated

Farmgate Nitrogen budget

Farmgate Imports (information)

- Purchased fertilizer (amount, analysis)
- Purchased feed (amount, analysis)
- Purchased livestock (number, type, weight)
- Seed (weight, N book value)
- Imported manure/ amendments/ AD effluent (amounts, analysis)
- Purchased bedding/ mulch (amount, book value)
- *N fixation (estimated, crop rotation)*
- Atmospheric deposition (factor- optional)

Farmgate exports

- Sold grain (weight, DM, analysis)
- Sold hay/ silage (weight DM. analysis)
- Sold straw (weight, book value)
- Exported manure (weight, analysis)
- Sold livestock, milk, eggs (weight, analysis, book value)

Farm Metrics

Surplus= Losses = (Imports – Exports)

Nitrogen use efficiency (NUE)= export/import

N Fixation estimates

Canadian Average N_2O emissions from legumes: (Rochette et al 2018)

- annual crops 1.0 kg N_2O-N/ha
- pure forage legume 1.8 kg N_2O-N/ha
- grass legume mixes 0.4 kg N_2O-N/ha

Legume_Fixed_N_Soybean

For soybeans, the total N fixed is approximately equal to 79% of soybean ***Grain_N***.

The equation for soybeans is thus:

$$\underset{\left(\frac{\text{lbs. N}}{\text{acre}}\right)}{Legume\_Fixed\_\mathbf{N}\_Soybean} = 0.79 \times \underset{\left(\frac{\text{lbs. N}}{\text{acre}}\right)}{Grain\_\mathbf{N}}$$

where ***Legume_Fixed_N*** in this case is the total amount of BNF for soybeans.

Legume_Fixed_N_Cover_Crop

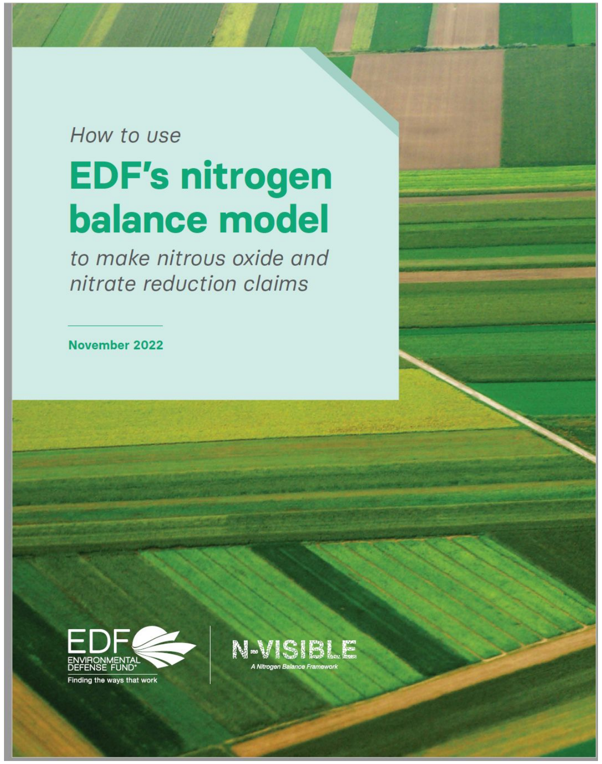
Winter cover crops that include legumes will also add N to the system. For these crops, use a conservative estimate of 50% of aboveground N coming from N fixation.

If a cover crop is composed of a mixture of legumes and non-legumes, this value is then adjusted by the proportion of legumes in the total biomass (preferred) or the proportion of legumes in the seed mixture (if biomass not available).

The equation for legume cover crops is thus:

$$\underset{\left(\frac{\text{lbs. N}}{\text{acre}}\right)}{Legume\_Fixed\_\mathbf{N}\_Cover\_Crop} = 0.50 \times \underset{\left(\frac{\text{lbs. N}}{\text{acre}}\right)}{Cover\_Crop\_Biomass\_\mathbf{N}}$$

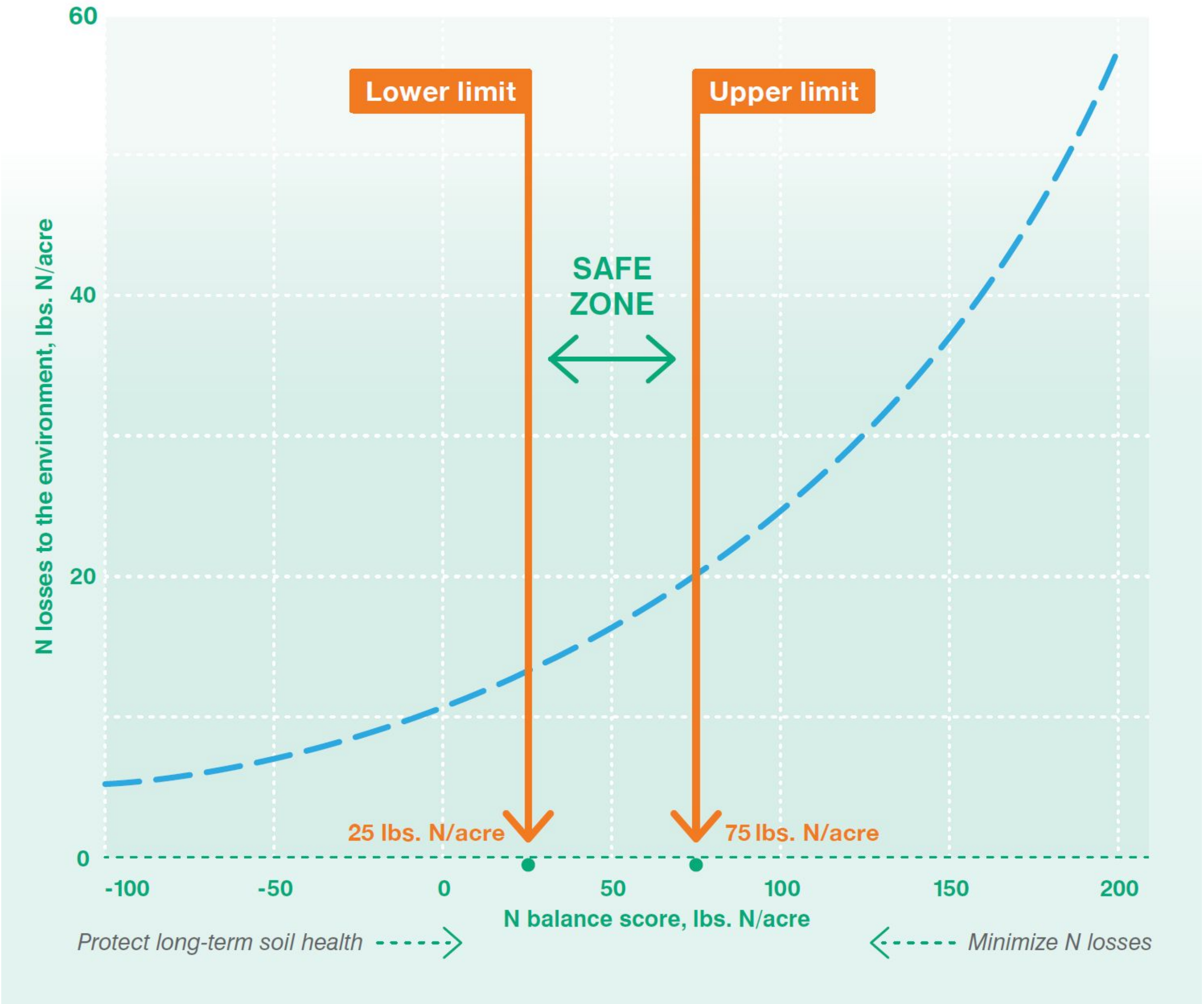
where ***Cover_Crop_Biomass_N*** is the total aboveground amount of N in the cover crop.[8]

