Modelling nitrous oxide (N_2O) emission from soils using the Soil and Water Assessment Tool (SWAT): A case study of Athabasca River Basin (ARB), Canada

Narayan K. Shrestha, Junye Wang*

[1]Athabasca River Basin Research Institute (ARBRI)

Athabasca University, 1 University Drive, Athabasca, Alberta T9S 3A3, Canada

*Correspondence to: junyew@athabascau.ca

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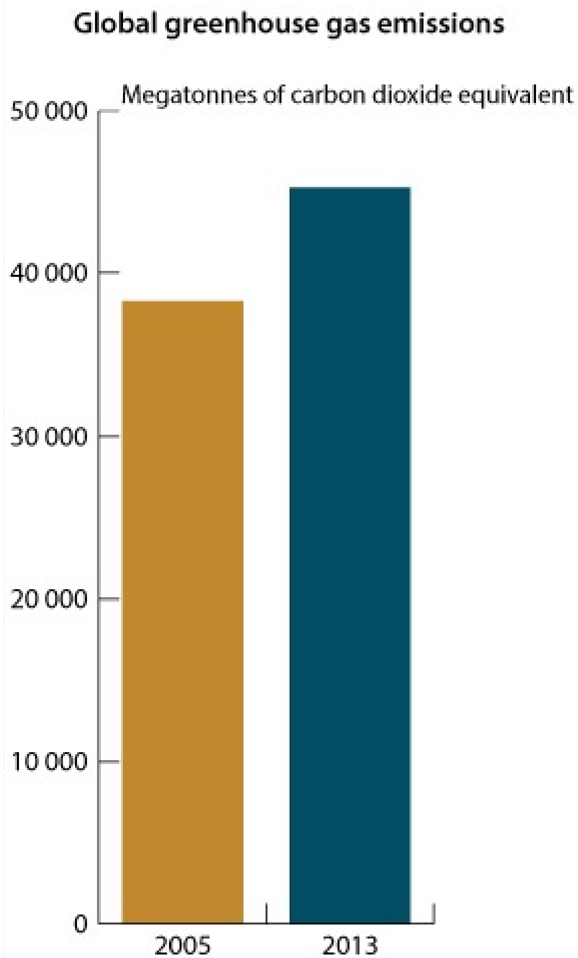
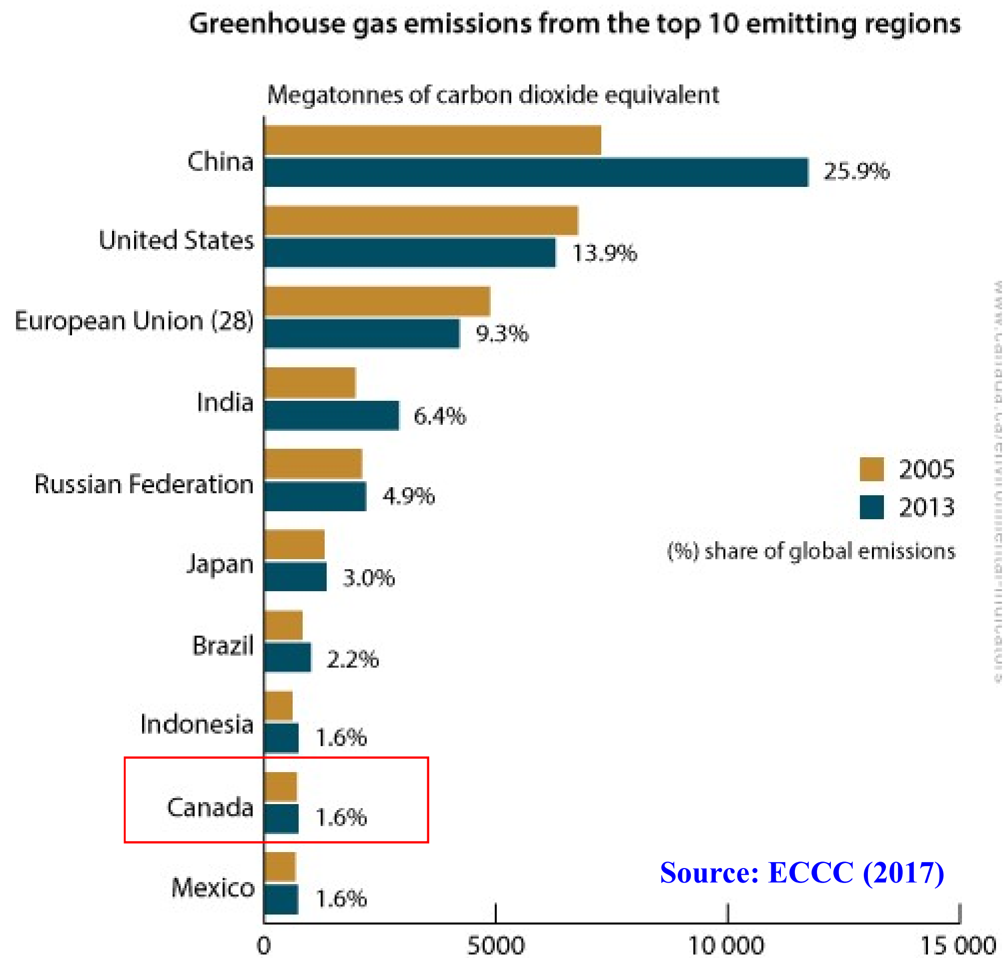
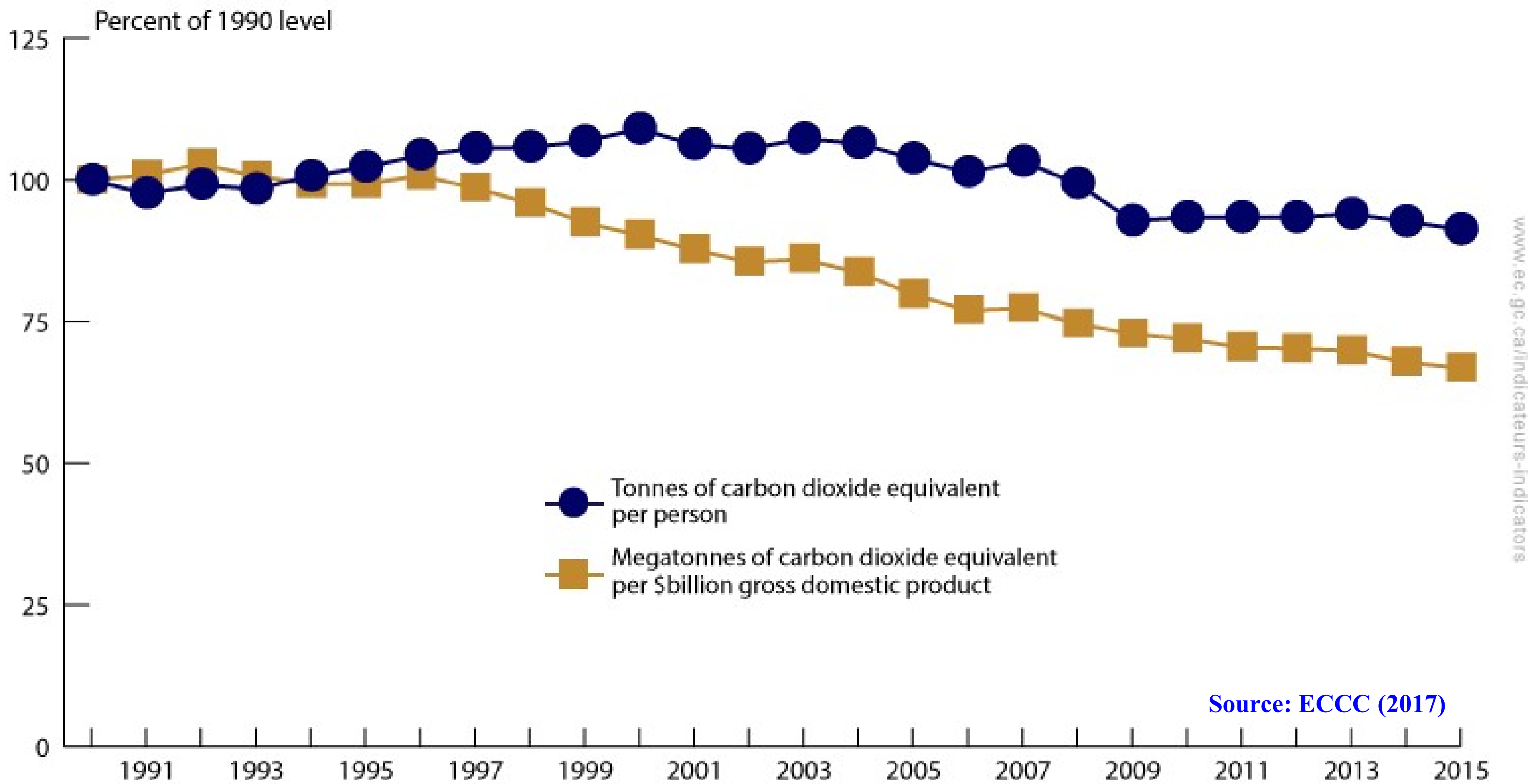
Background





Source: ECCC (2017)

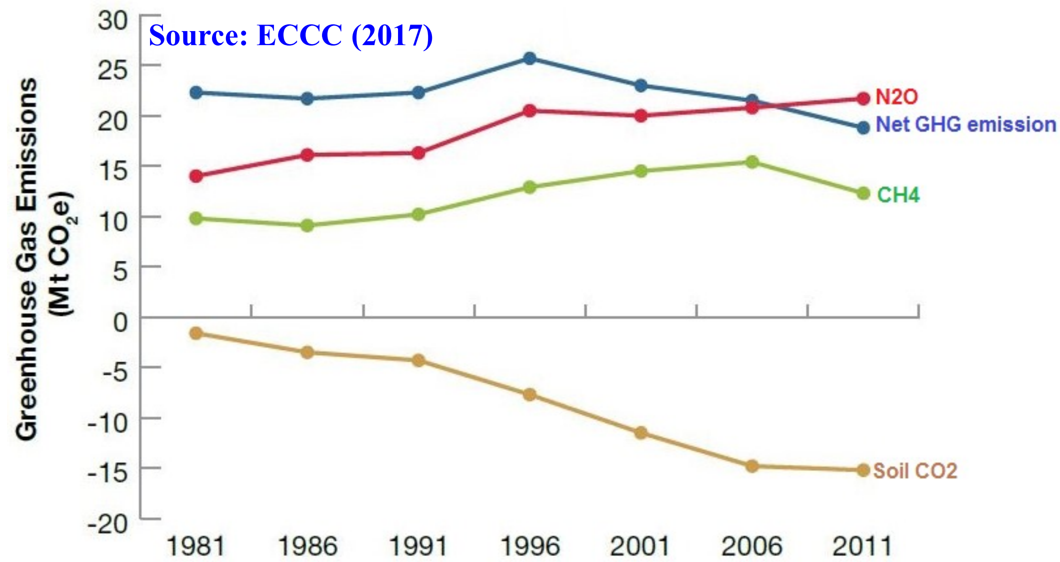
Background…

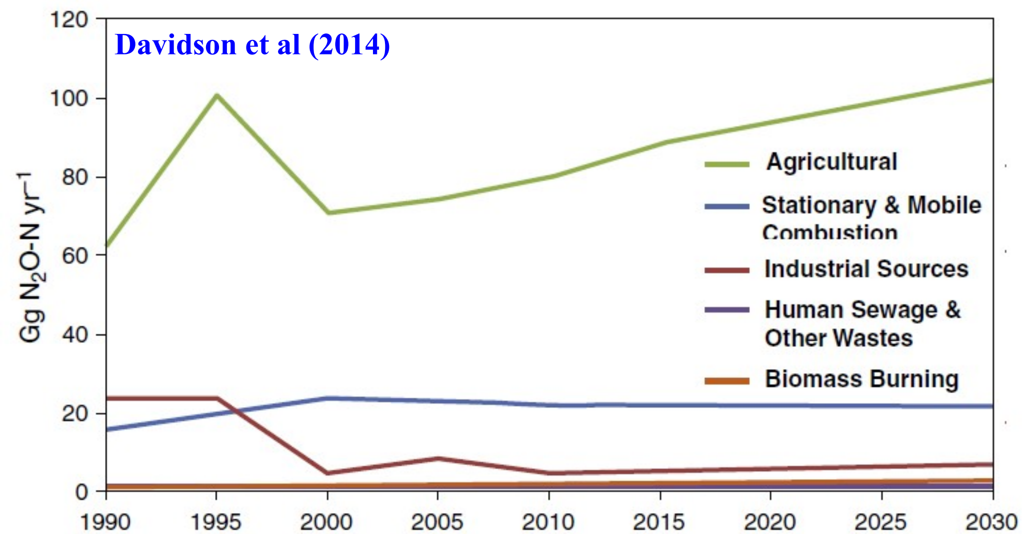


Source: ECCC (2017)

Background…

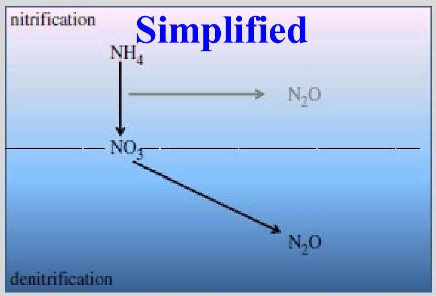
- Although Prairie farmlands have been significant CO_2 sink, N_2O increase attributed to nitrogen fertilizer increase
- N_2O is more potent (~300 times) than CO_2
- Site based measurements often fail to capture the spatial and temporal variability of N_2O
- Regional scale modelling is thus needed to test various adaptation measures
- Various tools (DNDC, DAYCENT, etc) are being used for such purposes, still regional scale estimations are often scare

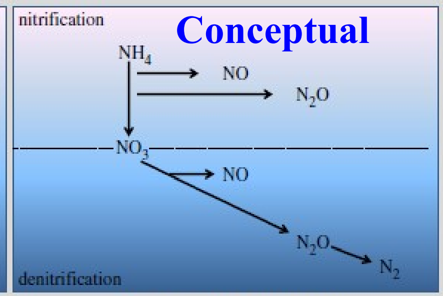


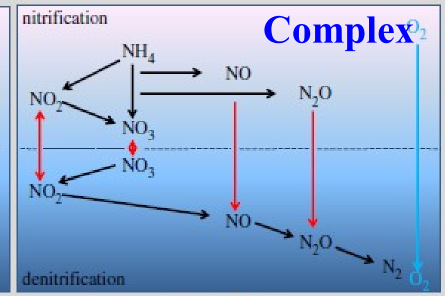


N_2O modelling – choice of a modelling tool

scheme :





