
Reducing greenhouse gas emissions from North American soybean production

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1. Annual nitrous oxide emissions by crop phase and system

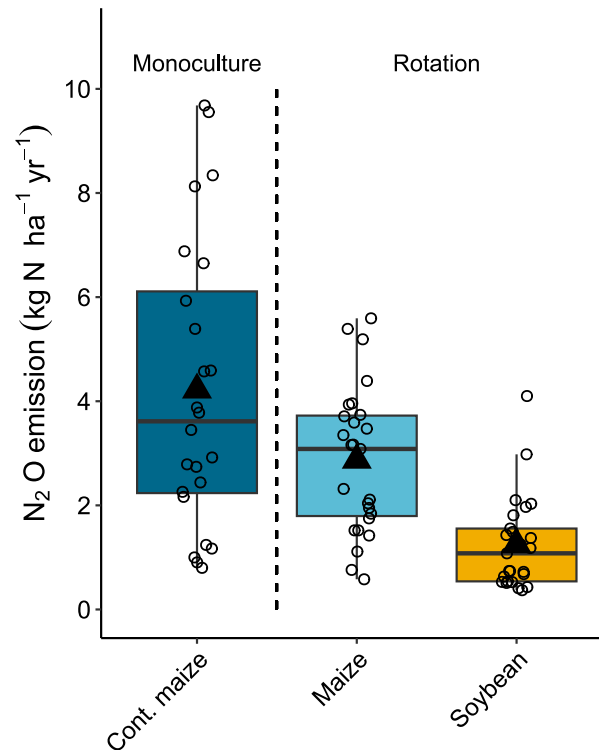


Fig. S1 | Annual N₂O emissions from maize monoculture, and maize and soybean in a rotation (n = 24 triplets, site-treatment-year cases from 6 studies) measured in paired plots grown in the same experiment under Business-As-Usual management conditions in the US and Canada. The lower, mid and upper hinges of the box correspond to the 25th, 50th, and 75th percentiles and whiskers extend to 1.5 times the inter-quartile range. The triangle shows the mean value and the central line shows the median value. The data used in this analysis were published by Behnke et al., (2018); Drury et al., (2008); Hernandez-Ramirez et al., (2009); MacKenzie et al., (1998); Osterholz et al., (2014) and Venterea et al., (2010).

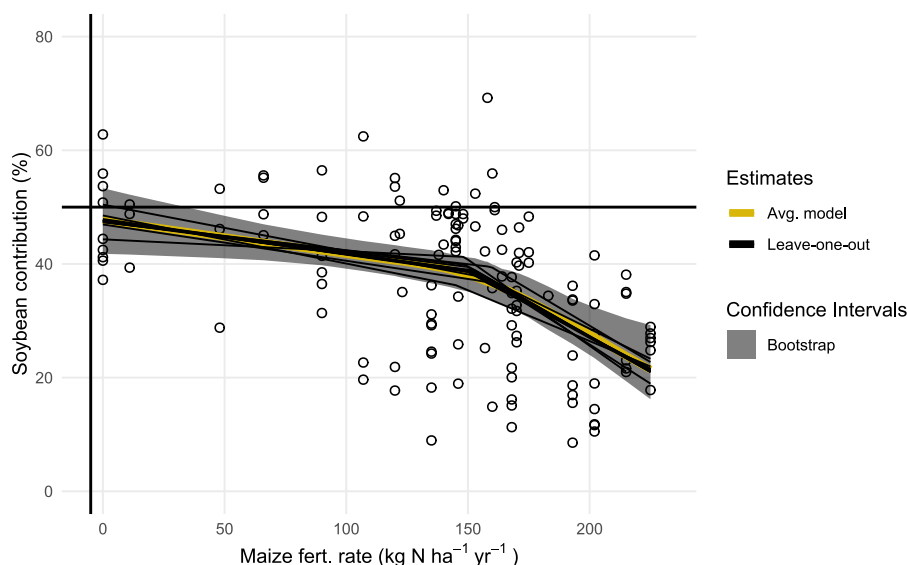


Fig. S2 | Cross-validation analysis of the bilinear model for the contribution of soybean crop to cumulative N₂O emission in the maize-soybean rotation as a function of maize fertilizer rate (n=131). Black and yellow lines show the bilinear models, and the gray area shows its 95% confidence intervals. The uncertainty associated with the bilinear model was assessed by estimating the regression using 2 different methods: Bootstrap and *leave-one-out*, and they showed similar results. For the *leave-one-out* method, we removed 1 of the 16 studies used in the analysis every time and refitted the model. For details on the methods see package ‘nlraa’ for R (Miguez, 2023).