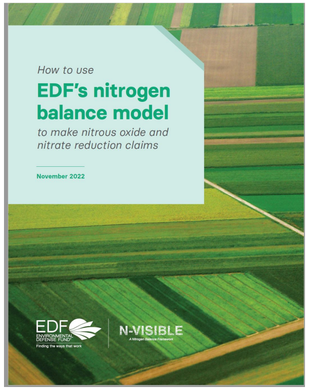


Helpful Additional Farm Information

- Year of entry to program.
- Program type (e.g., direct payments or agronomic support).
- N fertilizer and manure management practices (i.e., placement, timing, source, rate recommendations and manure nutrient testing).
- Tillage type and timing.
- Tile drainage type.
- Planting date for current crop.
- Pest management.
- Previous cash crop(s) and winter cover crops with planting and harvest dates.

How to use N budgets





How to determine **nitrous oxide emissions**

Calculate the amount of **nitrous oxide lost to the environment** for each unique field using the following area-based equation.

$$N_2O = 1.40e^{0.0047NBal}$$

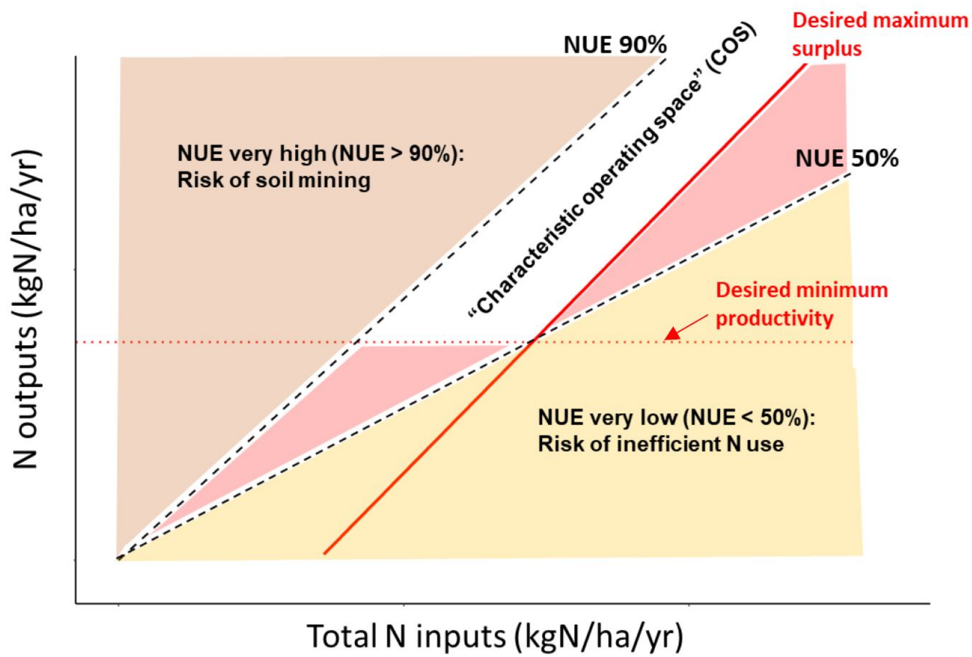
where ***N_2O*** denotes emissions in units of lbs. N_2O-N/acre/year, and ***N balance*** is N balance in units of kg N/hectare/year. Using this equation, fields with N balance scores of 25, 75 and 125 kg N/hectare/year would have average N_2O emissions equal to 1.6, 2.0 and 2.5 kg N_2O-N/hectare/year, respectively.

How to determine **nitrate leaching**

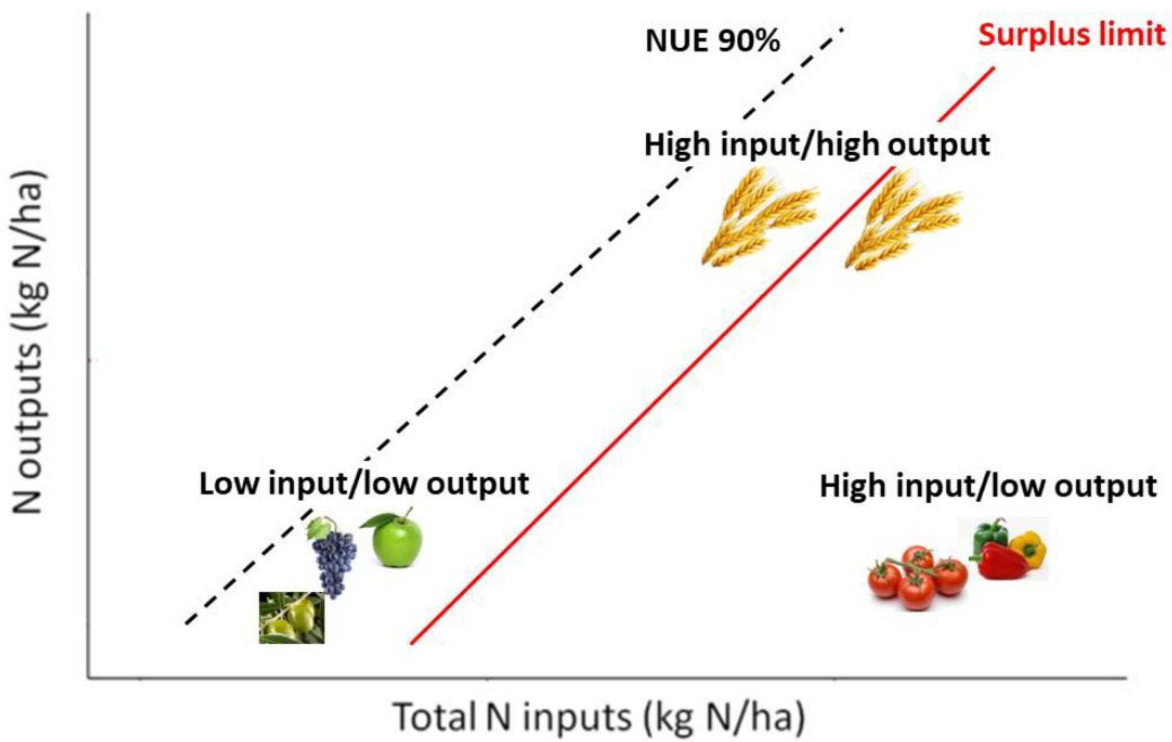
Calculate the amount of **nitrate lost to the environment** for each unique field using the following area-based equation.

$$NO_3 = 17.0e^{0.0036NBal}$$

where **NO_3** is leaching losses in units of kg NO_3-N/hectare/year, and **N balance** is N balance in kg N/hectare/year. Using this equation, fields with N balance scores of 25, 75 and 125 kg N/hectare/year would have average NO_3 leaching losses of 19, 22 and 27 kg NO_3-N/hectare/year, respectively.