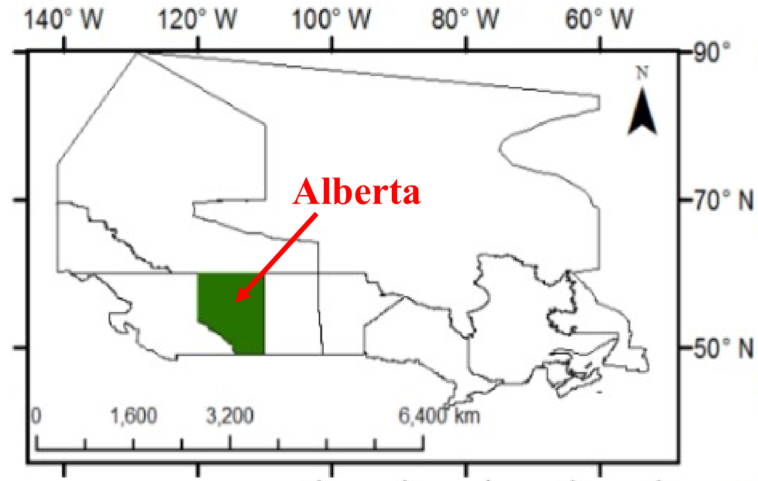


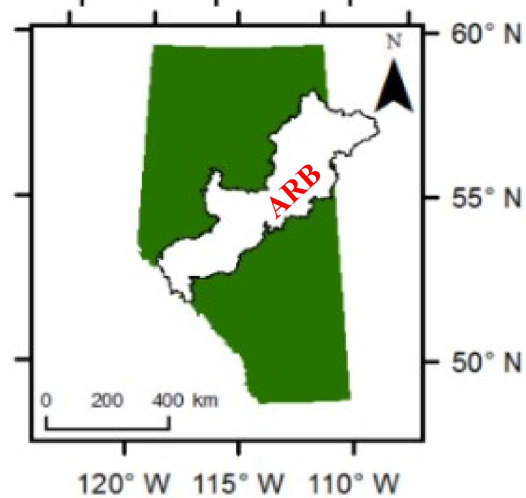
	Simplified	Conceptual	Complex
process description :	$pN_2O_{denit}[sl] = NO_3[sl] * f(temp, moisture, pH, availC)$ $flux\ N_2O = \Sigma pN_2O_{denit}[sl]$	$rate_{nit}[sl] = NH4[sl] * f(temp, moisture, pH)$ $pN_2O_{nit}[sl]=rate_{nit}[sl]*$ fixed fraction or $f(moisture)$ $pN_2O_{denit}[sl] = NO_3[sl] * f(temp, moisture, pH, availC)$ $flux\ N_2O = \Sigma(pN_2O_{nit}[sl] + pN_2O_{denit}[sl])$	$rate_{nit} = NH4 * f(temp, moisture, pH, micC, micC_{act}, concO_2)$ $pN_2O_{nit} = rate_{nit} *$ fraction $* f(temp, moist, pH)$ $pN_2O_{denit} = NO_3\text{-}NO_2\text{-}NO\text{-}N_2O\text{-}N_2 * f(temp, moisture, pH, micC, micC_{act}, availC, concO_2)$ $cN_2O[sl] = N_2O[sl] + pN_2O_{nit}[sl] + pN_2O_{denit}[sl]$ $dN_2O = cN_2O[sl] - cN_2O[sl+1]$ $diffusivity = f(porosity, moisture, temp)$ $flux\ N_2O = f(dN_2O, diffusivity)$
models:	see list in Heinen [99]	e.g. CERES-EGC [100] DAYCENT [101,102] ORCHIDEE [103]	e.g. ECOSYS [104] DNDC [105,106] COUPMODEL [107] MicNit [108]
temporal resolution	–	+	+
multi ecosystems	–	±	±
pulse emission	–	±	+
climate change scenarios	±	±	+
adaptation/ mitigation	±	±	+
input, validation	+	±	–
computational demand	+	±	–

Butterbach-Bahl et al. (2013)

The Athabasca River Basin (ARB)

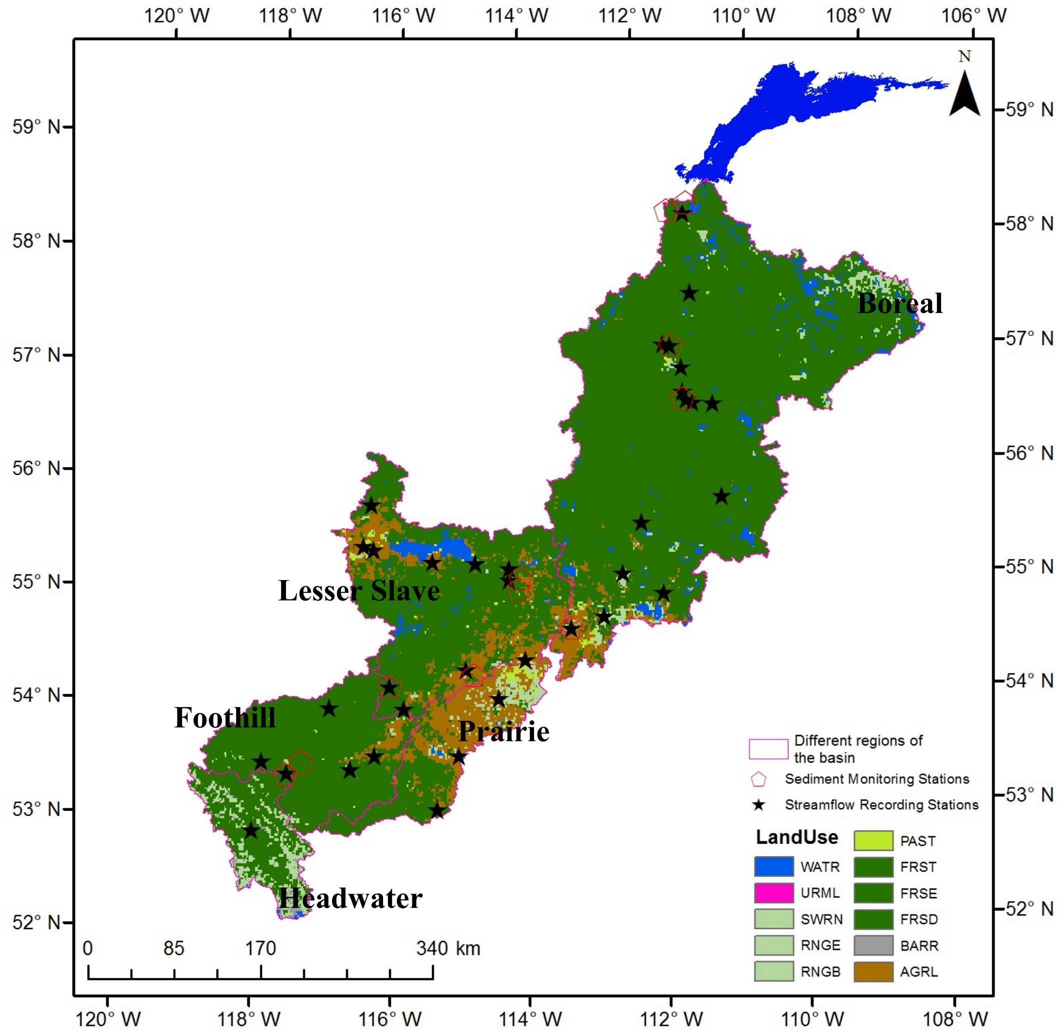
- The Athabasca River Basin (ARB), Canada contributes significantly to the provincial economy
- Ever increasing industrialization and growing population have posed on an immense pressure to the water resources of the basin
- Environmental impacts of industries and different human activities on the ecological functioning of the river are quite evident
- An integrated modeling framework encompassing both the terrestrial and aquatic systems is needed for holistic analysis of the river basin
- Soil and Water Assessment Tool (SWAT) is chosen as modelling framework





The SWAT model of ARB

- A SWAT model is built up using high resolution spatial and meteorological data set, considering point sources of pollution from WWTPs and industries, and using appropriate management practices for agriculture land, grass land, pasture and other land-use types
- Sensitivity, calibration and validation and uncertainty analysis have been carried out for streamflow, sediment and various water quality variables
- We refer to Shrestha & Wang (2017), Shrestha et al. (2017) for details of the SWAT model of the ARB



N_2O modelling in SWAT

- We incorporated semi-empirical equations of Parton et al. (1996, 2001) for N_2O emission from nitrification and denitrification
- In general, these equations calculate the potential N_2O flux rate subject to several 'reduction factors' that reflect environmental controls on the flux

Denitrification

$$DENIT_{total} = \min\left[F_{denit}(NO3), F_{denit}(C)\right] * F_{denit}(WFPS) * F_{denit}(SOLT)$$

$$F_{\mathrm{N2O,denit}} = \frac{DENIT_{total}}{\left(1 + Ratio_{\mathrm{N2:N2O}}\right)}$$

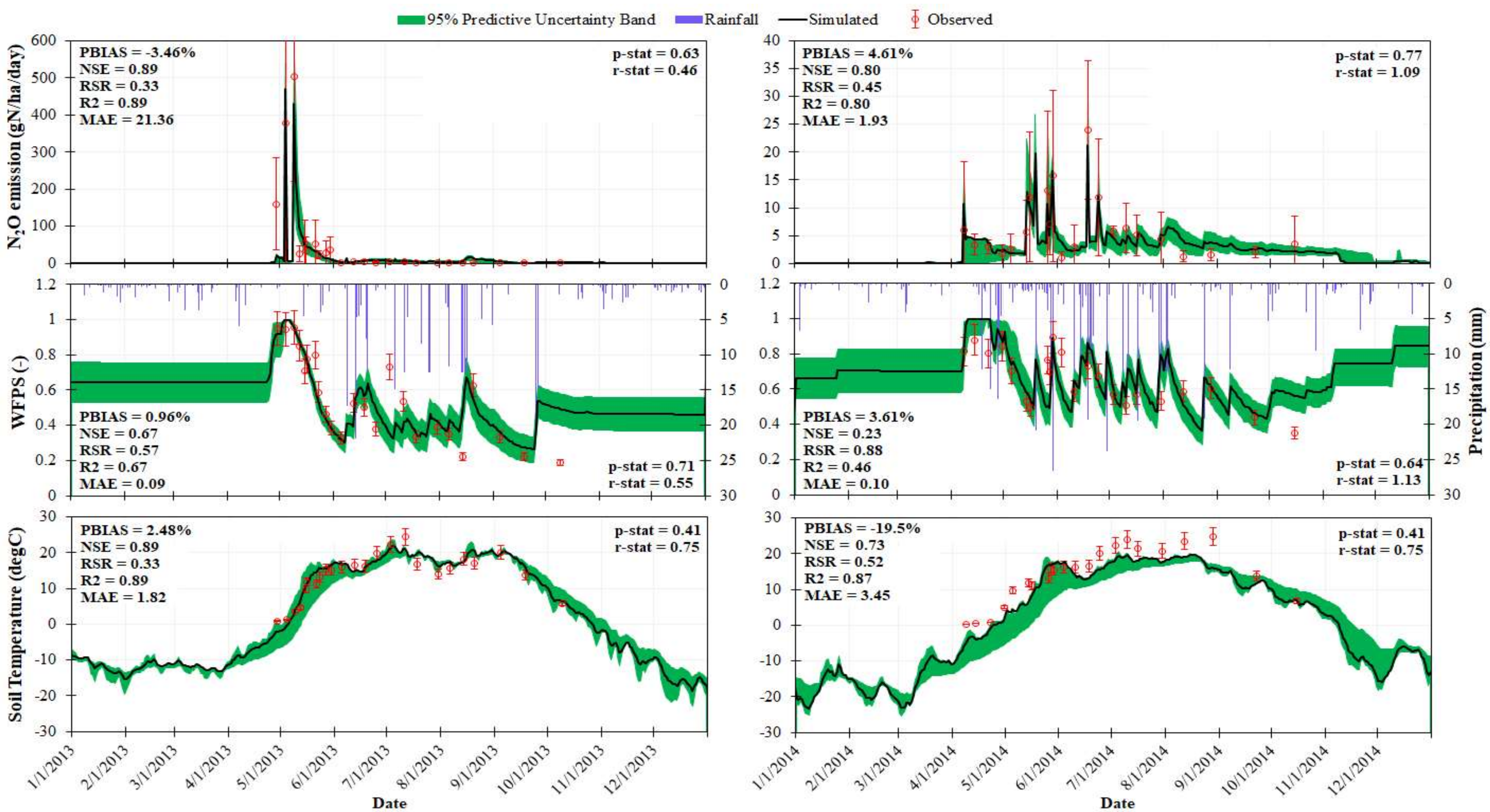
$$Ratio_{\mathrm{N2:N2O}} = \min\left[F_{ratio}\left(NO3\right), F_{ratio}\left(C\right)\right] * F_{ratio}\left(WFPS\right)$$

Nitrification

$$F_{\mathrm{NO3,nit}} = Net_{\min} * K_1 + K_{\max} * \mathrm{NH4} * F_{nit}(SOLT) * F_{nit}(WFPS) * F_{nit}(pH)$$

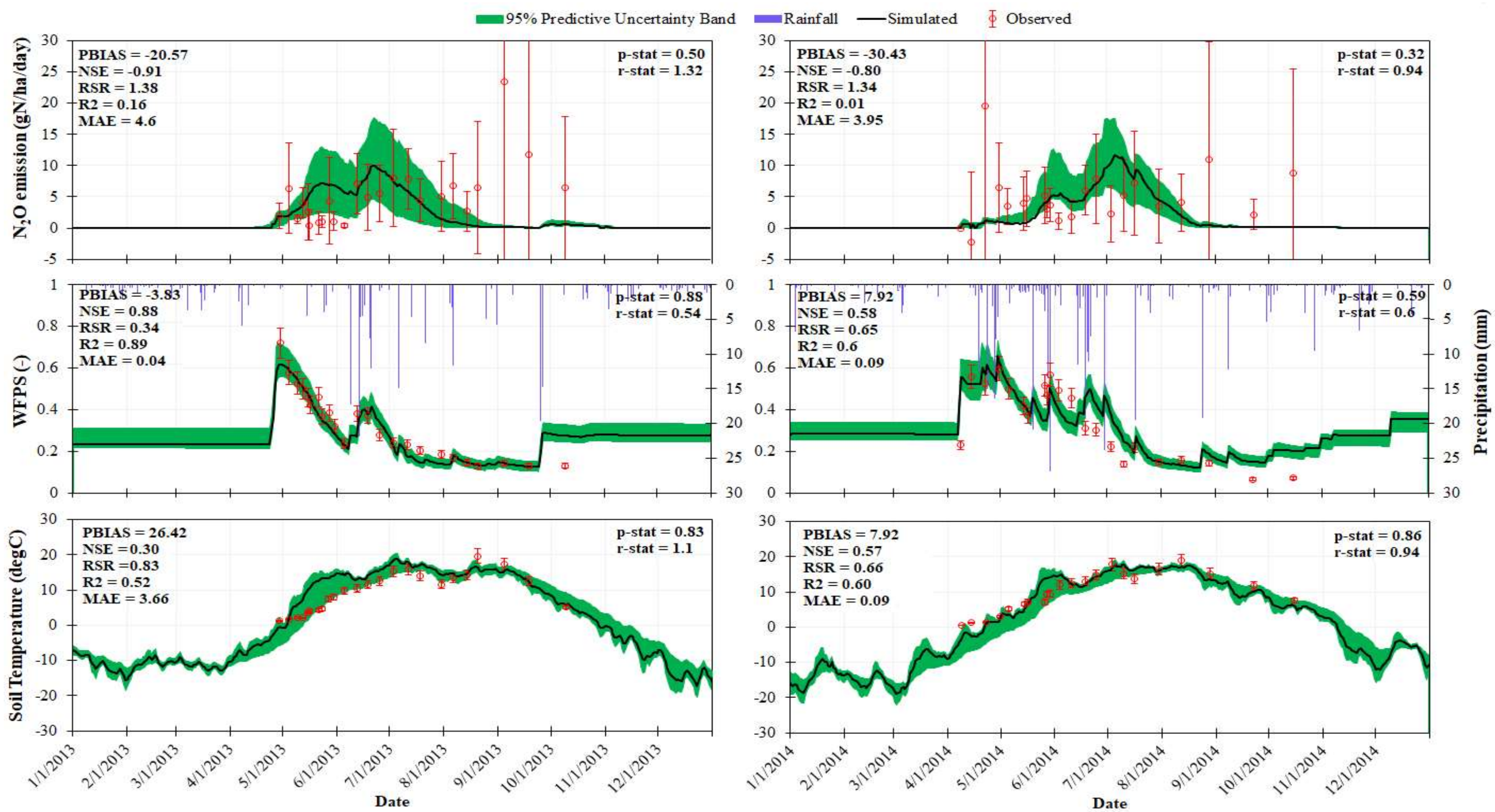
N_2O modelling in SWAT: Calibration and validation in a cropped field