References for figures S1 and S2

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2. Simulation results

Table S1 | Environmental nitrogen losses and grain yield in maize as well as the effects of Early Planting, Cover Crop, and Early Planting + Cover Crop. Data represents average outcomes across 15 locations x 30 weather-years per location. Note: Early planting applied only to soybean and a rye cover crop was planted following only the maize prior to soybean.

System	N₂O (kg N ha ⁻¹)	NO₃⁻ (kg N ha ⁻¹)	Grain yield (Mg ha ⁻¹)
Business-As-Usual	5.18	19.08	13.53
<i>Change respect to BAU</i>			
Cover Crop	+0.05 (+1%)	-0.36 (-2%)	+0.11 (+1%)
Early Planting	+0.00 (+0%)	+2.55 (+13%)	-0.01 (0%)
Cover Crop + Early Planting	+0.07 (+1%)	+2.36 (+12%)	+0.10 (+1%)

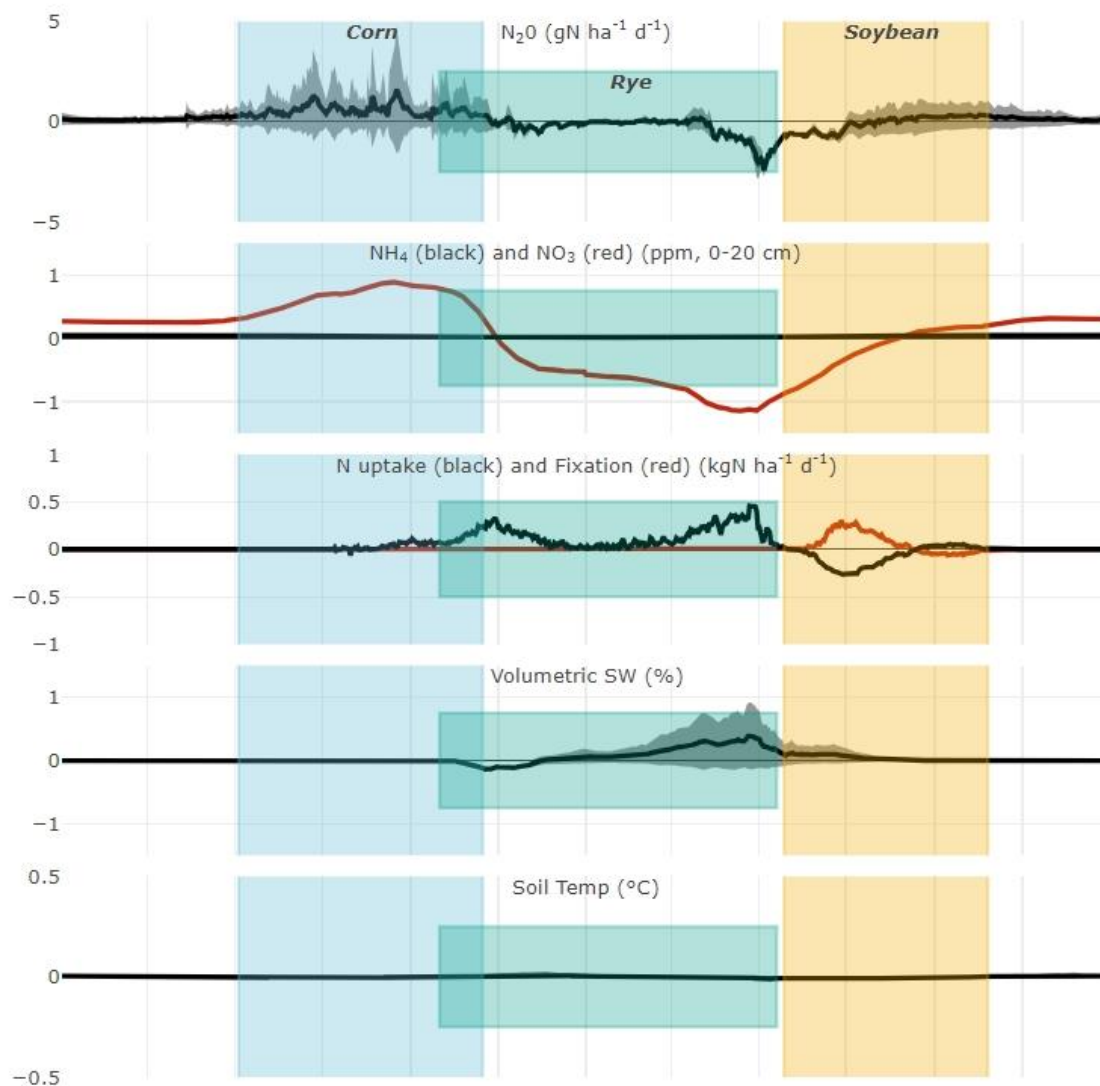


Fig. S3 | Simulated daily change in N_2O emissions and their main drivers during the 2-years maize-soybean rotation under Cover Crop + Early Planting management with respect to Business-As-Usual (BAU) management. Black lines represent the average across 15 sites and 30 years. Since different sites had different temporal patterns in the variables and spanned a wide range of values, the variables are expressed as a percentage change from BAU. Colored shade areas indicate the mean growing season (from planting until harvesting or cover crop termination) of crops. In the simulations, the planting and harvesting dates changed each year and site based on USDA survey data at a state level.

3. Linear and non-linear model comparison

Table S2 | Comparison of the models tested to evaluate the relationship between LRR and maize fertilization rate. df: degree of freedom, AIC: Akaike Information Criteria, BIC: Bayesian Information Criteria, dAIC, delta in the AIC, and weight: Akaike weight.

Model	df	AIC	AICc	BIC	dAIC	weight
Bilinear	5	227.54	228.02	241.91	0.00	0.71
Plateau linear	4	230.25	230.57	241.75	2.72	0.18
Linear	3	231.24	231.43	239.86	3.70	0.11

