Supplementary materials

Nitrous oxide emissions from northern barley croplands after injections of liquid manure and nitrification inhibitors

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Supplementary Materials and Methods

Similar to EF_d, the N use efficiency (NUE) and N uptake efficiency (NUEff) of barley were calculated to make the aboveground biomass and barley N content comparable among different manure injections (Eq. [S1] and Eq. [S2]).

$$NUE = \frac{DM_m - DM_c}{Ninp}; \quad [S1]$$

$$NUEff = \frac{PN_m - PN_c}{Ninp}, \quad [S2]$$

where NUE is the N use efficiency of barley (kg plant dry matter kg^{-1} N), DM_m is the aboveground dry matter of barley from the manured soil (kg ha^{-1}), DM_c is the aboveground dry matter of barley from the nonmanured soil (kg ha^{-1}), Ninp is the amount of total N in the liquid manure (kg N ha^{-1}), NUEff is the N uptake efficiency of barley (kg plant N kg^{-1} N), PN_m is the N uptake of barley for each treatment receiving manure (kg N ha^{-1}), and PN_c is the N uptake of barley for the controls (kg N ha^{-1}).

Supplementary Table S1. Barley aboveground dry matter and N uptake (with standard errors) as harvested in Lacombe and Edmonton in Aug. 2016.

Treatment	Lacombe	Edmonton
	Aboveground dry matter (DM)	
	kg DM ha^{-1}	
CZ†	3360.3 ± 171.3d‡	2759.6 ± 213.8b
FMD	5626.3 ± 549.8ab	5675.7 ± 330.1a
FMN	6121.6 ± 212.1a	4118.1 ± 805.3ab
FMW	5401.1 ± 216.7ab	5366.6 ± 994.3a
CT	2086.2 ± 88.0e	3347.8 ± 434.5b
SMD	4968.1 ± 284.5bc	4208.2 ± 720.9ab
SMN	4915.3 ± 639.8bc	4361.6 ± 482.6ab
SMW	4210.4 ± 470.5cd	4337.8 ± 730.9ab
	N uptake	
	kg N ha^{-1}	
CZ	26.7 ± 3.2d	26.8 ± 2.6b
FMD	73.9 ± 7.4bc	47.2 ± 6.4ab
FMN	88.1 ± 4.3ab	52.4 ± 16.0ab
FMW	63.4 ± 6.0b	59.3 ± 11.3a
CT	24.2 ± 1.9d	28.3 ± 3.8b
SMD	106.9 ± 5.8a	52.8 ± 9.6ab
SMN	97 ± 10.6a	49.9 ± 4.5ab
SMW	91.5 ± 8.3ab	61.8 ± 10.7a

† CT, control treatment where the soil was disturbed by the manure applicator (without applying manure); CZ, control without disturbance; FMD, fall application of liquid manure with the inhibitor 3, 4-dimethylpyrazole phosphate (DMPP); FMN, fall application of liquid manure with the inhibitor nitrapyrin; FMW, fall application of liquid manure without inhibitors; SMD, spring application of liquid manure with the inhibitor DMPP; SMN, spring application of liquid manure with the inhibitor nitrapyrin; SMW, spring application of liquid manure without inhibitors.

‡ Different letters indicate significant differences among the eight treatments in each location ($P < 0.05$).

Supplementary Table S2. ANOVA results of manure application timing and nitrification inhibitor (NI) effects on the N use efficiency and N uptake efficiency from barley biomass harvest in Aug. 2016 in Lacombe and Edmonton.

	Lacombe		Edmonton	
	F-value	*p*-value	*F*-value	*p*-value
	N use efficiency			
Timing†	8.119	0.065	2.848	0.234
Addition‡	1.504	0.261	4.195	0.057
Timing × addition	0.315	0.736	5.471	0.032*
	N uptake efficiency			
Timing	0.498	0.531	0.198	0.700
Addition	2.880	0.095	1.010	0.406
Timing × addition	1.992	0.179	0.126	0.883

* $P < 0.05$

† Timing includes the fall and spring manure injections.

‡ Addition includes the manure without NI addition, manure with nitrapyrin, and manure with DMPP.

Supplementary Table S3. ANOVA results of manure injection timing (T) and nitrification inhibitor (NI) addition effects on N_2O emission factors in Lacombe and Edmonton sites. There different comparisons of N_2O emission factors across treatments were assessed using different timeframes of flux accumulation†.