- **Location:** SK, Canada; **Crop:** Winter wheat; **Fertilizer:** 70 kg N/ha; **Calibration:** 2013; **Validation:** 2014



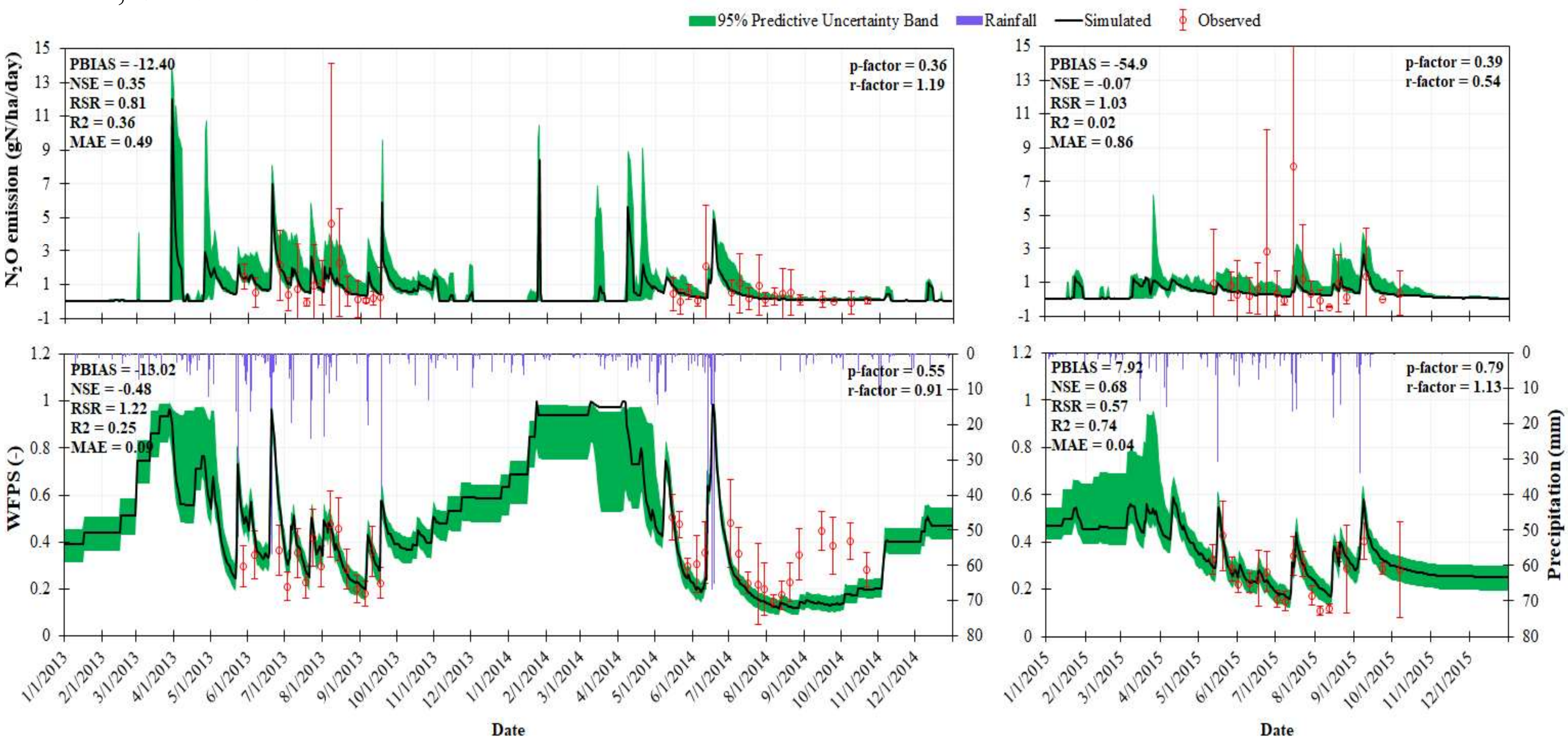
N_2O modelling in SWAT: Calibration and validation in a shelterbelt

- **Location:** SK, Canada; **Treeline:** Pine; **Fertilizer:** None; **Calibration:** 2013; **Validation:** 2014



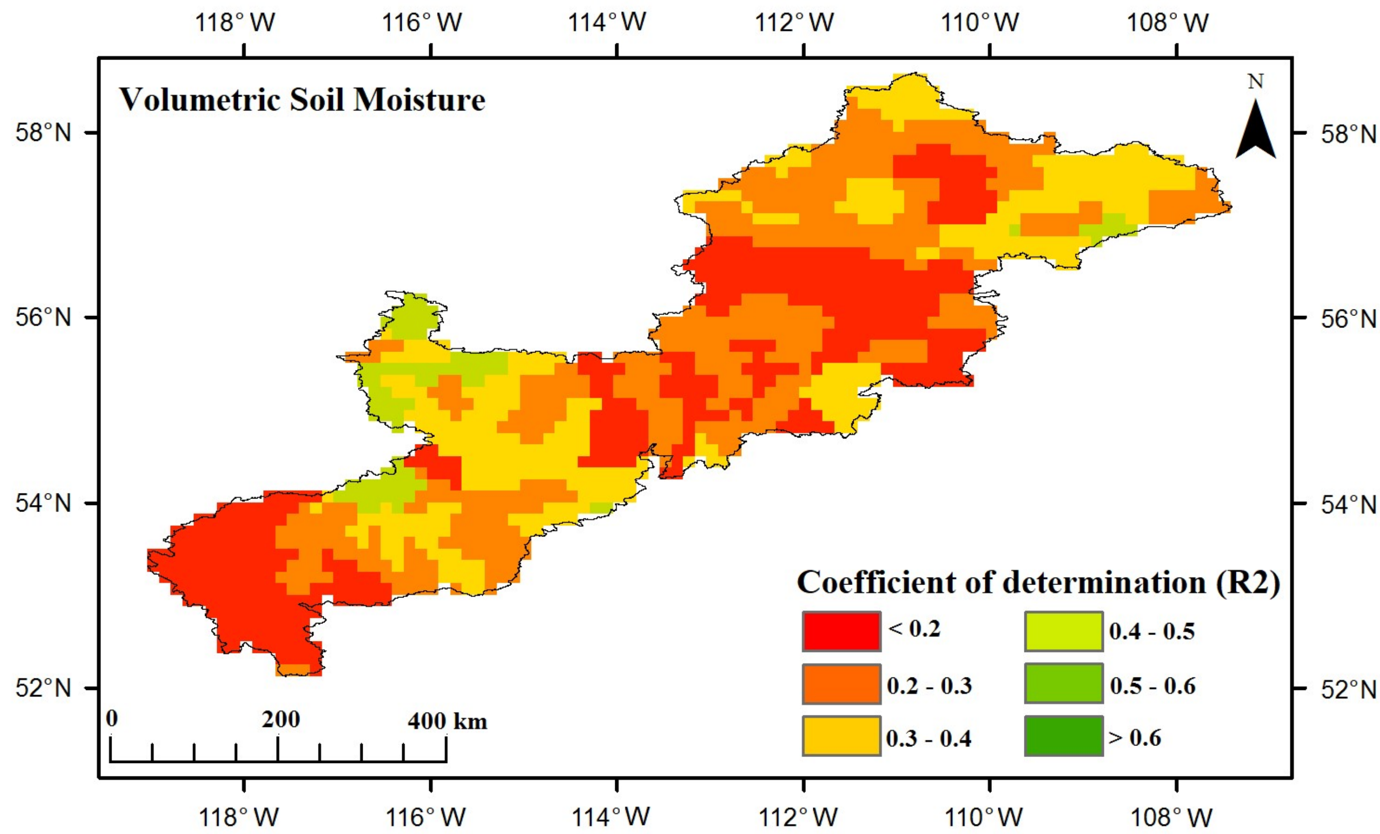
N_2O modelling in SWAT: Calibration and validation in a grassland site

- **Location:** AB; **Grazing intensity:** Heavy (4.8 AMU/ha) **Fertilizer:** Urine and manure; **Calibration:** 2013-14; **Validation:** 2015



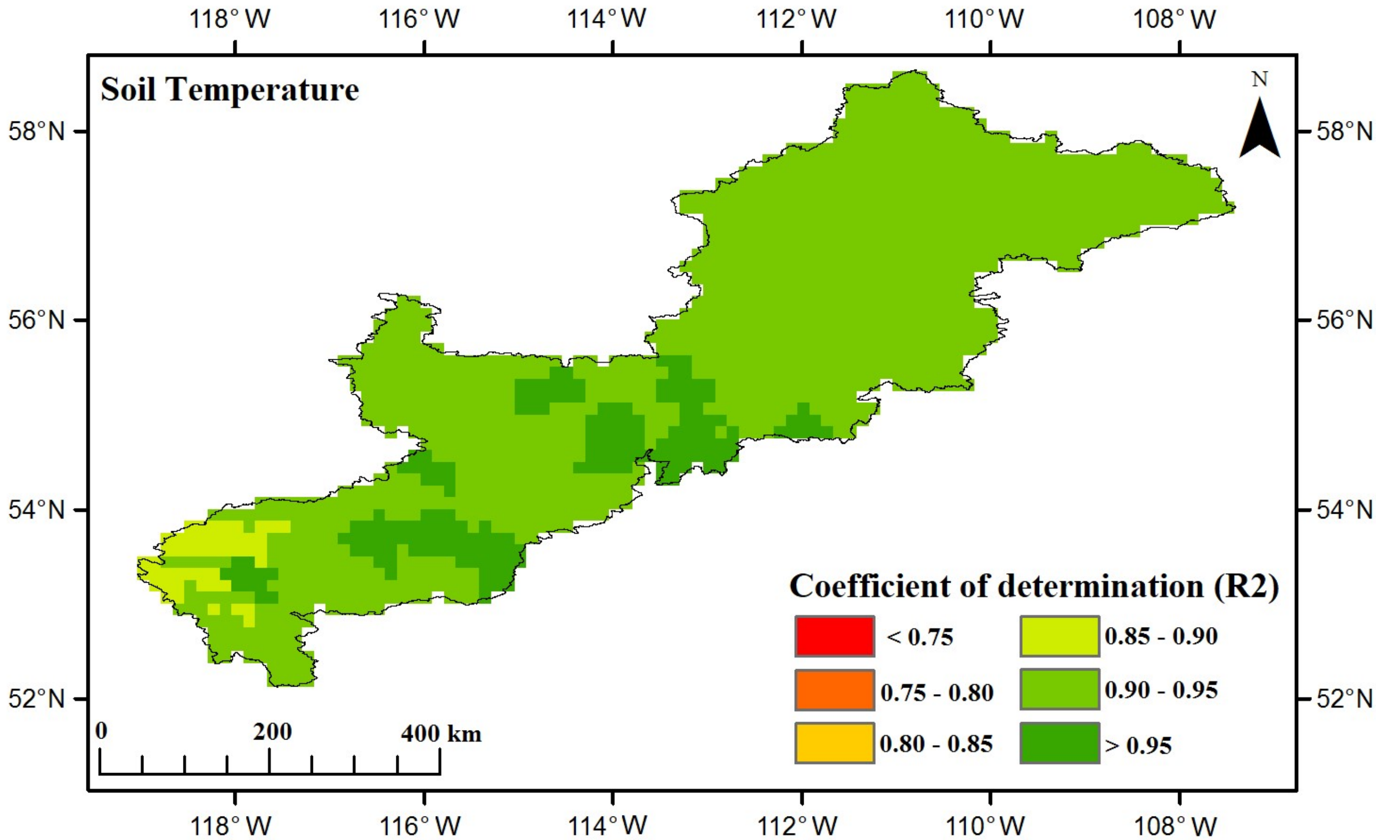
N2O modelling in SWAT: WFPS simulations

- SWAT simulated soil moisture (volumetric) vs 0.125° ERA-Interim reanalysis product (Dee et al. 2011) at each pixels (resampled to 0.05°x0.05°) for a period of 1990-2005



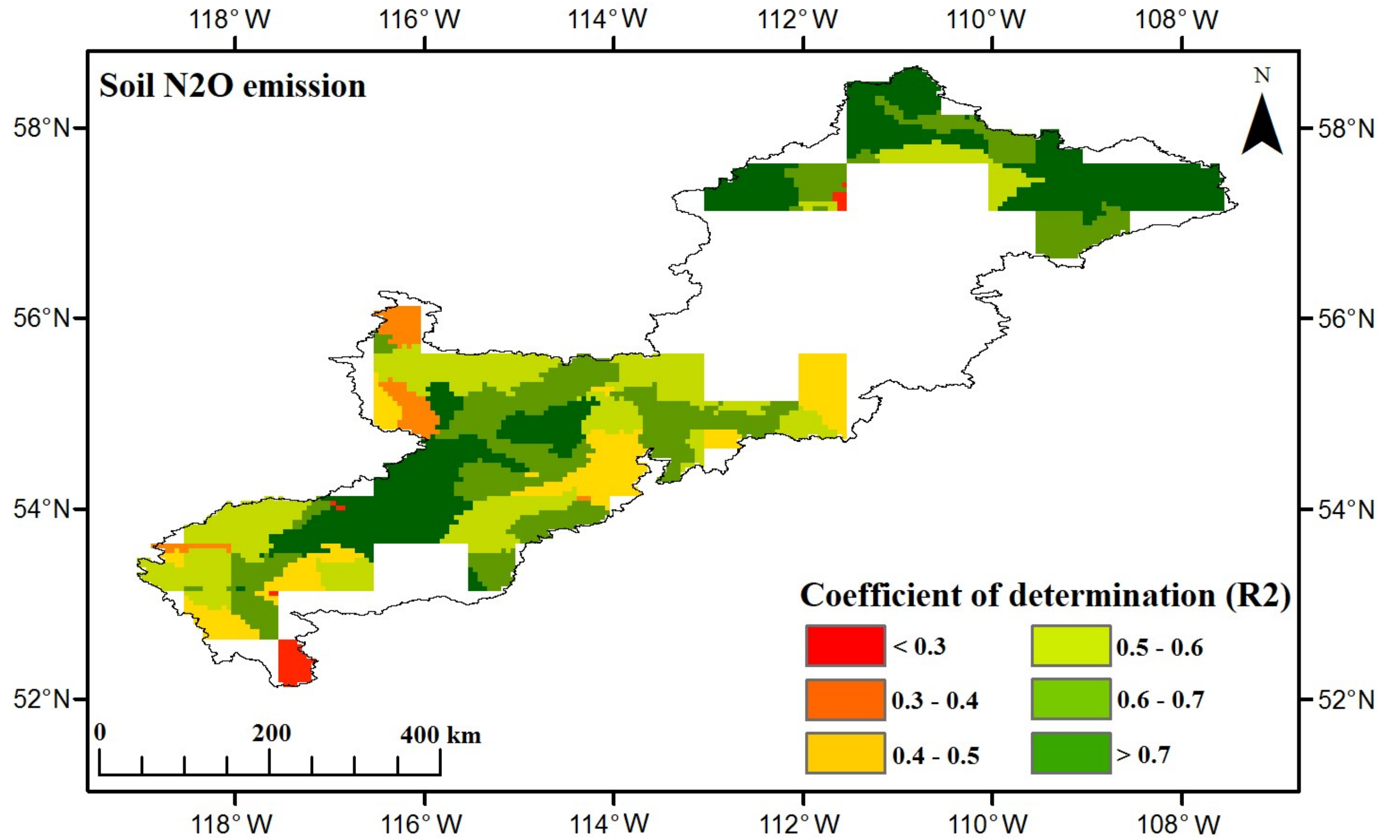
N_2O modelling in SWAT: Soil temperature simulations