Table S3 | Comparison of the models tested to evaluate the contribution of soybean to the 2 years rotation N₂O emission (%) as a function of maize N rate. df: degree of freedom, AIC: Akaike Information Criteria, BIC: Bayesian Information Criteria, dAIC, delta in the AIC, and weight: Akaike weight.

Model	df	AIC	AICc	BIC	dAIC	weight
Bilinear	5	1015.54	1016.02	1029.91	0.00	0.43
Declining logistic	5	1016.62	1017.10	1030.99	1.08	0.25
Plateau-exponential	4	1017.35	1017.67	1028.85	1.81	0.17
Plateau linear	4	1018.87	1019.19	1030.37	3.33	0.08
Linear	3	1019.86	1020.05	1028.49	4.32	0.05

4. APSIM model evaluation

Table S4 | Description of the 13 experiments used for APSIM model evaluation showing the factors analyzed (green cells) and the experimental period (light blue cells). Individual daily data for experiments number 1-4, 7, and 11 was available at USDA GRACEnet repository (USDA Agricultural Research Service 2015), for experiment number 8, at CSCAP repository (Abendroth, et al., 2016) and for experiments 5 and 6 were provided by the author. For experiments 9, 10, 12 and 13 we used cumulative annual (not daily) data reported in the articles. The factors were Rate: fertilizer rate; Source: fertilizer source, Inhib.: use of nitrification or urease inhibitors; P. Date: planting date; CC: cover crop; Rot.: crop rotations; Tillage: tillage system.

EXPERIMENTS				FACTORS								PERIOD									
ID	State	Loc.	Reference	Rate	Source	Inhib.	Time	P.Date	CC	Rot.	Tillage	2004	2006	2008	2010	2012	2014	2016	2018	2020	
1	MN	Rosemount	Venterea et al. (2010)																		
2	MN	Rosemount	Venterea et al. (2011)																		
3	MN	Rosemount	Venterea & Coulter (2015)																		
4	MN	St. Paul	Venterea et al. (2016)																		
5	IA	Boone	Iqbal et al. (2015)																		
6	IA	Boone	Iqbal et al. (Unp.)																		
7	IA	Ames	Parkin et al. (2016)																		
8	IL	Monmouth	Behnke et al. (2018)																		
9	IL	Urbana	Graham et al. (2018)																		
10	IL	Pana	Preza-Fontes et al. (2022)																		
11	IN	Lafayette	Smith et al. (2011)																		
12	IN	Lafayette	Burzaco et al. (2013)																		
13	IN	Lafayette	Omonode & Vyn (2019)																		