	Lacombe		**Edmonton**	
	F-value	*p*-value	*F*-value	*p*-value
	Emission factors – All-fall-to-fall Comparison†			
Manure timing (T)‡	14.405	0.032*	0.093	0.790
NI addition§	11.607	0.002*	1.805	0.225
T × NI	5.488	0.020*	1.422	0.296
	Emission factors – From-manure-timing Comparison†			
Manure timing (T)‡	52.185	0.006*	4.318	0.173
NI addition§	7.244	0.009*	3.262	0.092
T × NI	3.746	0.054	2.230	0.170
	Emission factors – All-spring-to-spring Comparison†			
Manure timing (T)‡	71.971	0.003*	3.533	0.201
NI addition§	5.091	0.025*	2.033	0.193
T × NI	6.371	0.013*	4.201	0.057

* $P < 0.05$

† Timeframe A was based on fall-to-fall cumulative fluxes for all eight experimental treatments. Timeframe B was based on a combination of fall-to-fall cumulative fluxes for the four fall treatments (i.e., CZ, FMW, FMD, and FMN) and spring-to-spring cumulative fluxes for the four spring treatments (i.e., CT, SMW, SMD, and SMN) (this represents annual fluxes starting from the times of manure injections). Timeframe C was based on spring-to-spring cumulative fluxes for all eight experimental treatments (this represents annual fluxes starting from the time of seeding). See method section 2.3 for further details as well as the start and end dates of each timeframe and experimental site.

‡ Timing (T) represents the fall-manure vs. spring-manure injections.

§ NI addition includes the manure alone (without NI addition), manure with nitrapyrin, and manure with DMPP.

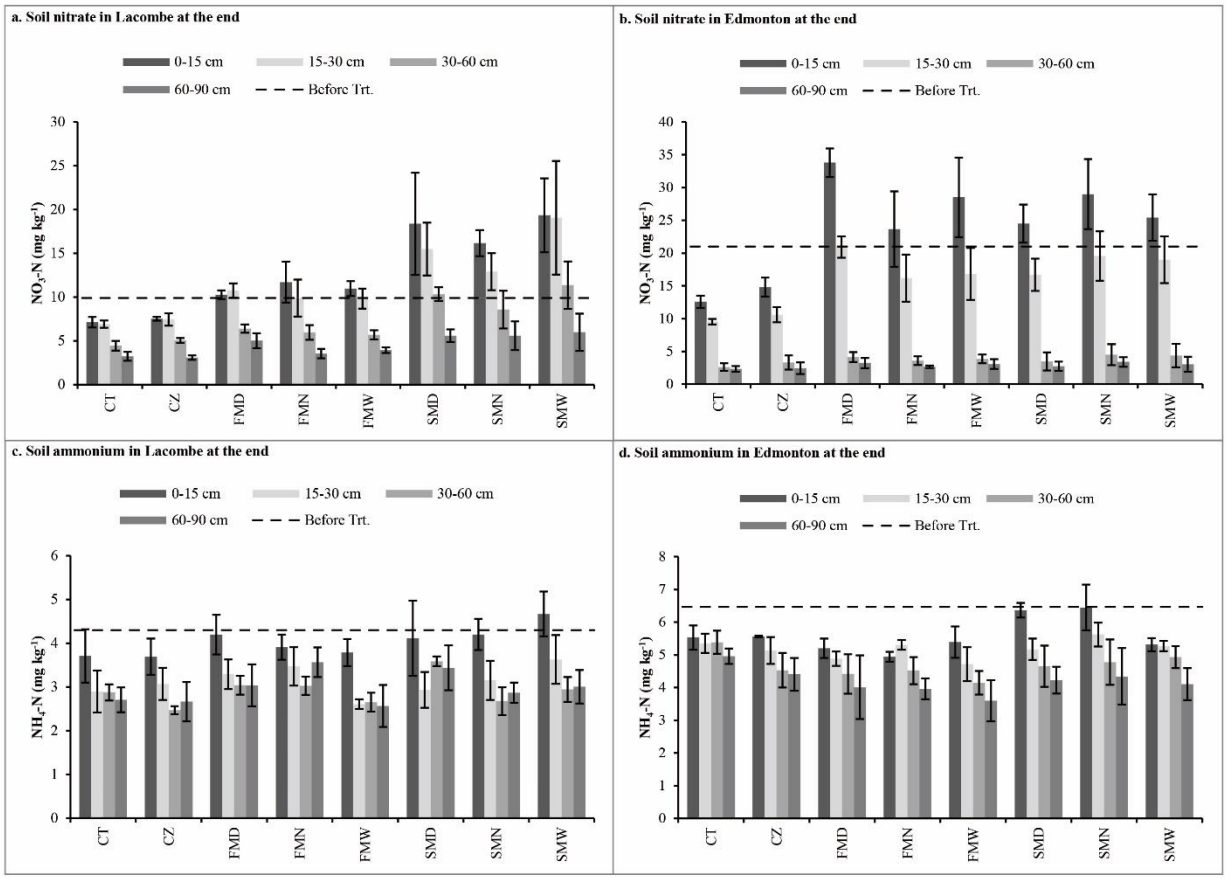
Supplementary Table S4. ANOVA – Tukey tests outputs for soil NH_4-N and NO_3-N concentrations among treatments at different depths in both locations. †