Desired maximum surplus
NUE 90%
"Characteristic operating space" (COS)
NUE very high (NUE > 90%):
Risk of soil mining
NUE 50%
Desired minimum productivity
NUE very low (NUE < 50%):
Risk of inefficient N use
N outputs (kgN/ha/yr)
Total N inputs (kgN/ha/yr)

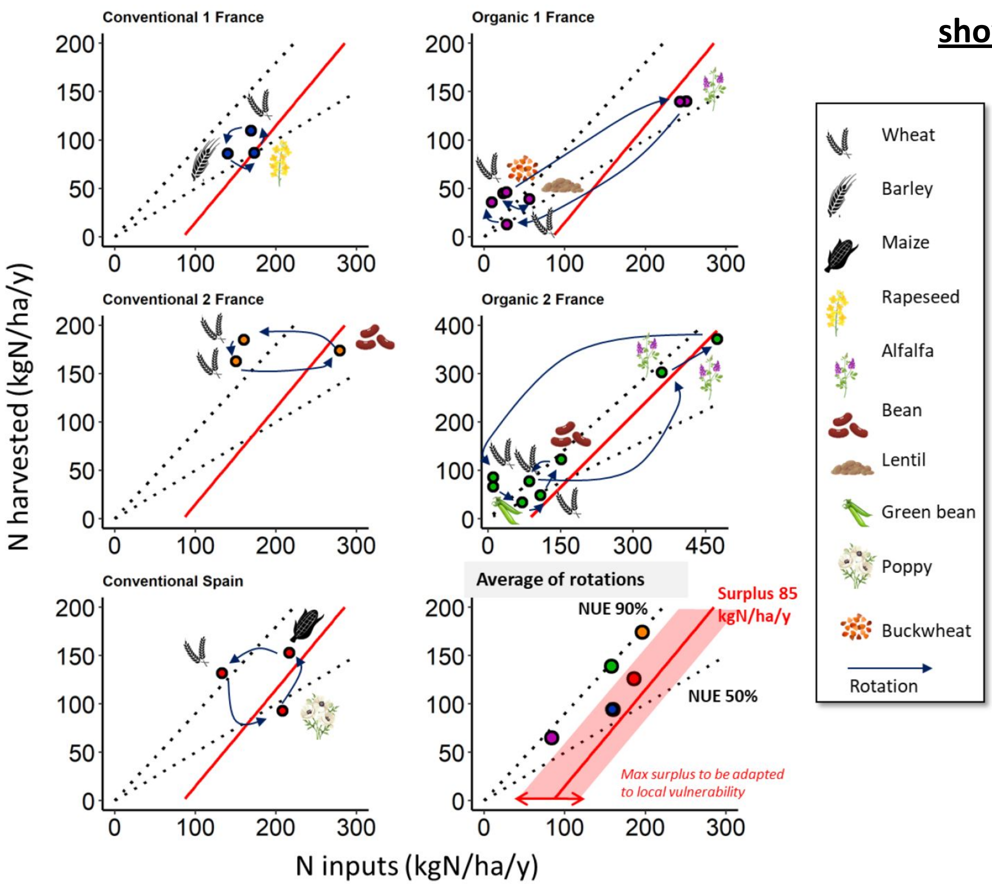
NUE varies for different crop types



Hayashi, K, Hooper, D, Quemada, M, Lassaletta, L, Bittman, S, 2021. NUE of 1535 non-protein or low protein crops. In: Lassaletta, L., Sanz-Cobena, A. (Eds.), Guidance Document on 1536 Nitrogen Use Efficiency Methodology for Different Purposes. INMS, Madrid, ISBN: xxx p. xxx.