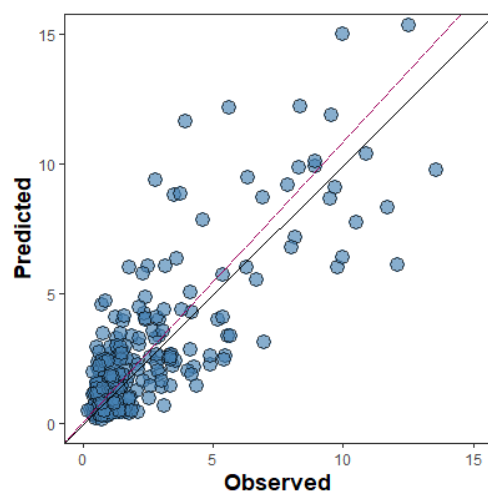
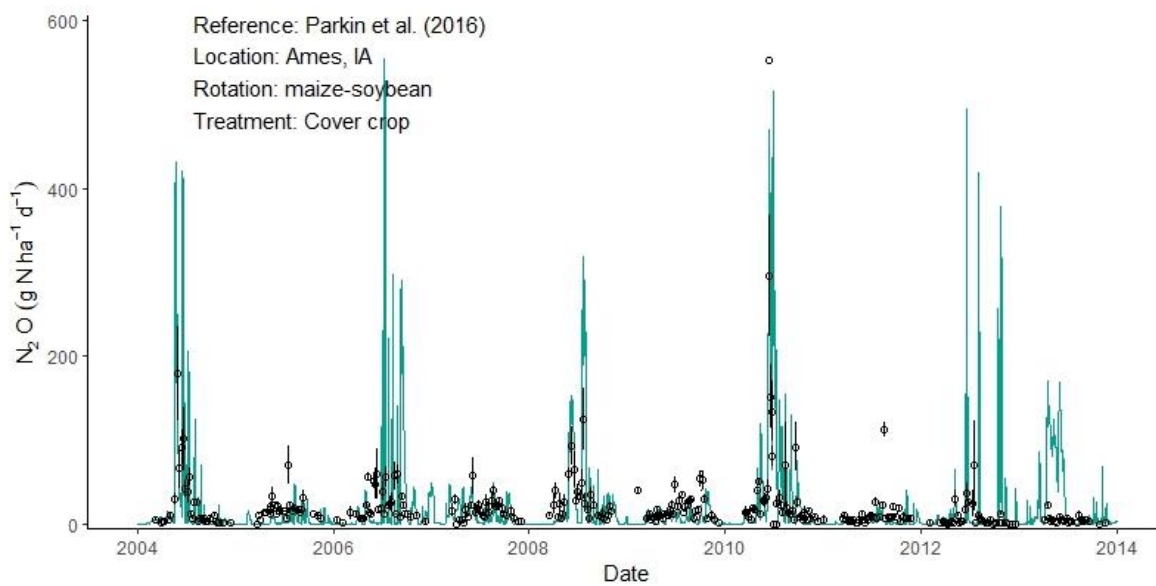
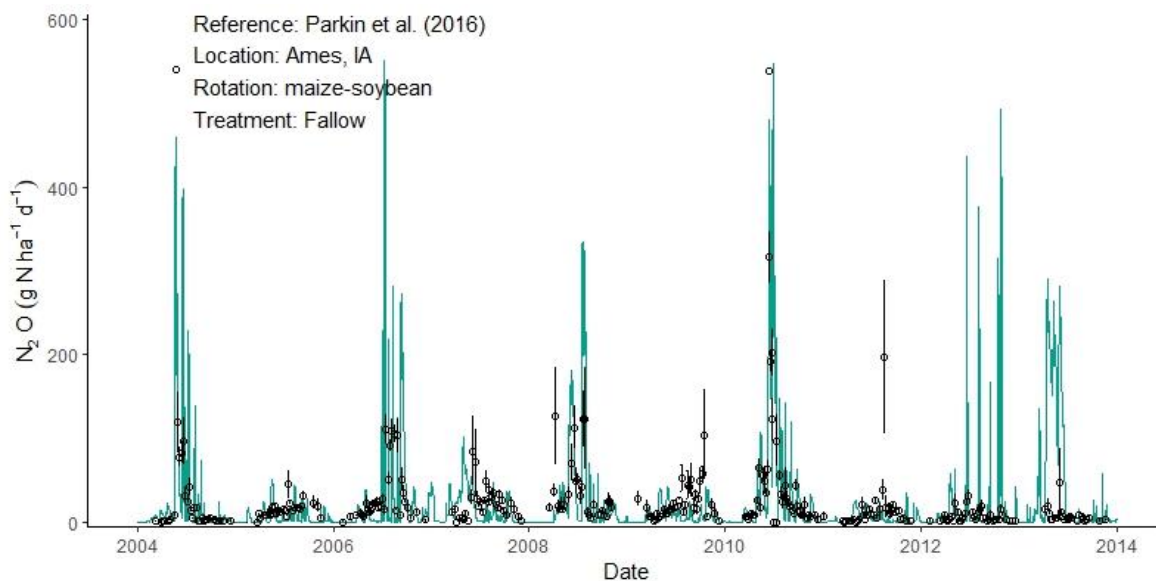