	Lacombe								Edmonton							
	NH_4–N				NO_3–N				NH_4–N				NO_3–N			
Depth (cm)	0-15	15-30	30-60	60-90	0-15	15-30	30-60	60-90	0-15	15-30	30-60	60-90	0-15	15-30	30-60	60-90
BE‡		ab	ab	a	bc	c	c	b	a	ab	a	a	bcd	bc		
CT		ab	cd	bc	c	c	c	b	abc	ab	ab	b	d	c		
CZ		ab	d	bc	c	c	c	b	abc	ab	b	b	cd	c		
FMD		ab	abc	bc	bc	bc	bc	ab	c	ab	b	b	a	a	N.S.	N.S.
FMN	N.S.§	b	bc	b	bc	bc	bc	ab	c	ab	b	b	abc	abc		
FMW		ab	cd	c	bc	bc	bc	ab	bc	b	b	b	ab	abc		
SMD		ab	a	bc	a	ab	a	ab	abc	ab	b	b	abc	abc		
SMN		ab	cd	bc	ab	abc	ab	ab	a	ab	ab	b	ab	a		
SMW		a	cd	bc	a	a	a	a	c	a	ab	b	abc	ab		

† All soil NH_4-N and NO_3-N concentration data were shown in Supplementary Fig. 1 a-d.

‡ BE, baseline before beginning of the experiment; CT, control treatment where the soil was disturbed by the manure applicator (without applying manure); CZ, control without disturbance; FMD, fall application of liquid manure with the inhibitor 3, 4-dimethylpyrazole phosphate (DMPP); FMN, fall application of liquid manure with the inhibitor nitrapyrin; FMW, fall application of liquid manure without inhibitors; SMD, spring application of liquid manure with the inhibitor DMPP; SMN, spring application of liquid manure with the inhibitor nitrapyrin; SMW, spring application of liquid manure without inhibitors.

§ N.S., not significant among treatments; different letters indicate significant differences among the eight treatments in each site ($P < 0.05$).



Supplementary Fig. 1. Soil nitrate and ammonium concentrations at different depth increments prior to the beginning of the experiment (shown as discontinuous reference horizontal lines) and near the end of the study in (a, c) Lacombe and (b, d) Edmonton sites. The soil samples towards the end of the experiment were collected on 12 Oct. 2016 in Lacombe and on 30 Sept. 2016 in Edmonton. The comparisons for soil NH_4-N and NO_3-N among treatments at different depth increments in both locations among treatments are shown in Supplementary Table S3. Note the different y-axis scales across panels. CT, control treatment where the soil was disturbed by the manure applicator (without applying manure); CZ, control without disturbance; FMD, fall application of liquid manure with the inhibitor 3, 4-dimethylpyrazole phosphate (DMPP); FMN, fall application of liquid manure with the inhibitor nitrapyrin; FMW, fall application of liquid manure without inhibitors; SMD, spring application of liquid manure with the inhibitor DMPP; SMN, spring application of liquid manure with the inhibitor nitrapyrin; SMW, spring application of liquid manure without inhibitors. Discontinuous horizontal reference lines indicate soil nitrate or ammonium concentrations at 0-15 depth increment measured as baseline prior to the initial establishment of the experiment plots on 30 Sept. 2014.