- SWAT simulated soil temperature vs 0.125° ERA-Interim reanalysis product (Dee et al. 2011) at each pixels (resampled to 0.05°x0.05°) for a period of 1990-2005

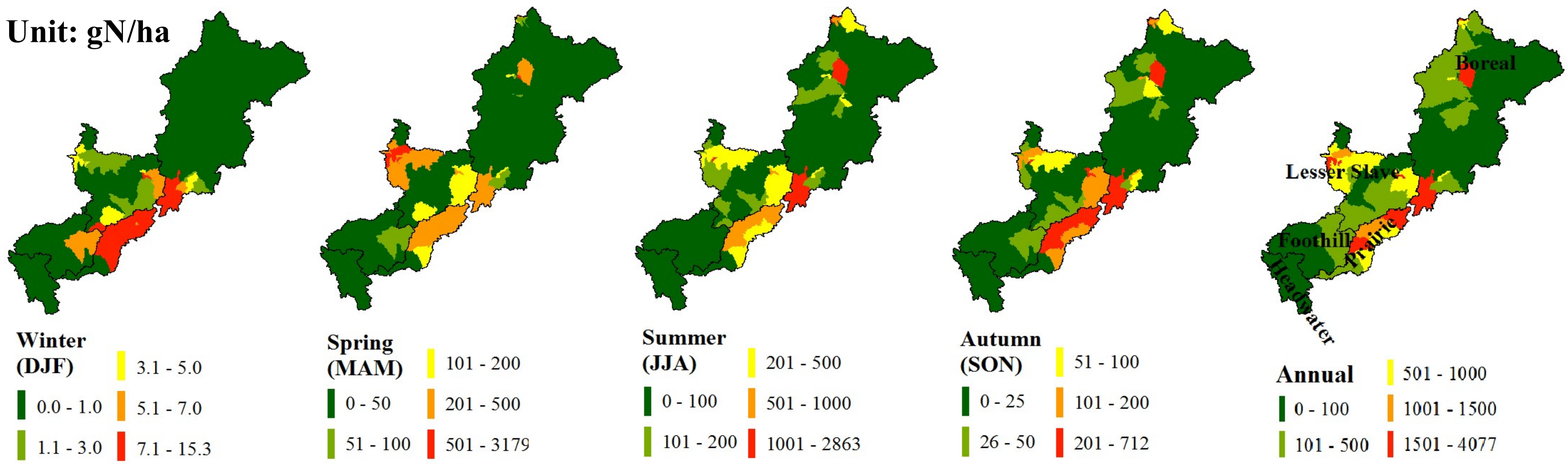


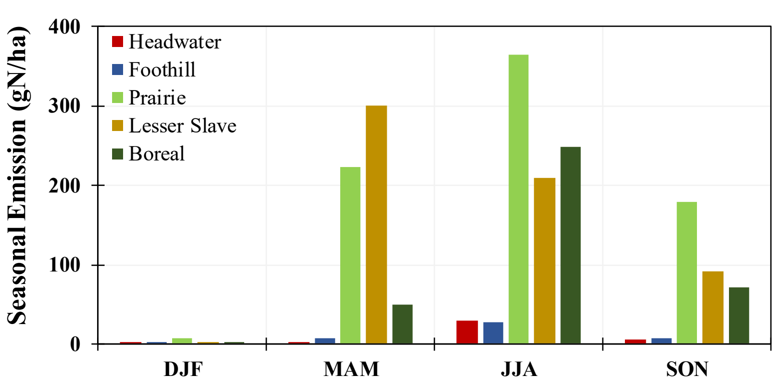
N_2O modelling in SWAT: N_2O simulations

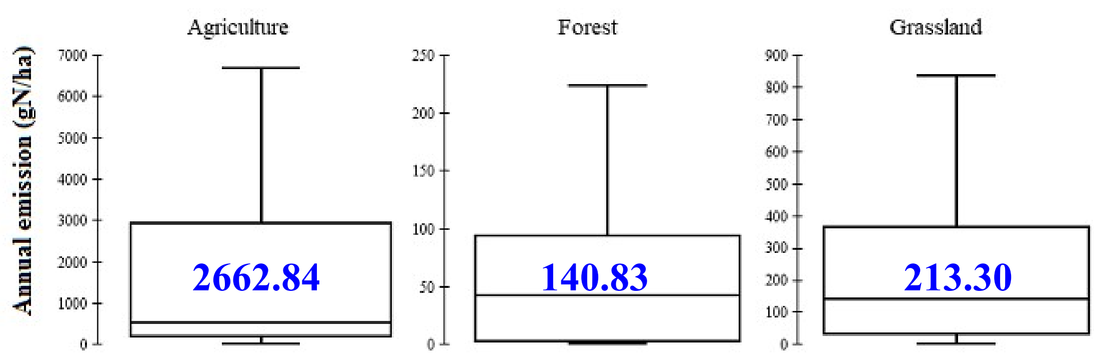
- SWAT simulated soil moisture (volumetric) vs 0.5° model-based estimates of Hashimoto (2012) at each pixels (resampled to 0.05°x0.05°) for a period of 1990-2005



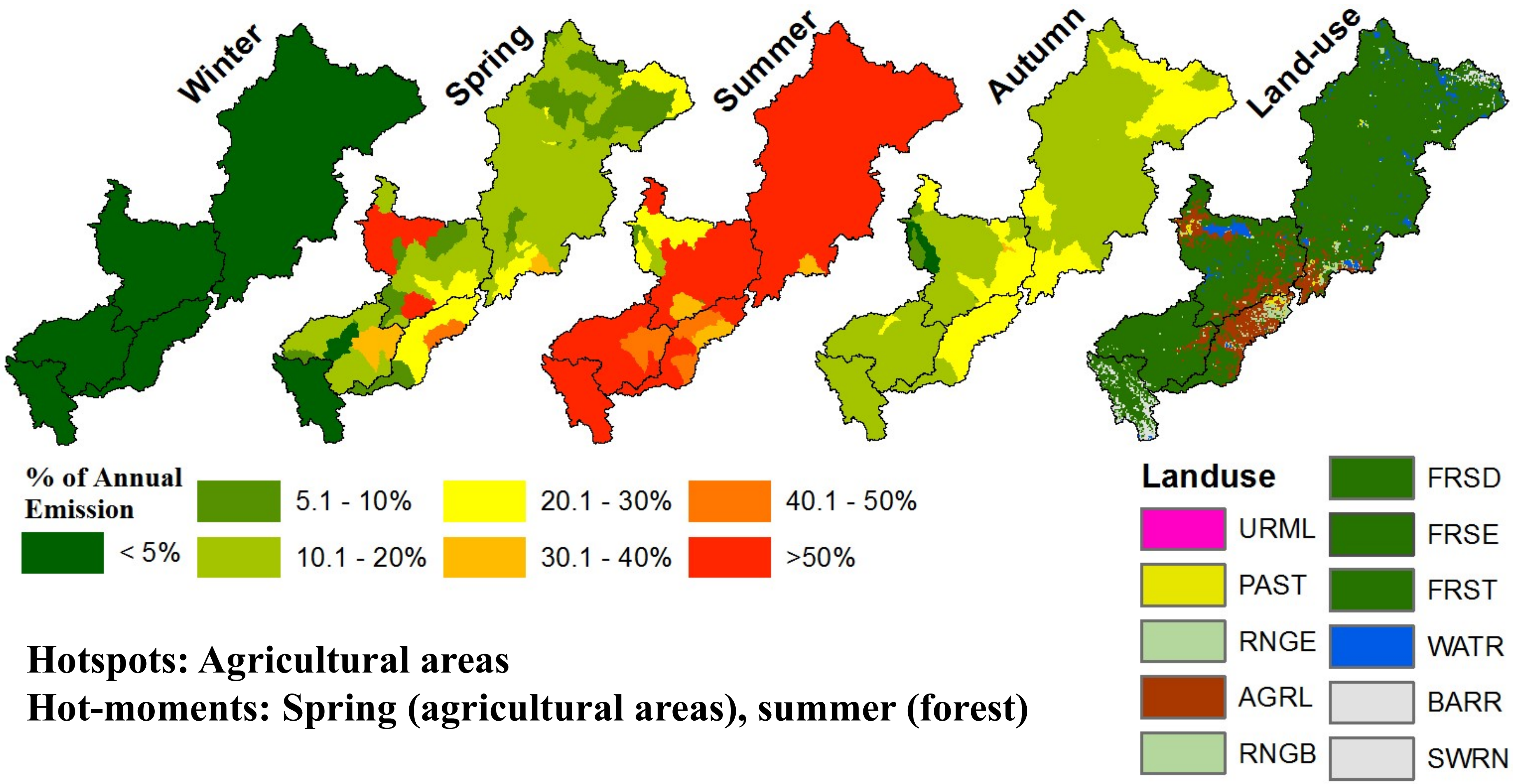
N_2O modelling in SWAT: Temporal and spatial trends (period: 1990-2005)





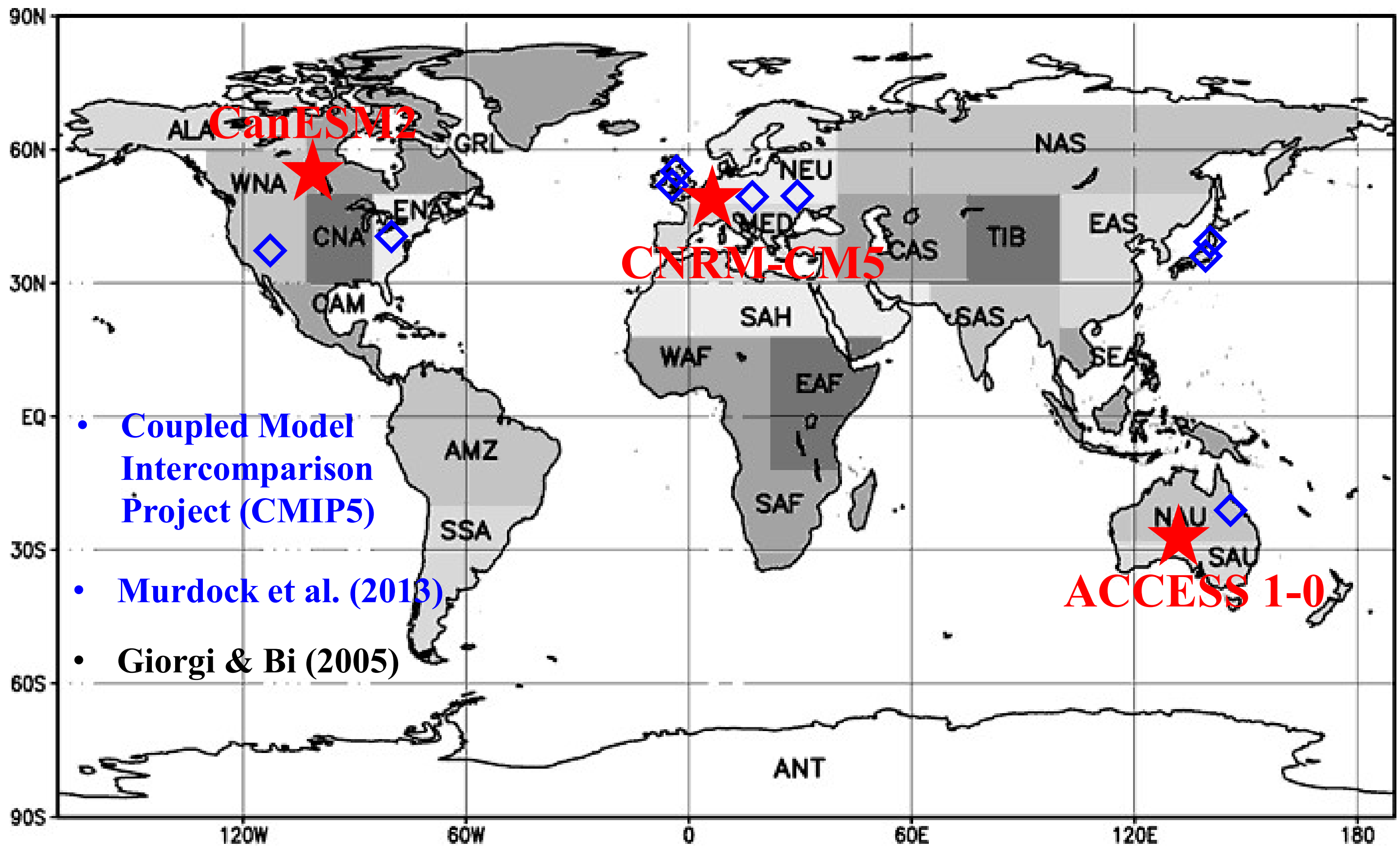


N_2O modelling in SWAT: Temporal and spatial trends (period: 1990-2005)



- **Hotspots: Agricultural areas**
- **Hot-moments: Spring (agricultural areas), summer (forest)**

N_2O modelling in SWAT: Emission in changing climate



- **Coupled Model Intercomparison Project (CMIP5)**
- **Murdock et al. (2013)**
- Giorgi & Bi (2005)

ALA	Alaska
WNA	Western North America
CNA	Central North America
ENA	Eastern North America
GRL	Greenland
CAM	Central America
AMZ	Amazonia
SSA	Southern South Americ
NEU	Northern Europe
MED	Mediterranean
CAS	Central Asia
SAH	Sahara
WAF	West Africa
EAF	East Africa
SAF	Southern Africa
ANT	Antarctic
NAS	Northern Asia
TIB	Tibet
EAS	Eastern Asia
SAS	Southern Asia
SEA	South East Asia
NAU	Northern Australia
SAU	Southern Australia