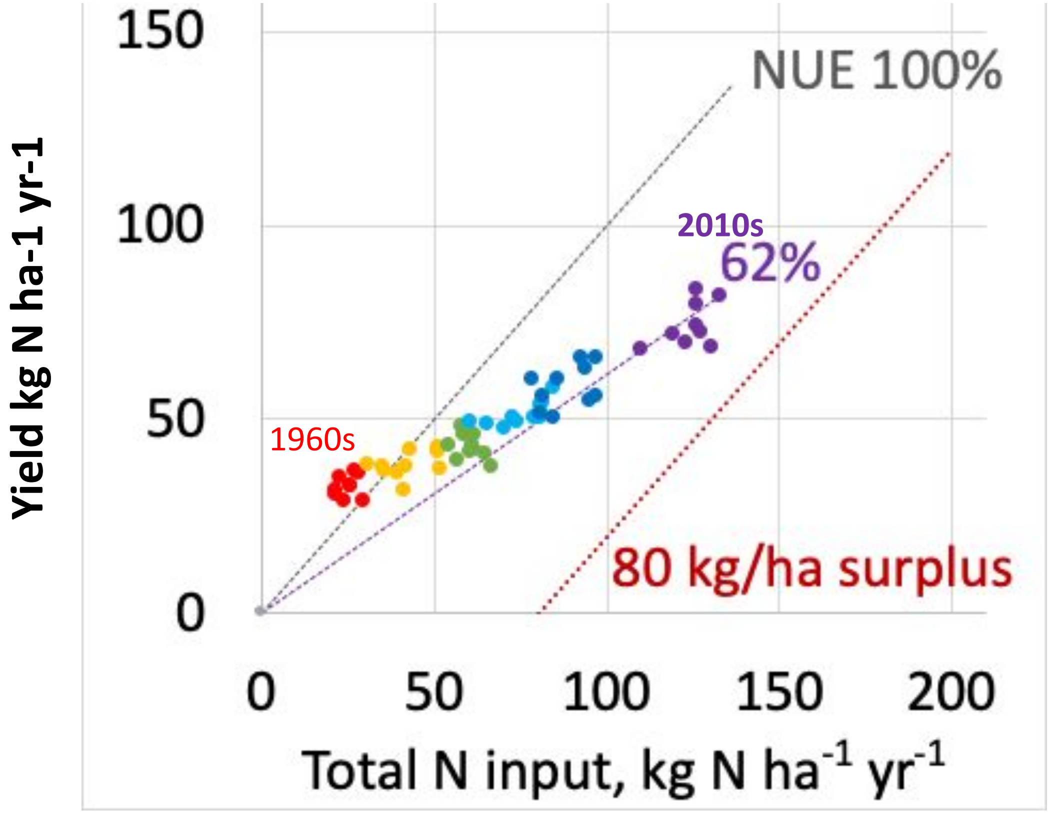
NUE for different cropping rotations

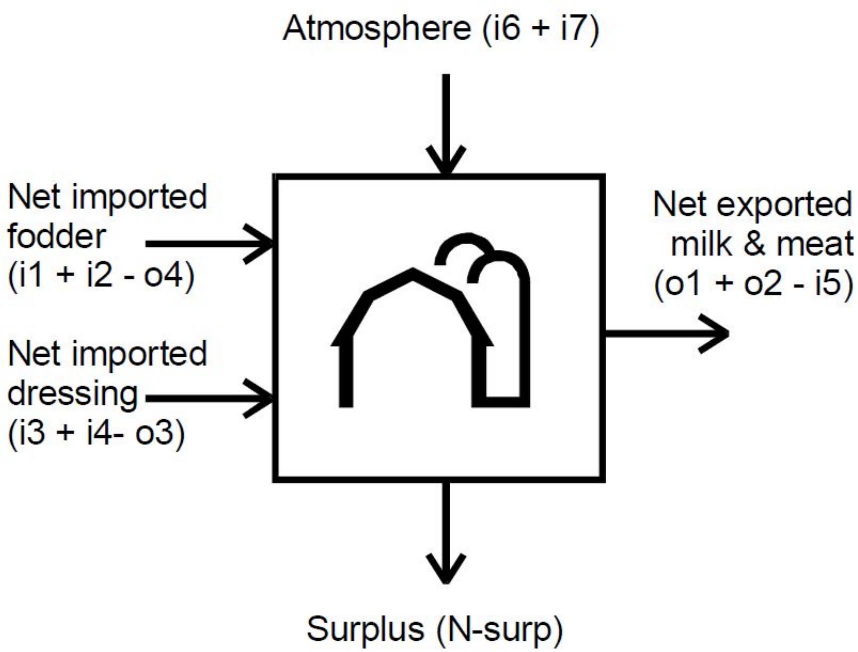
showing need for multi-year assessment



From Lassaletta, L., Garnier J., Quemada, M., Sanz-Cobeña, A., Mateo, A., Billen, G. 1403 2021. Considering the whole rotation when estimating NUE indicators. In: Lassaletta, L., Sanz-Cobena, A. 1404 (Eds.), Guidance Document on Nitrogen Use Efficiency Methodology for Different Purposes. INMS, 1405 Madrid, ISBN: xxx p. xxx.

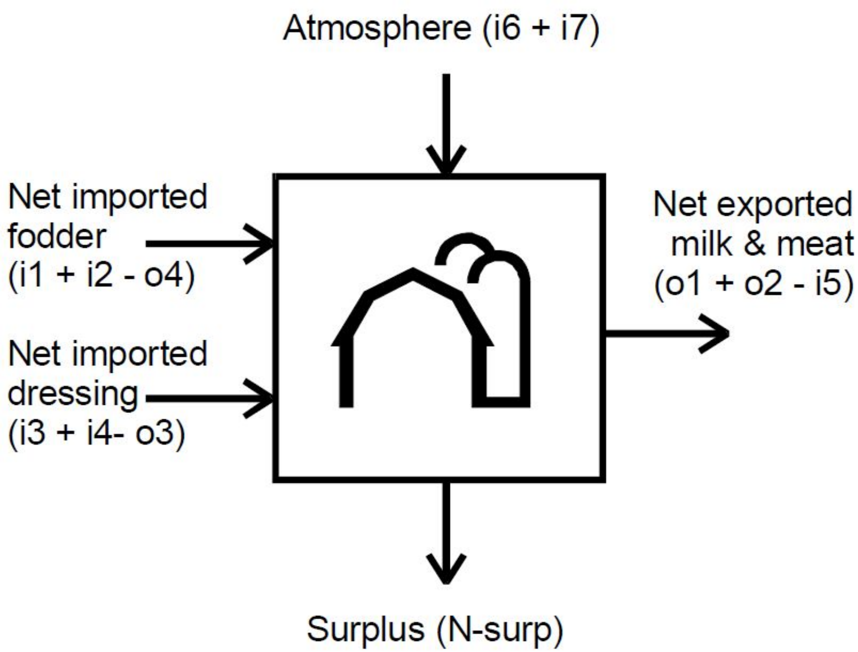
Trend in Nitrogen inputs and outputs and NUE from crop production in Canada between 1960s and 2010s

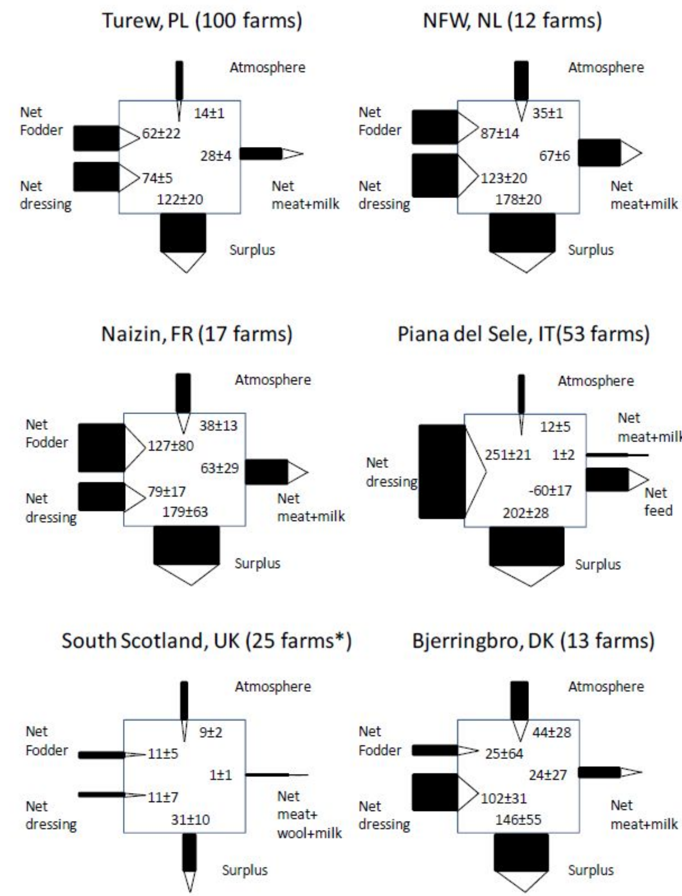




N-inputs:
i1= imported fodder
i2= imported seeds
i3= imported fertilisers
i4= imported manure
i5= imported animals
i6= deposited atmospheric N
i7= fixed atmospheric N

N-outputs:
o1= exported milk
o2= exported meat
o3= exported manure
o4= exported sales crops