-Base period: 1990-2005

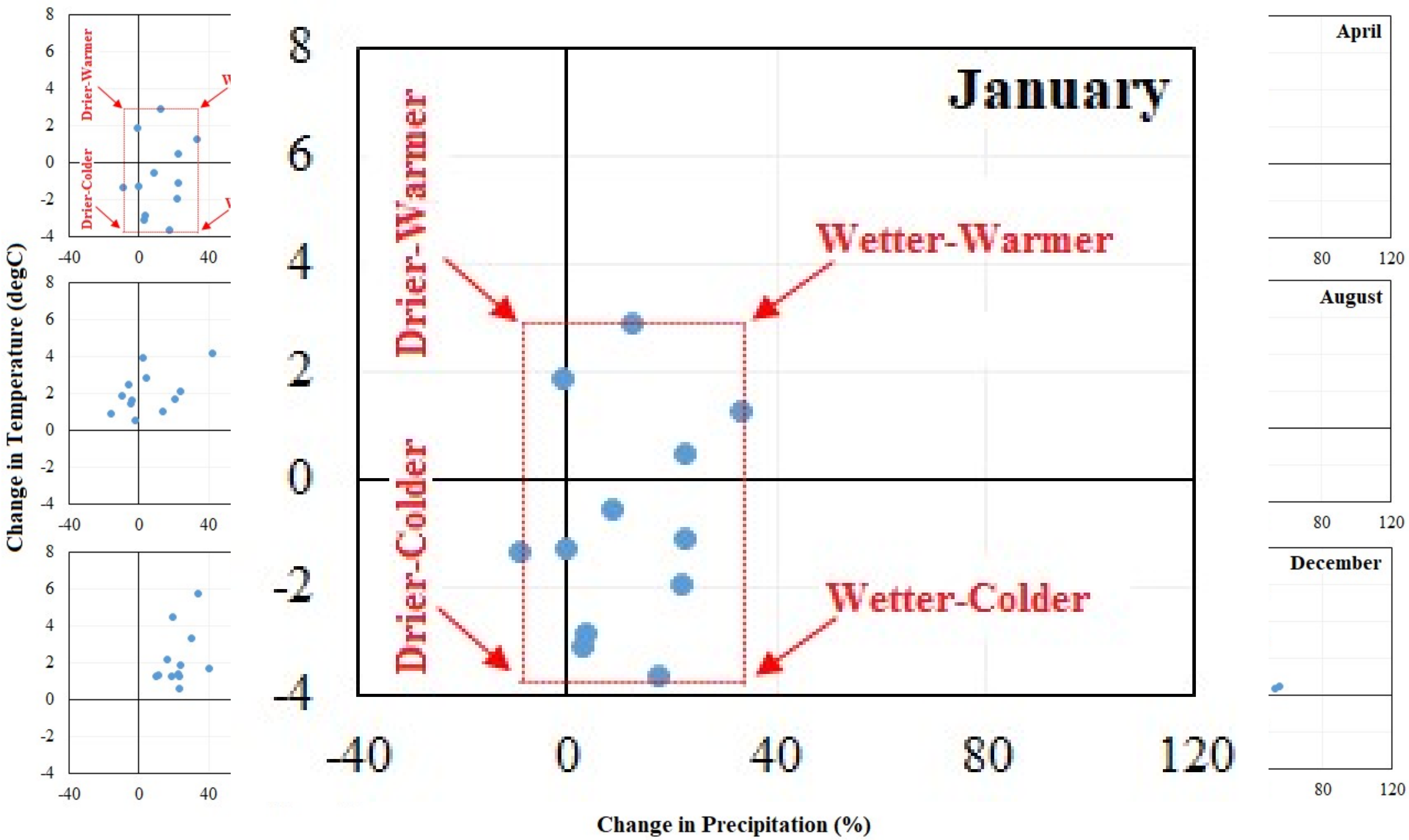
-Future periods:

(a) mid-century: 2021-2060

(b) end-century: 2061-2100

-RCP scenarios: 4.5 and 8.5

N_2O modelling in SWAT: Emission in changing climate

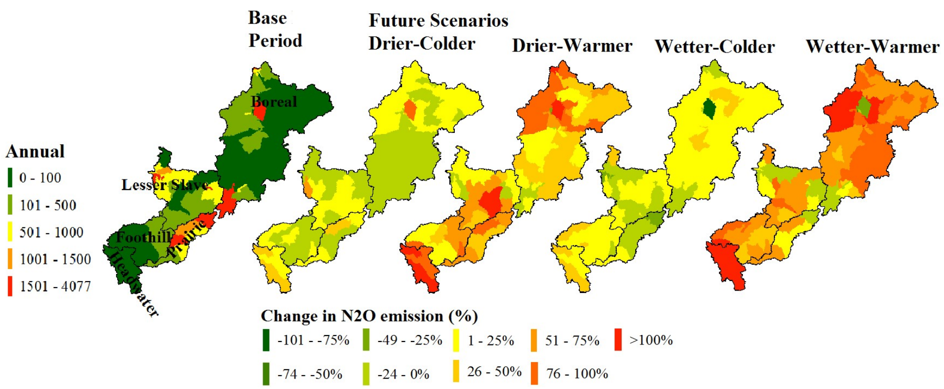


- **2 RCP scenarios**
- **2 Future periods**
- **3 GCMs** (Bias-Correction/Spatial Disaggregation (BCSD))

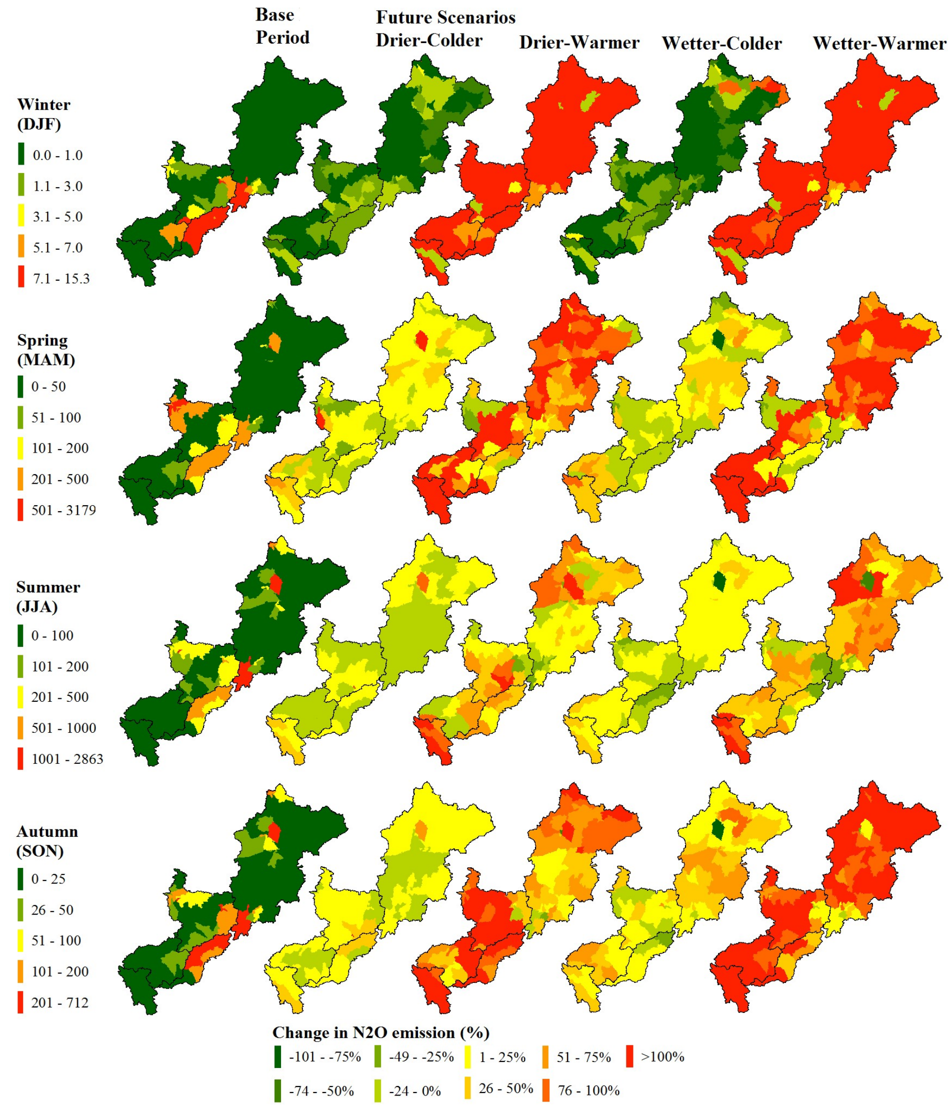
- **12 data points for each months**

- **Lutz et al (2016): envelop based selection approach**

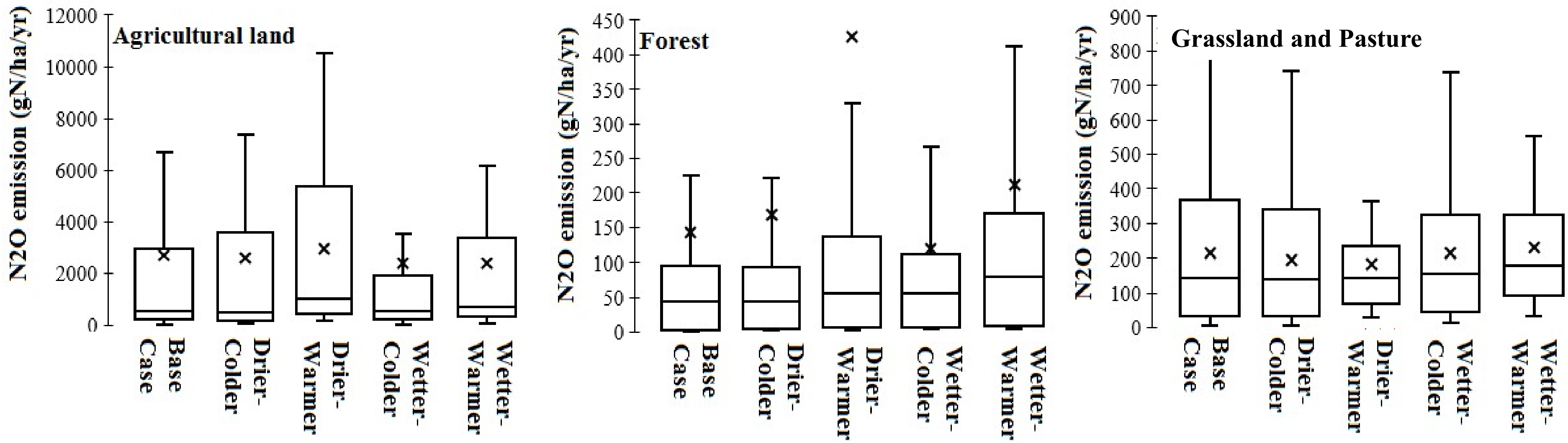
N_2O modelling in SWAT: Emission in changing climate



Periods→ Regions↓	Base Period (gN/ha/yr)	Drier Colder	Drier Warmer	Wetter Colder	Wetter Warmer
Headwater	35.6	21%	112%	27%	126%
Foothill	43.4	-3%	57%	7%	60%
Prairie	773.9	6%	54%	-17%	21%
Lesser Slave	604.5	-7%	24%	-12%	-3%
Boreal	370.6	13%	172%	-23%	21%
Watershed	412.5	5%	106%	-19%	13%



N_2O modelling in SWAT: Emission in changing climate



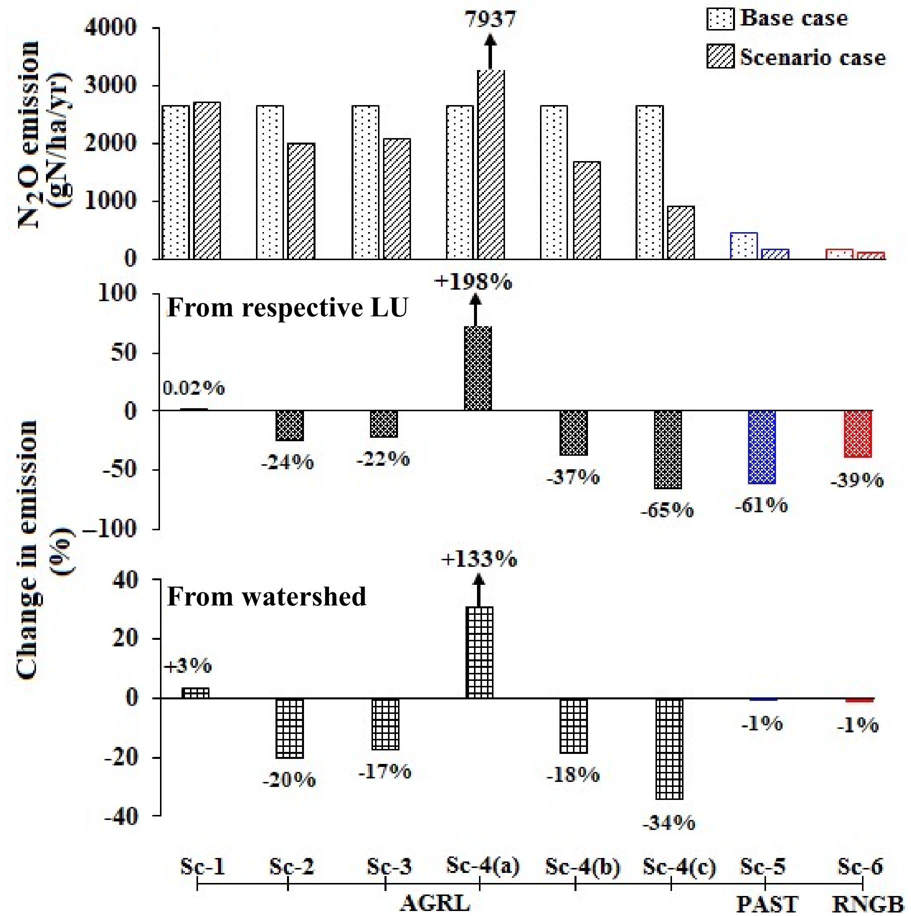
N_2O modelling in SWAT: Adaptation measures

1. Agriculture

- Base case: optimal dose of N-fertilizer (100 lb N/ac, early spring banded application)
- Sc1: same as base but split fertilizer application (4 times: 40% spring, 10% seedling, 25% tillering, 25% flowering)
- Sc2: minimum recommended dose of N (40 lb N/ac)
- Sc3: same as Sc2 but split into 4 applications
- Sc4(a): 99% crop residue left on ground, 1% biomass harvested
- Sc4(b): 75% biomass harvested (25% left)
- Sc4(c): 99% biomass harvested (1% left)

2. Pasture: minimum recommended dose of N (base: 200 lb N/ac, 4 applications, minimum: 70 lb N/ac)

3. Grassland: light grazing (BIO_EAT: 2.4 kg/ha/day and MANURE_KG = 0.89 kg/ha/da, as per Gao et al., 2017)



Conclusions

- Incorporated several semi-empirical equations to estimate N_2O emission from nitrification and denitrification in the SWAT model
- Tested against field data of a cropped field, a shelterbelt site and a grassland site of cold climate regions of Canada
- Upscaling of site-specific parameters to watershed scale (of Athabasca River Basin, ARB of Western Canada)
- Temporal and spatial heterogeneity of N_2O emission in the ARB
- Agricultural areas are hot-spots of N_2O emission
- Significant spring N_2O emission (hot-moment), more than 50% of annual emission at agricultural areas
- N_2O emission from ARB would increase in future, especially in Drier-Warmer condition (watershed scale increment in annual emission is more than two-fold)
- Different adaptation measures in the agriculture areas especially fertilizer and residue management, would decrease the emission substantially

Acknowledgements

- Yang et al. (2017) and Wagena et al (2017) for sharing their version of module
- Amadi et al. (2016) for sharing N_2O, WFPS and Soil Temperature data for Cropped Area and Shelterbelts of Outlook, SK, Canada
- Gao et al. (2017) for sharing N_2O and WFPS data for Grassland of Stavely, AB, Canada
- Xinzhong Du for helping to process climate change data
- My colleagues at Athabasca River Basin Research Institute, Athabasca University, AB, Canada