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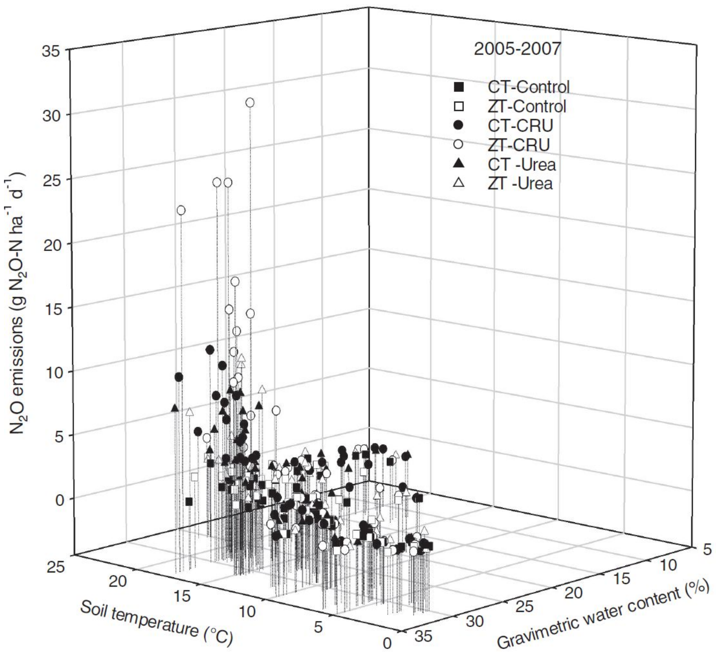
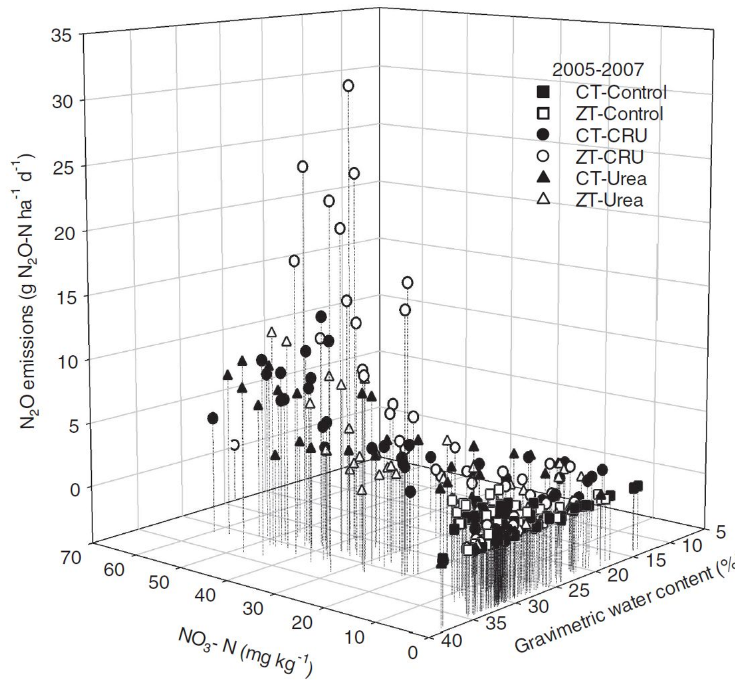
Effects of temperature water content and soil NO_3 on N_2O emissions



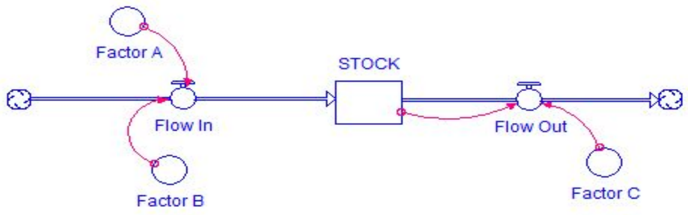


Message: high N_2O requires high soil moisture and temperature and soil nitrate (and fine textured soils) Avoid these combinations to reduce emissions

Bespoke nitrogen modelling for farmers using NLOS

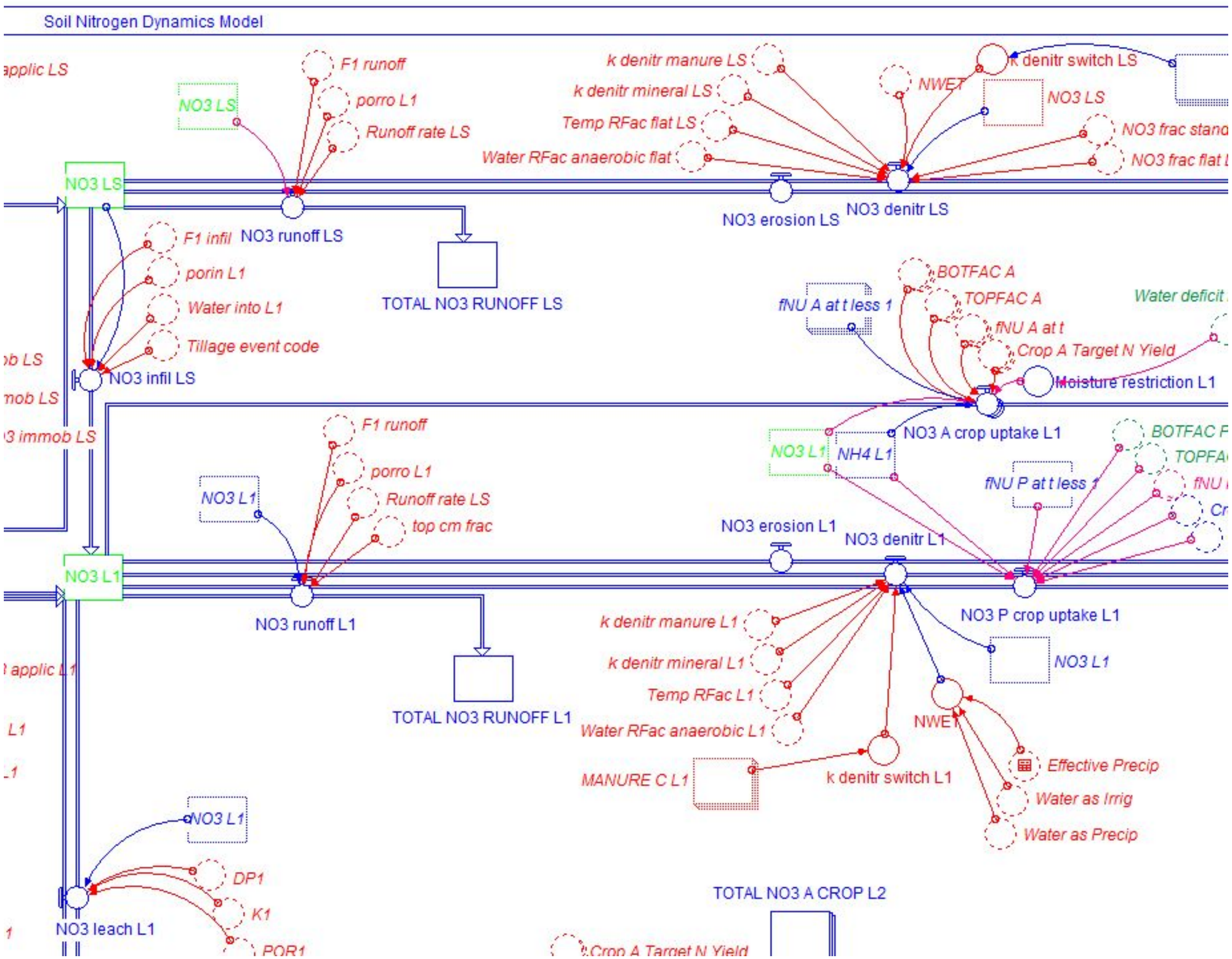
What is NLOS?