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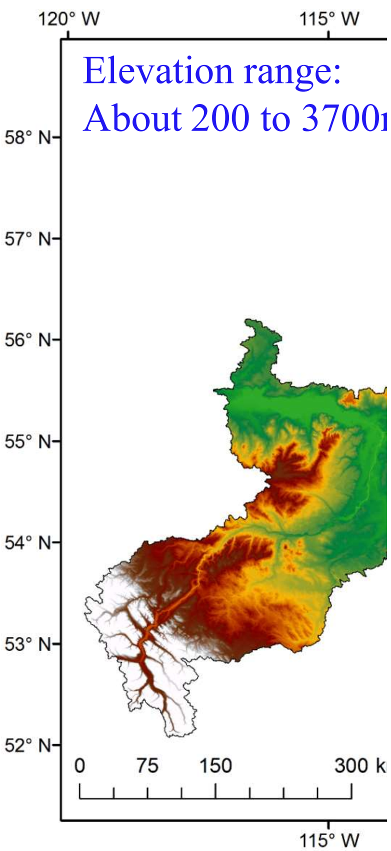
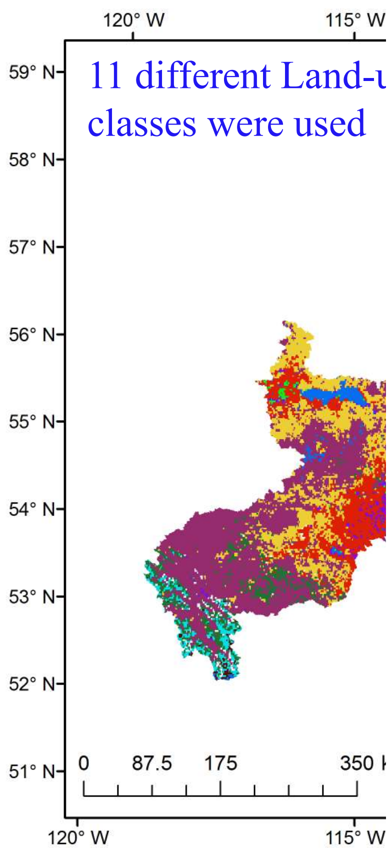
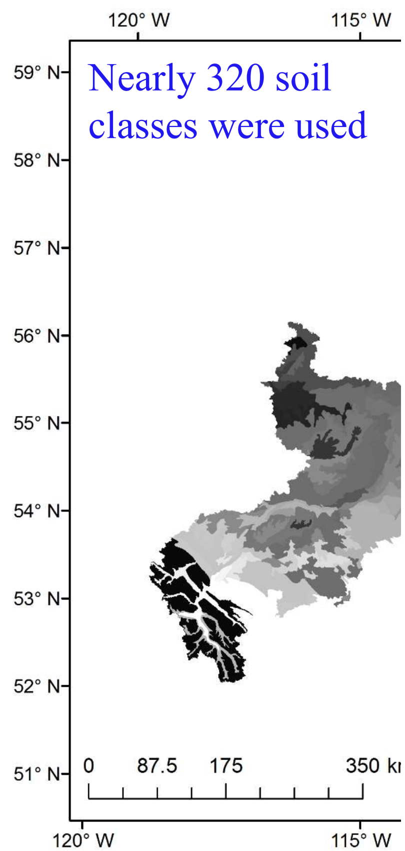
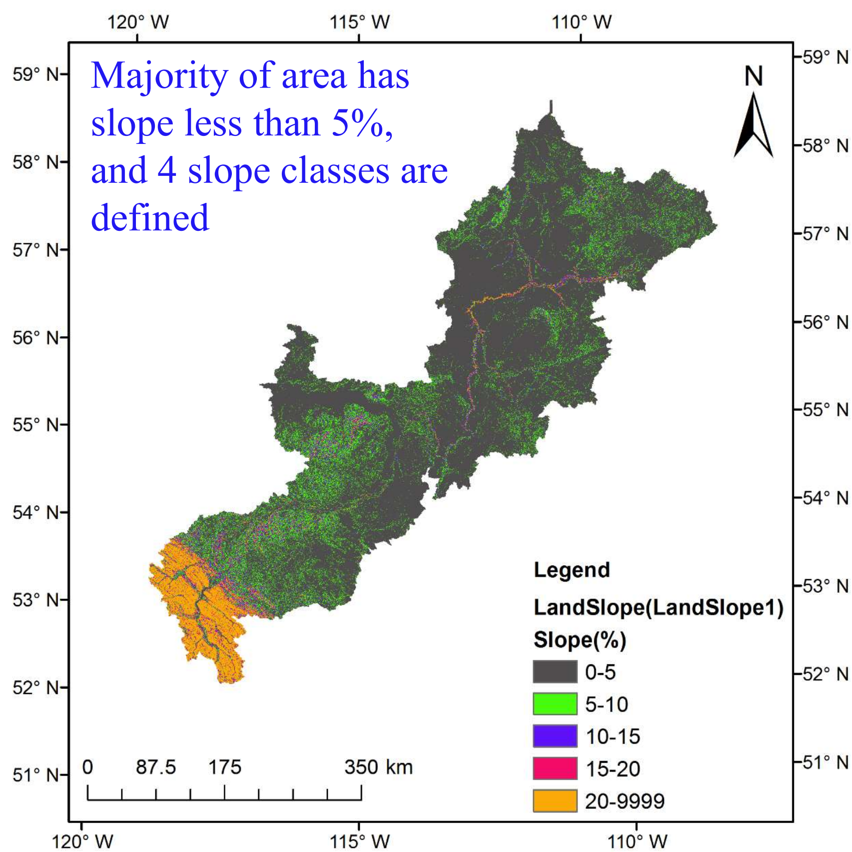
Supplementary Slides

Model built-up: Spatial Data set

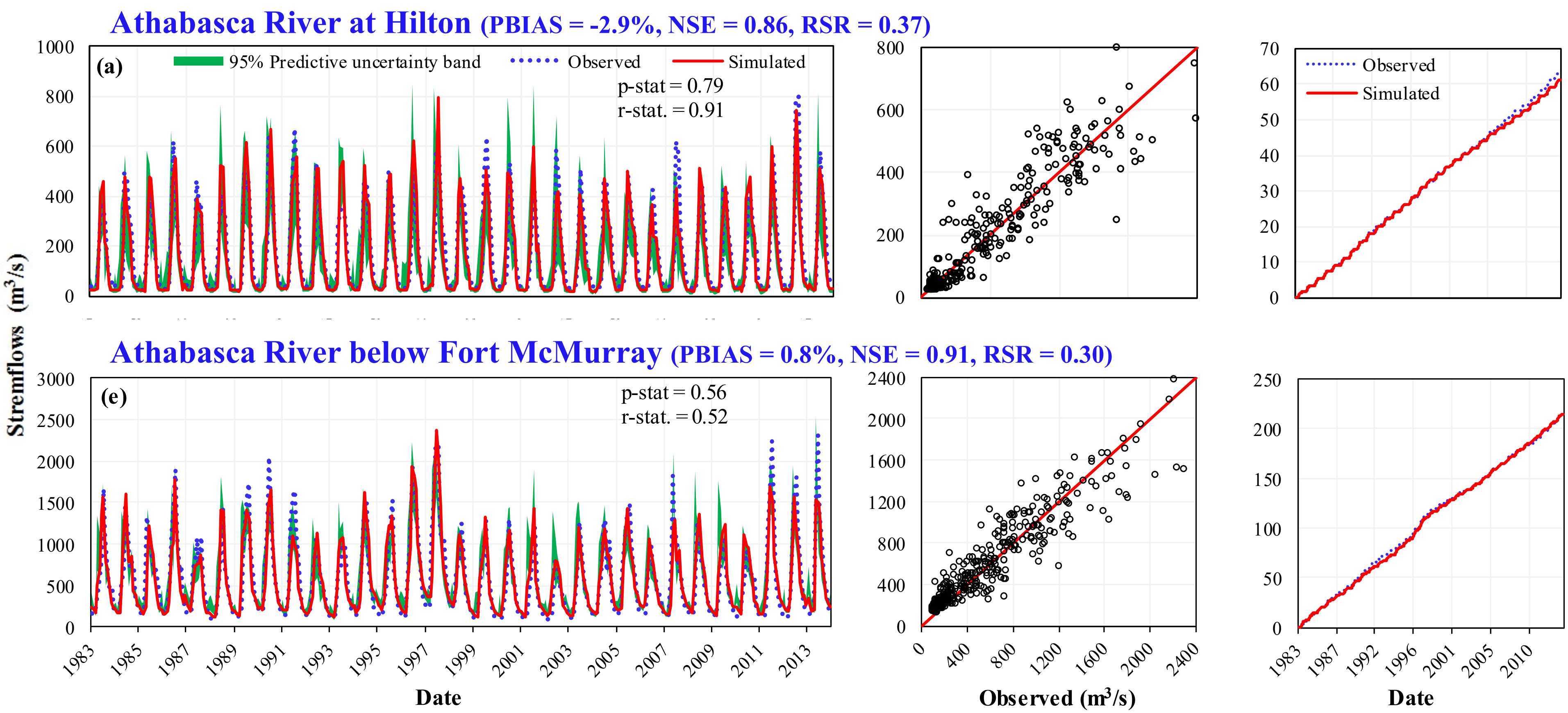






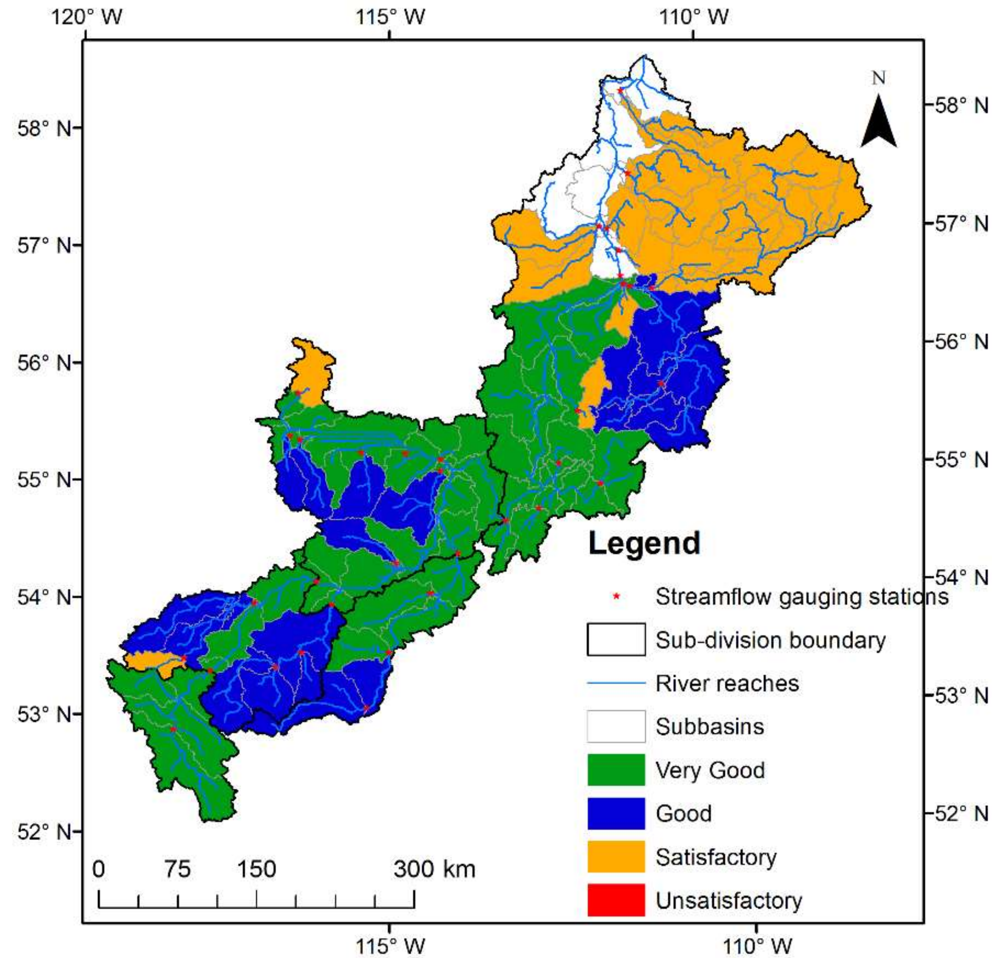


Streamflow results: some graphical illustrations



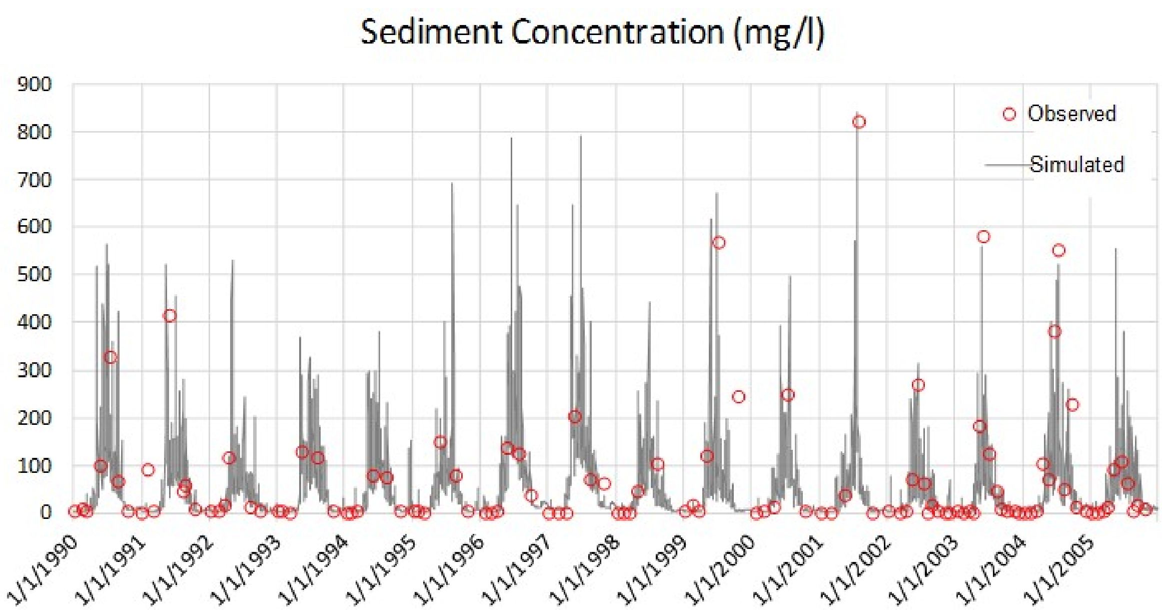
Streamflow results: overall qualitative rating