- NLOS (NLEAP on STELLA) is a dynamic mechanistic model that simulates soil N with a daily time step, using empirical knowledge of farm conditions
- The model uses climate, soil and management data to simulate all the major soil processes
- NLOS uses the system dynamics modeling approach and is constructed in an open-source code environment where all algorithms, equations, parameters, and assumptions can be readily viewed and manipulated by lay users.



This depicts most of the modelling lexicon used in NLOS

NLOS Model portion
depicting nitrate denitrification, runoff and crop uptake from upper soil layers



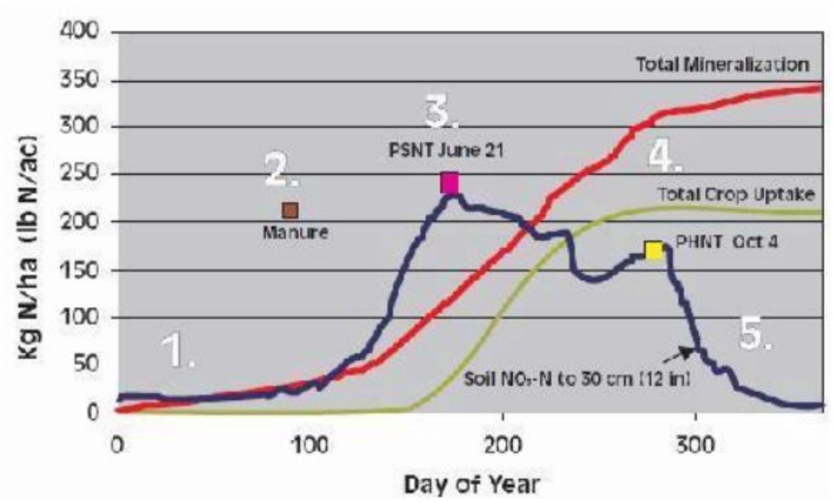
Unique aspects of NLOS

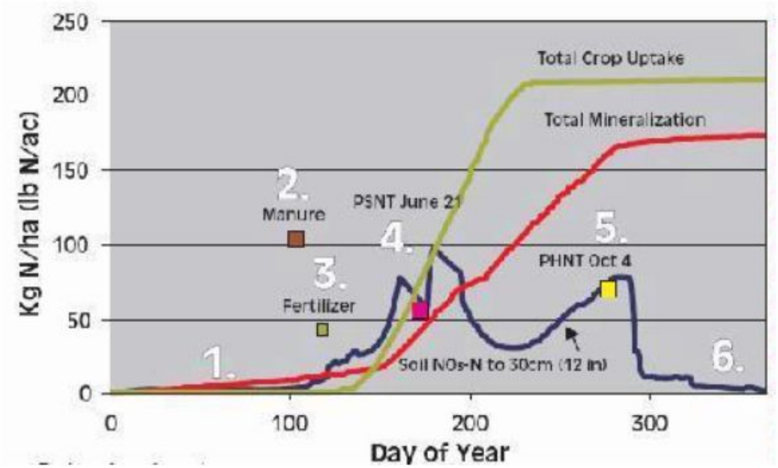
- **Coupling in real-time** of on-farm weather data, soil temperature and soil moisture with a complete soil N-plant-water simulation model
- Capability of **users to enter their own soil data and management information** and see in real-time the consequences of their management decisions.
- The model can be tested, customized and retested for each farm and each field, *i.e. according to the innovation cycle of a living lab.*
- The modelling is on the iconic STELLA platform that is *accessible to non-modelers*

Benefit of NLOS

- The real-time internet format allows for the most recent extension and research information to be provided to farmers for adoption in BMPS

NLOS application in soil testing based on Clark et al. 2004





Conclusions

- Canada is committed to reducing GHG; reducing N_2O emissions form agriculture as an important part of this
- Estimating emissions is done by emission inventories which are based on *emission factors based on N inputs x activity data, i.e. actual* N inputs.
- Canada uses empirical national emission factors to better estimate N_2O emissions than the IPCC default
- Reducing N inputs is a simple defensible systems for mitigating emissions. Good management practices (BMPS) can minimize or prevent yield loss.
- This can be documented with field and farm nitrogen budgets.
- Nutrient balances (surpluses) are correlated to N_2O emissions so reducing surpluses reduces direct and indirect (ammonia, nitrate leaching)
- Hence field and farm N budgets can be used to help estimate N_2O emission and reduce impact of N on air and water quality

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Thank You

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Canada

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N2O emission factors for manure and fertilizer on grass over 5 full years at Agassiz (2008-2013)

TABLE 5 | Mean N_2O-N emission factors for whole slurry, separated liquid fraction, and mineral fertilizer applied to perennial grass over a 5 year period in south-coastal BC, Canada.

(Hunt et al. 2019)

Treatment	Total (mineral) N applied kg ha^{-1}	2008–09		2009–10		2010–11		2011–12		2012–13		Mean	
FERT400	400 (400)	0.72	a+	0.78	a	0.94	a	0.95	a	0.80	a	0.84	a
WS400	406 (234)	0.21	b	0.28	c	0.62	b	0.46	c	0.32	b	0.38	c
SLF400	**405 (293)**	**0.72**	**a**	**0.49**	**b**	**0.67**	**b**	**0.64**	**bc**	**0.64**	**ab**	**0.63**	**b**
WS600	**584 (339)**	**0.31**	**b**	**0.61**	**ab**	**1.07**	**a**	**0.79**	**ab**	**0.44**	**b**	**0.65**	**b**
SLF600	559 (403)	0.97	a	0.59	ab	0.72	b	0.45	c	0.50	ab	0.65	b
Mean		0.59		0.55		0.80		0.66		0.54		0.63	
LSD		0.25		0.19		0.19		0.25		0.32		0.10	

Bolded treatments received similar rates of mineral-N.
+Values in a column not followed by the same letter are statistically different at P<0.05 using Fisher's protected LSD.

The N balance equation

N balance is calculated by:

$$N\ balance\left(\frac{lbs.\ N}{acre}\right) = Total\_N\_Applied\left(\frac{lbs.\ N}{acre}\right) - N\_Removed\left(\frac{lbs.\ N}{acre}\right)$$

Details on how to determine ***N_Removed*** and ***Total_N_Applied***, as well as sample **N balance** calculations, are provided below.

How to determine N_Removed

The amount of ***N_Removed*** at harvest is calculated by:

$$N\_Removed\left(\frac{lbs.\ N}{acre}\right) = \left[Grain\_N\left(\frac{lbs.\ N}{bu\ grain}\right) \times Crop\_Yield\left(\frac{bu\ grain}{acre}\right)\right] + \left[0.5 \times Grain\_N\left(\frac{lbs.\ N}{bu\ grain}\right) \times Crop\_Yield \times \%Stover\_Removed\right]$$

where ***N_Removed*** is the total ***N_Removed*** in the crop grain and stover, ***Grain_N*** is the concentration of N in the crop (e.g., the amount of N in each metric ton or bushel of grain) and ***Crop_Yield*** is the grain yield at standard moisture content (e.g., at 15.5% moisture for corn grain). To calculate the amount of ***N_Removed*** in stover (if applicable), the N harvest index of 0.5[1], ***Grain_N***, ***Crop_Yield*** and ***%Stover_Removed*** are multiplied.

Grain_N can be measured by testing a sample of grain for N content or by using the standard nutrient removal estimates from the International Plant Nutrition Institute (IPNI).[2]

How to determine Total_N_Applied

Total_N_Applied includes N from fertilizer, manure or legumes,[3] depending on which sources are added to a farm field:

$$Total\_N\_Applied\left(\frac{lbs.\ N}{acre}\right) = Fertilizer\_N\left(\frac{lbs.\ N}{acre}\right) + Manure\_N\left(\frac{lbs.\ N}{acre}\right) + Legume\_Fixed\_N\left(\frac{lbs.\ N}{acre}\right)$$

To effectively account for changes due to the impacts of farm management practices, more complex modelling approaches are required, both in the collection of activity data and in the estimation

but at typical Canadina rates this has not been observed (Rochette et al. 2018).

The IPCC default EF does not account for variations that occur due to types of soil, crop, land use, sources of N and climate. Some of the key factors that influence the N_2Oemissions are; N inputs, land use, soil temperature, water-filled pore space or soil water content, clay, sand, organic C and N content, and precipitation(Butterbach-Bahl et al. 2013; Sozanska et al. 2002;Freibauer and Kaltsmith 2003; Lu et al. 2006).Methodologies to quantify N_2O emissions from agricultural sources are mostly empirical (Bouwman et al.2002a, b; Da¨mmgen and Gru¨nhage 2002; Sozanskaet al. 2002; Freibauer 2003; Roelandt et al. 2005; Luet al. 2006; Dechow and Freibauer 2011). All these methods are based on multivariate linear regressions.

For instance, a spatial inventory of N_2O emissions from agricultural and non-agricultural soils in Great Britain was proposed using a simple regression model within a GIS framework (Sozanska et al. 2002). The underlying regression model was based on published N_2O data from soils of temperate climates, describing emissions as a function of N input (N), water filled pore space (WFPS), soil temperature (TS) and land use (A):

N2O kgN ha1 yr1 ¼ 2:7 þ 0:60InN kgNha1 yr1 þ 0:61lnWFPSð%Þ þ 0:035TSðCÞ0:99A:

Some references

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- McLellan, E.L., K.G. Cassman, A.J. Eagle, P.B. Woodbury, S. Sela, C. Tonitto, et al. 2018. The nitrogen balancing act:Tracking the environmental performance of food production. BioScience 68:194-203. doi:10.1093/biosci/bix164.
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New approach is real time field calibrated Modelling

- NLOS model and NLOS on the web (NOW)

Reducing N inputs and surpluses

- It is well known that fertilizer and manure efficiency can be improved with better practices and sometimes these are summarized as 4 Rs practices. Best methods include fertilizer and manure applicators that minimize emission of ammonia which can account for sizable losses of N, especially where the pH is high. High pH occurs when urea is rapidly hydrolyzed and this can lead to losses of 30-60% so injection, banding or slow release with a urease inhibitor can help. With manure low emission applicators, rapid infiltration and lower pH especially for biogas effluent which has about a point higher pH. Timing application is effective when it can be accomplished for example when rain of greater than 1 cm will follow.
-

Proxy for N2O

- N2O emission form soils (main emission) are counted in inventories by accounting for emissions associated with N inputs to soils. N2o is product of amount of each N product x an emission factor, mineral fertilizer > Manure > biological fixation. Farmers can show reduced emission by using less fertizler or by replacing fertizlr with fixation and manure.

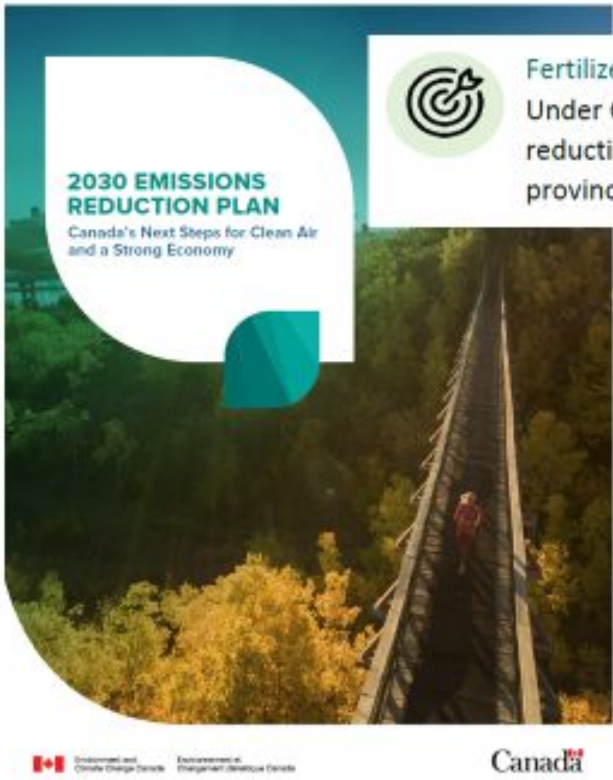
Tier 2 Country specific N2O emission factors

	Soil N_2O EF kg N_2O-N kg^{-1}N
Synthetic Nitrogen	0.0211 ± 0.0092
Organic Nitrogen	0.0177 ± 0.0064
Crop Residue Nitrogen	0.0059 ± 0.0027
Fine	0.0304 ± 0.0108
Medium + Coarse	0.00585 ± 0.0035
Mean	0.0119

Canada	Cropping System (RF_CS)	Annual	0.0211 ± 0.0092
		Perennial	0.0041 ± 0.0013

Average N_2O emissions from legumes are
N ha$_1$ for annual crops, 1.8 kg N ha$_1$ for pu
0.4 kg N ha$_1$ for grass legume mixes.