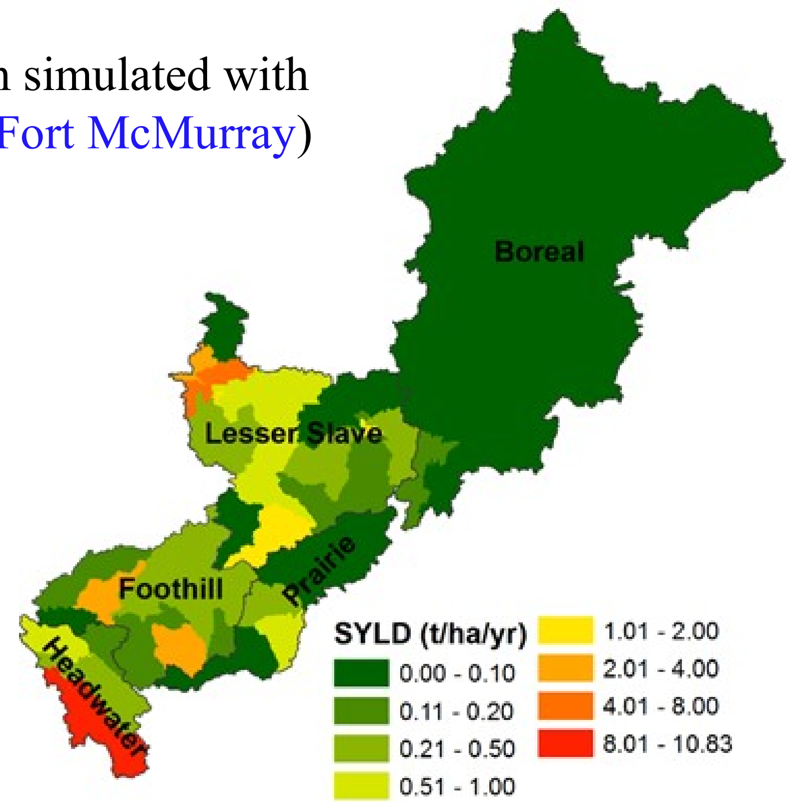
- Ability of the SWAT model to simulate the streamflow at various locations with varying degrees of accuracy
- Headwater: "Very Good"
- Foothill: "Very Good" at main river, "Good" at tributaries
- Prairie: "Good" at upstream reaches and "Very Good" at downstream reaches
- Lesser Slave: "Satisfactory" to "Good" for some tributaries and "Very Good" at main river
- Boreal: underperformed at the lower parts of the boreal region, especially the North-Eastern part



Erosion and sediment transport modelling of the ARB

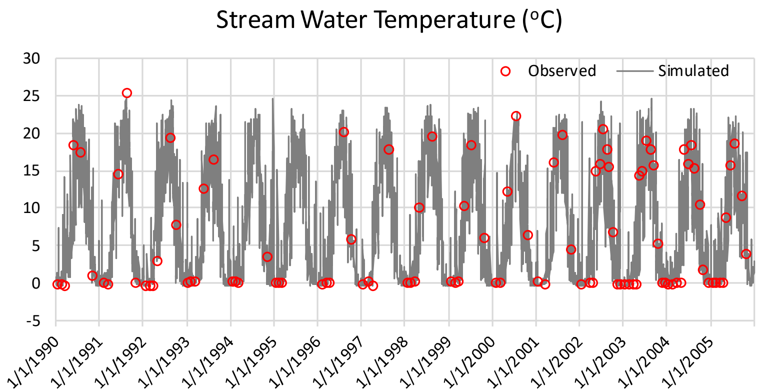
- The erosion rates (sediment yield: SYLD) depend on land-use, soil and slope of the basin
- Sediment concentrations at different stations have been simulated with reasonable accuracy (below: at Athabasca river above Fort McMurray)

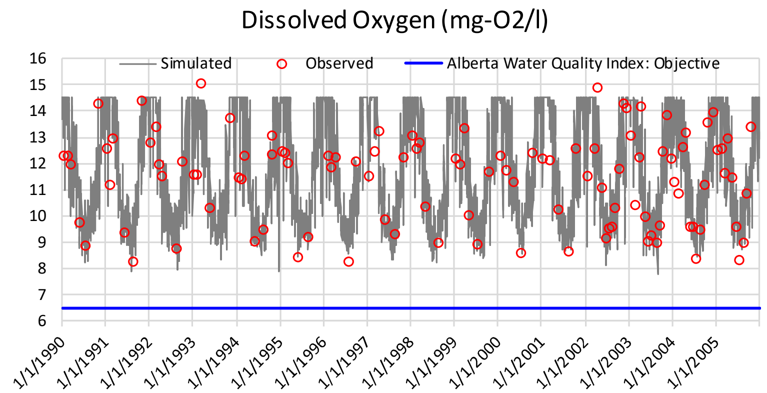


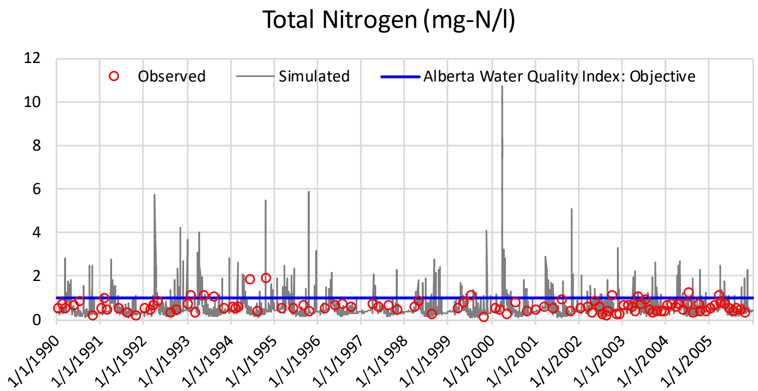


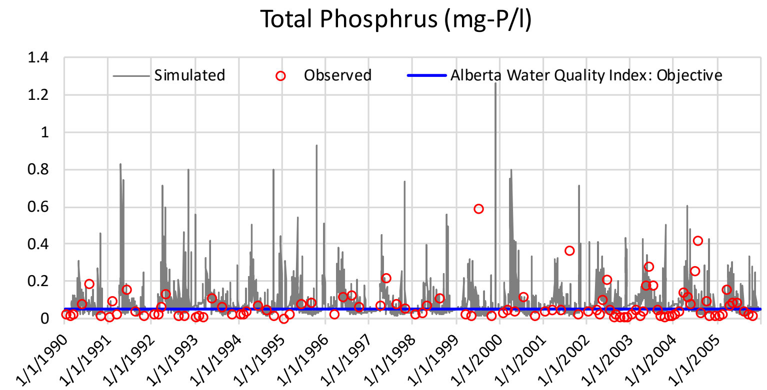
Water quality modelling of the ARB

- At Athabasca river above Fort McMurray



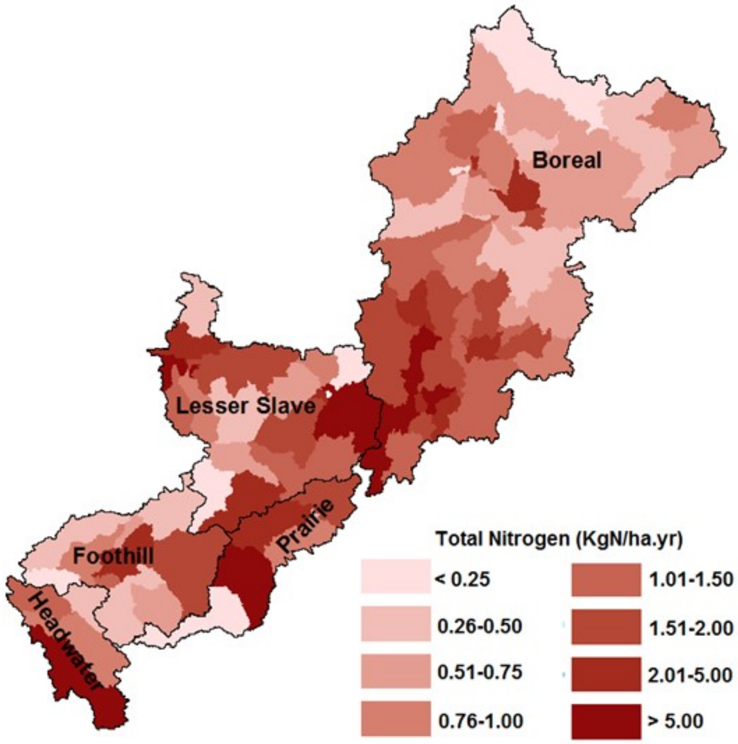


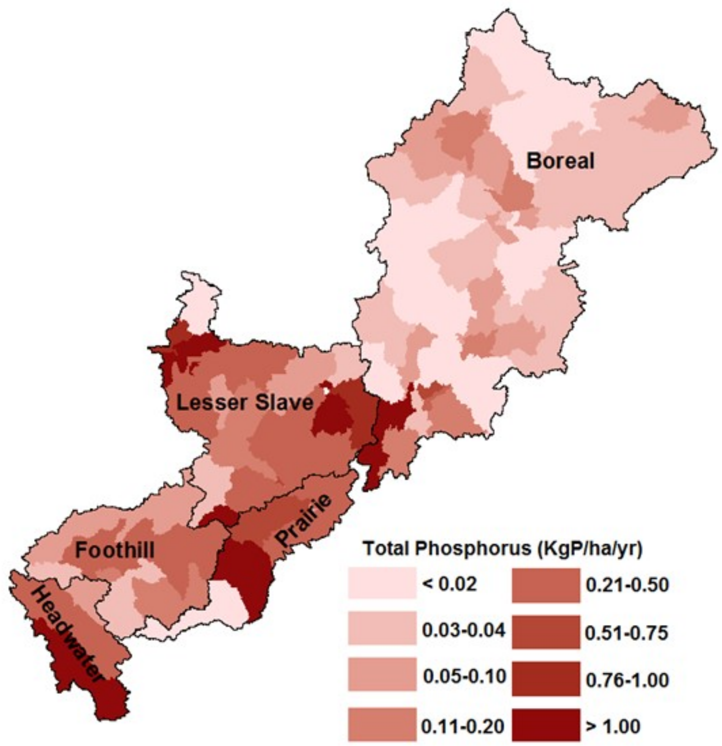




Water quality modelling of the ARB

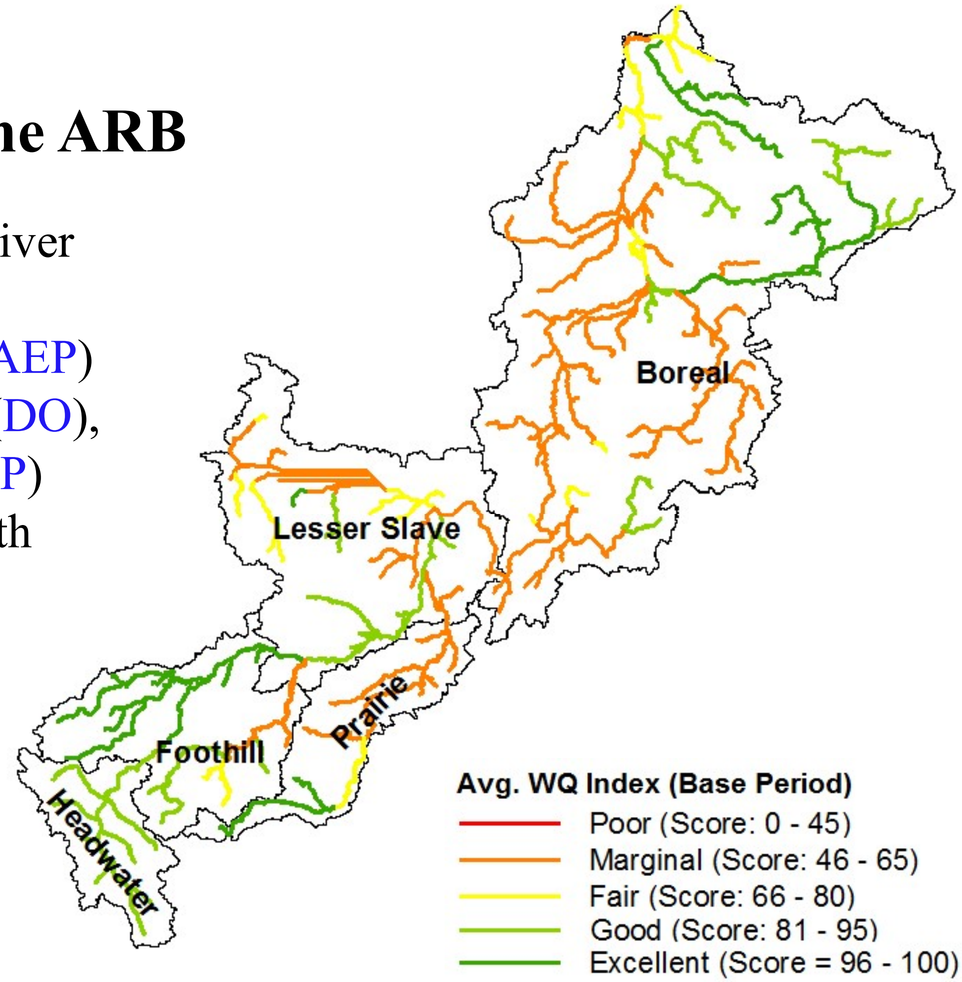
- Spatial variation of nutrient loading rates (Total Nitrogen: TN and Total Phosphorus: TP) from sub-basins





Water quality status assessment of the ARB

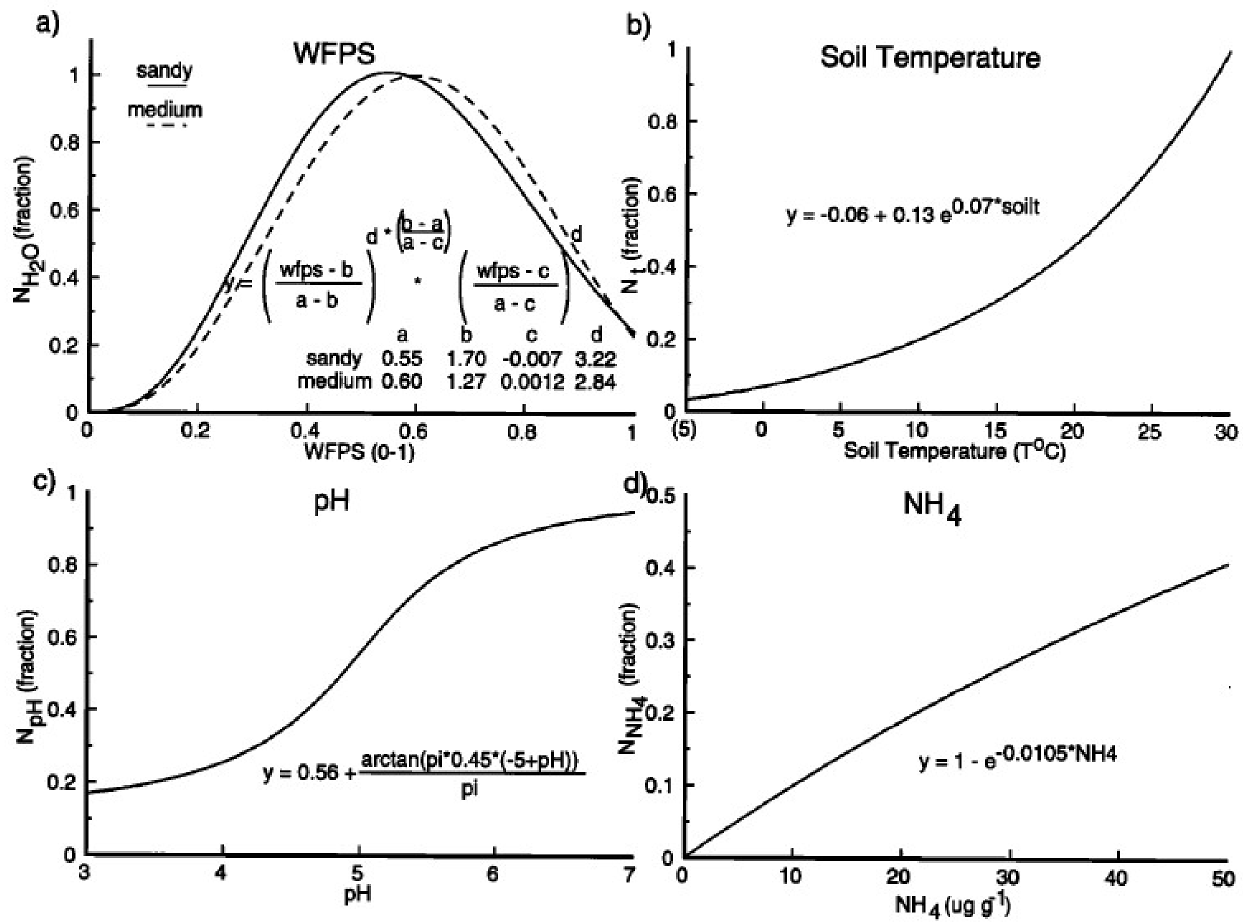
- Spatial variation of water quality status of river reaches
- Based on Alberta Environment and Parks (AEP) formulation considering dissolved oxygen (DO), total nitrogen (TN) and total phosphorus (TP) simulation results, and their comparison with "objective values" as set by the AEP