Driving Factor



Fertilizer Emission Reductions

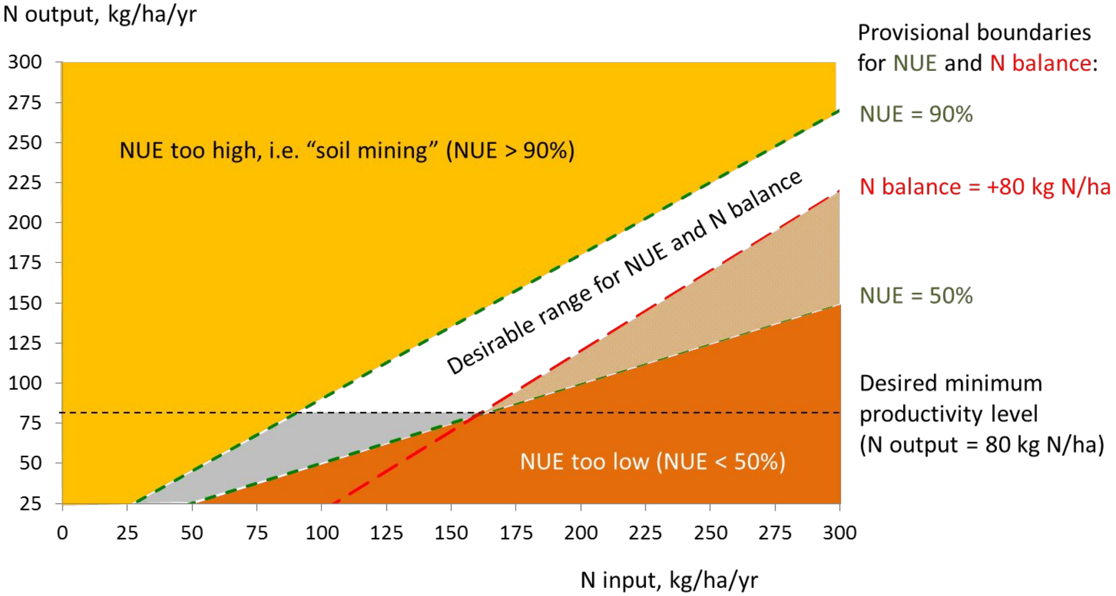
Under Canada's strengthened climate plan, Canada committed to setting a national fertilizer emission reduction target of 30% below 2020 levels by 2030 and to work with fertilizer manufacturers, farmers, provinces and territories to develop an approach to meet it.

- In 2019, Canada's direct N_2O emissions from synthetic fertilizer application was ~11 Mt CO_2e.
- Implies a reduction on the order of 3 Mt CO_2e by 2030.
- Absent BMPs that can reduce emissions, this would require a reduction in synthetic fertilizer consumption on the order of 0.8 Mt nitrogen.
- There are 8 growing seasons until 2030.

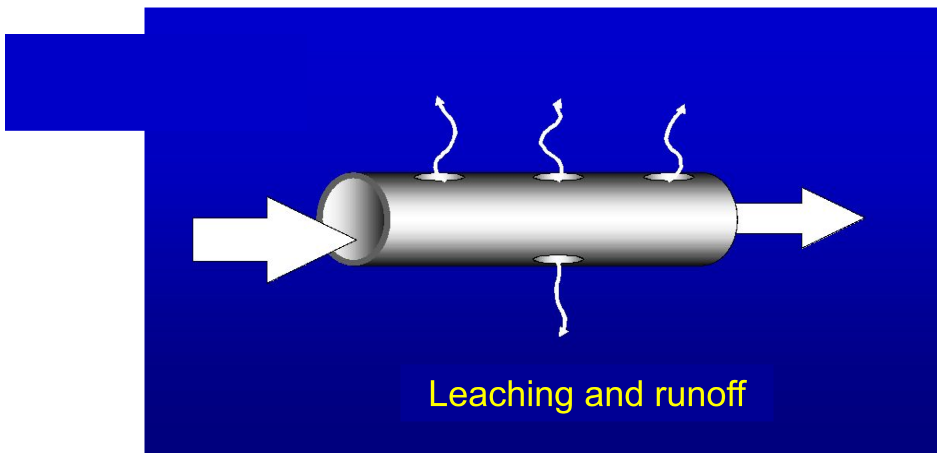
March 29, 2022

A graphical presentation of N balance

Fig. 1c: Definition of acceptable boundaries for N output/input ratios giving a desirable range for NUE – supplemented by an acceptable N balance surplus
(all values are provisional and only serve as examples)

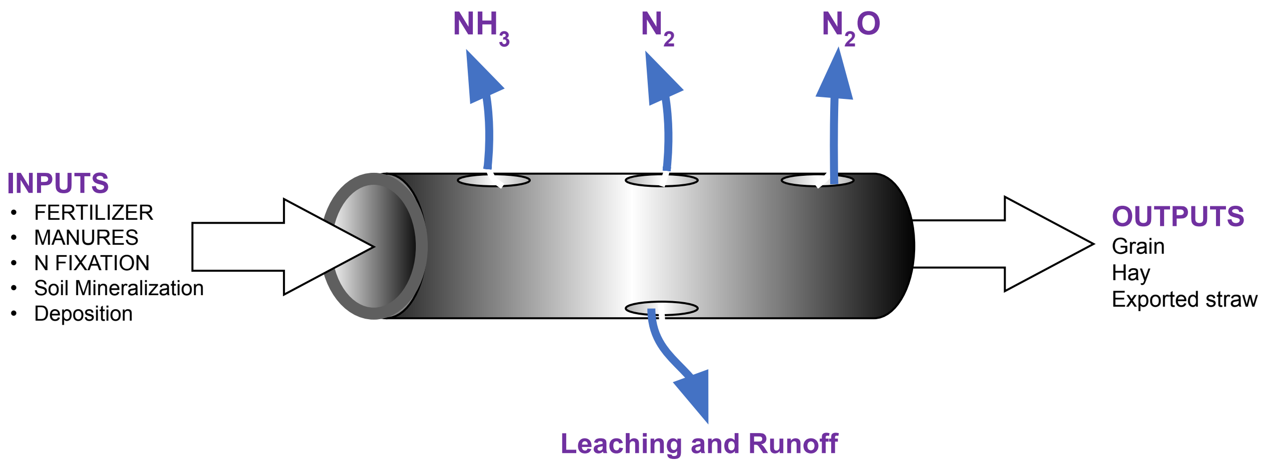


Nutrient Budgets- Field



Leaky Pipe Model

Nitrogen Budget (field)



Sources of N

- There are three primary de novo sources of plant N, mineral fertilizer and biological fixation and chemical fixation by lightening. Purple arrows
- The recycled sources are manure, atmospheric deposition and soil mineralization (green arrows
- Losses to water are blue and losses to air are orange red boxes are fates of lost N

Inputs to Canadian Agroecoystesm Bilogical fixation 0.94, Fertilizer 2.54, atmospheric fixation 0.32= 3.8

Crop outputs 1.93, livestock outputs 0.33, =2.26

Surplus 1.54 NUE =59%

What is efficiency of whole food system and how can N be returned to source?

based on Karimi et al.