Equations of Parton et al. (1996, 2001)

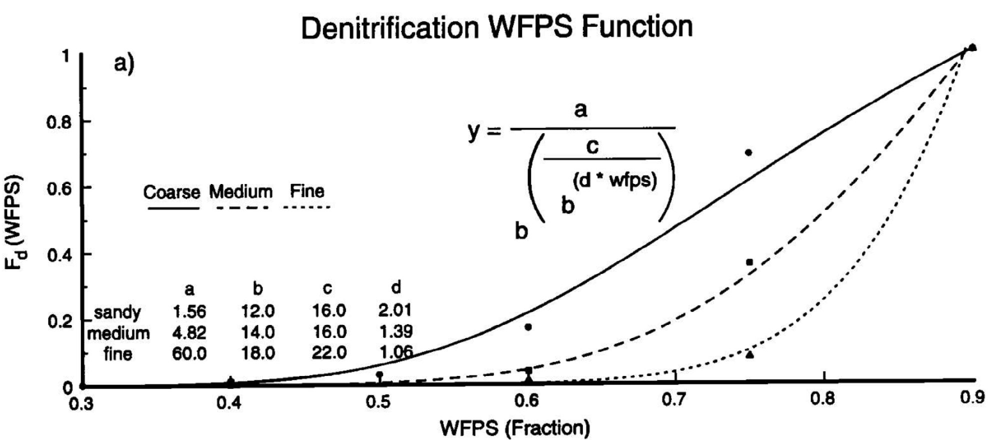
- Effect on nitrification:

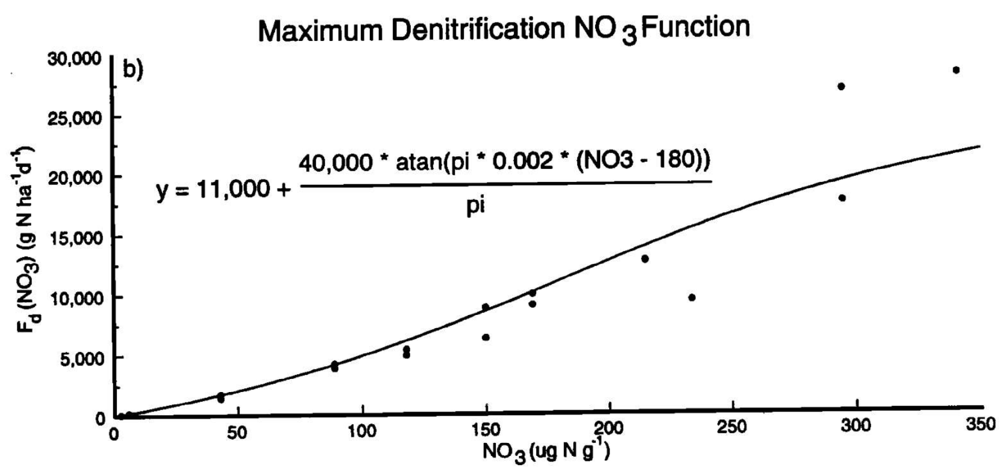
(a) WFPS
(b) Soil Temperature
(c) pH
(d) Soil NH4



Equations of Parton et al. (1996, 2001)

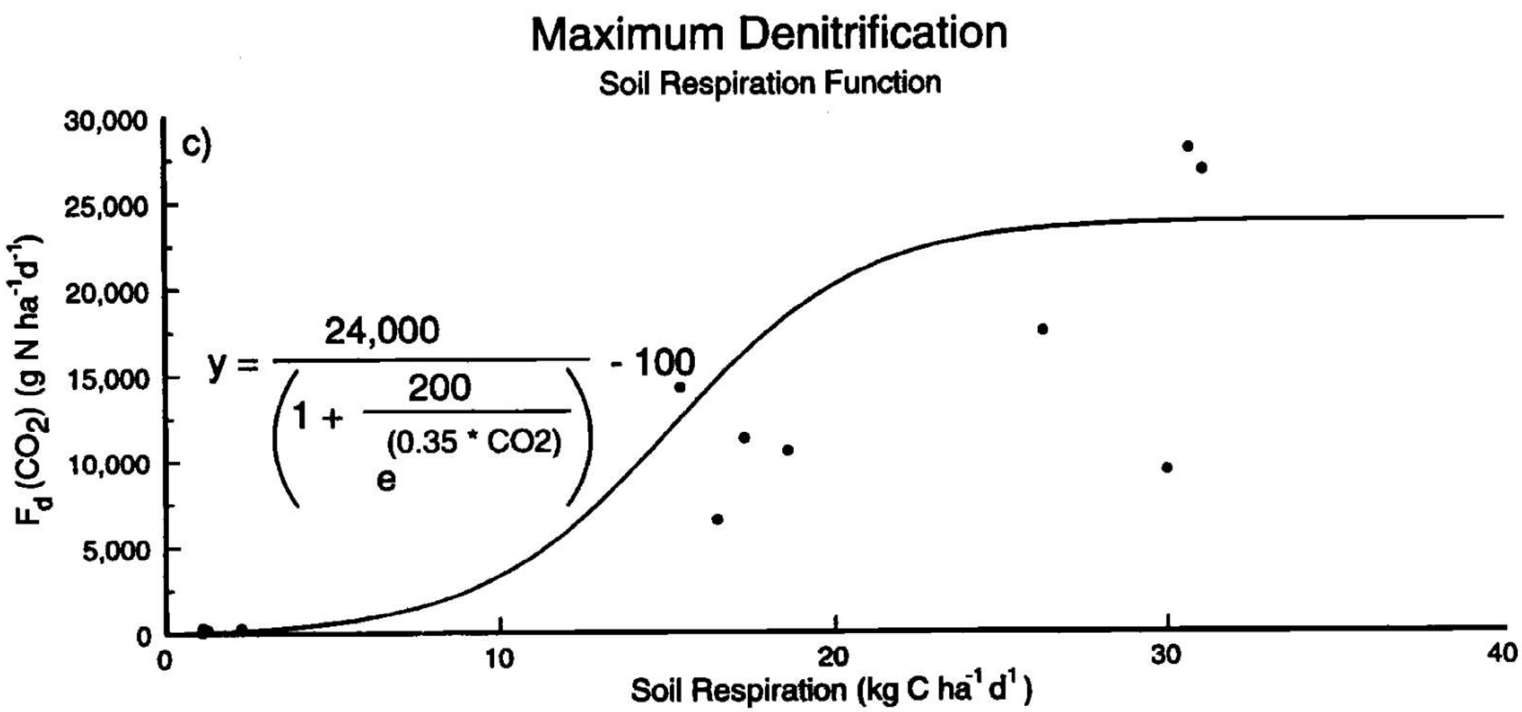
- Effect on potential denitrification rate:





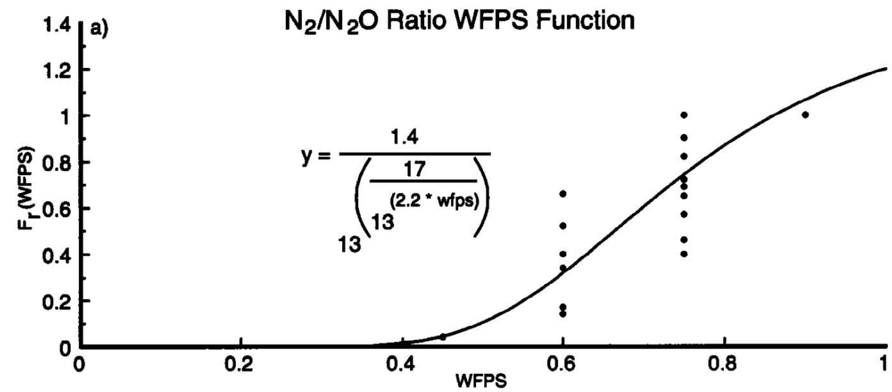
Equations of Parton et al. (1996, 2001)

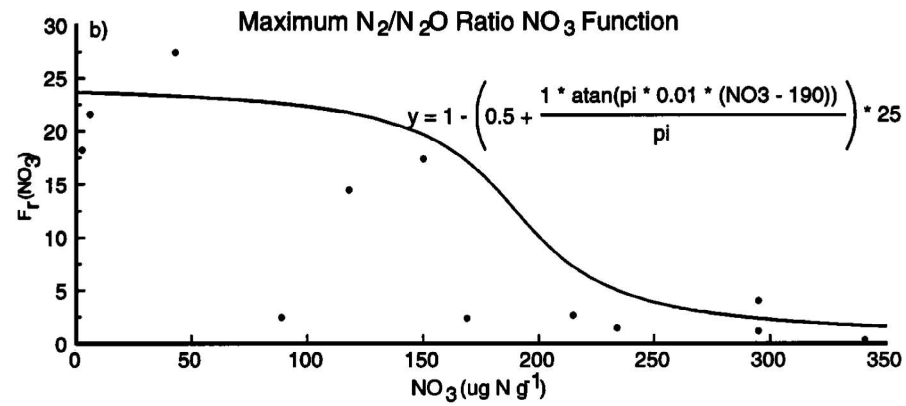
- Effect on potential denitrification rate:

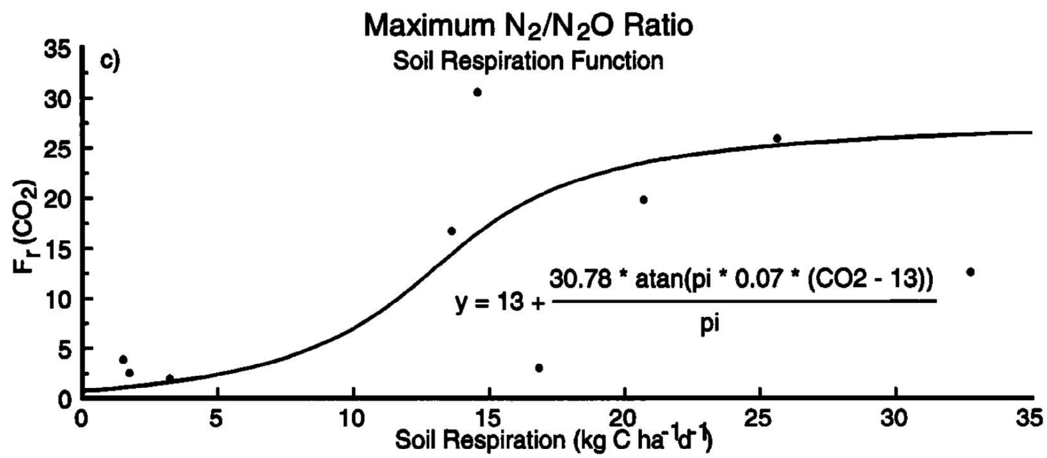


Equations of Parton et al. (1996, 2001)

- Effect on ratio of N2O and N2:







Scenarios

Land-use Types→		Agriculture land*			Pasture			Grassland	
Cases↓		N-Application	P-Application	Frequency and Timing	N-Application	P-Application	Frequency and Timing	Grazing	Manure
Base Case		100 lb N/ac[1]	35 lb P2O5/ac[2]	1 and Spring (April 1)	200 lb N/ac[3]	60 lb P2O5/ac[4]	4 and refer[3]	6 kg/ha/day[9]	5.5 kg/ha/day[9]
Scenarios	**Sc-1**	same as base	same as base	4 and see below[#]	-	-	-	-	-
	Sc-2	40 lb N/ac	20 lb P2O5/ac2	same as base	-	-	-	-	-
	Sc-3	same as Sc-2	same as Sc-2	same as Sc-1	-	-	-	-	-
	Sc-4(a)	same as base	same as base	same as base but different redsidue management[5]	-	-	-	-	-
	Sc-4(b)	same as base	same as base	same as base but different redsidue management[6]	-	-	-	-	-
	Sc-4(c)	same as base	same as base	same as base but different redsidue management[7]	-	-	-	-	-
	Sc-5	-	-	-	70 lb N/ac[8]	35 lb P2O5/ac[8]	4 and refer[3]	-	-
	Sc-6	-	-	-	-	-	-	2.4 kg/ha/day[10]	0.89 kg/ha/day[10]

*Spring Wheat or Barley

[#]40% in Spring (April 1), 10% at seedling (May 1), 25% at Tillering (June 15), 25% at Flowering/Stem Elongation

[1]Economically optimal rate of N-application as per AGRI-FACTS (2013), range 40-130 lb N/ac.

[2]Average of the range of values (20-50 lbP2O5/ac) as per AGRI-FACTS (2004)

[3]Four applications for 2 cuttings, 60 lb N/ac in early spring, 50 lb N/ac in mid-June, 50 lb N/ac in mid-July, 40 lb N/ac mid-August. Range 70-110 ln N/ac without irrigation and 200lb N/ac with irrigation. Refer AGRI-FACTS (2005a,b)

[4]One application of 60 lb P2O5/ac in early spring. Range 70-110 ln N/ac and 35-45 lb P2O5/ac for without irrigation and 60 lb P2O5/ac with irrigation. Refer AGRI-FACTS (2005a,b)

[5]In base case, residue Harvest Index (HI_OVR) would vary between 0.25 (at worst water stressed condition) and 0.45 (optimal condition) as per water stress factor, so as the Stover Fraction Removed (FRAC_HARVK). Refer Arnold et al. (2011). In this scenario, values of HI_OVR and FRAC_HARVK are fixed at 1% (meaning 99% left in the field)

[6]Values of Harvest Index (HI_OVR) and Stover Fraction Removed (FRAC_HARVK) are fixed at 75% (meaning 25% left in the field)

[7]Values of Harvest Index (HI_OVR) and Stover Fraction Removed (FRAC_HARVK) are fixed at 99% (meaning only 1% left in the field)

[8]Minimum value of the range as specified in AGRI-FACTS (2005a,b)

[9]Values calculated considering 2 ac/cow, dry weight of biomass consumed = 11 kg/ha/day (5-16 lb/ac/day) and moisture content = 85%. Refer AGRI-FACTS (1998)

[10]As per Light Grazing (1.2 AMU/ha) intensity, as per Gao et al. (2017)