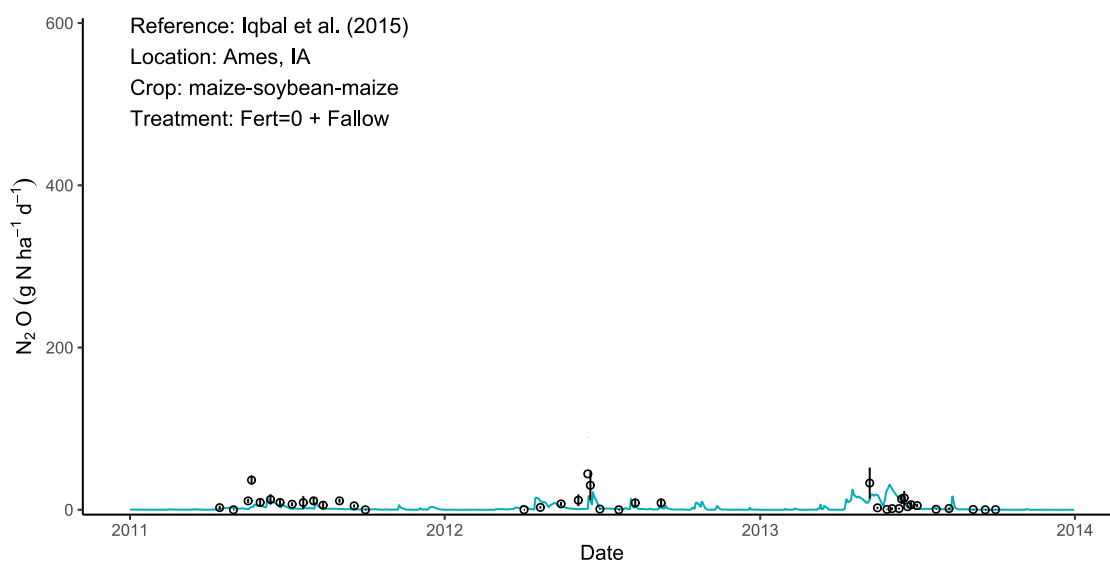
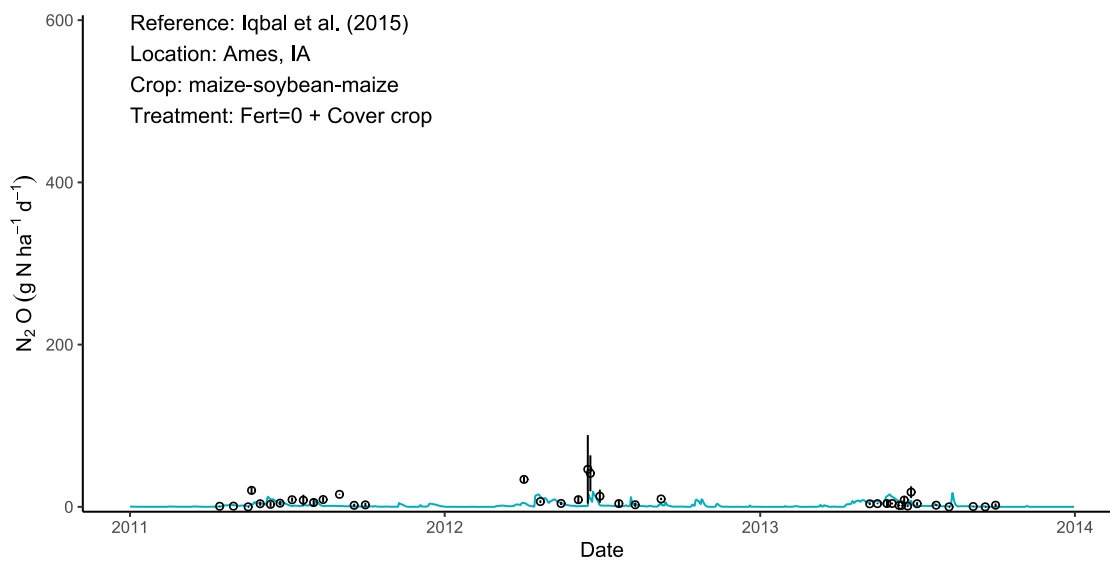
Fig. S4 | Relationship between the N₂O emissions (kg N ha⁻¹ yr⁻¹) predicted by APSIM model and observed in field experiment. N=248; Intercept=0.13; slope=1.08; R²=0.64; RMSE=1.76.

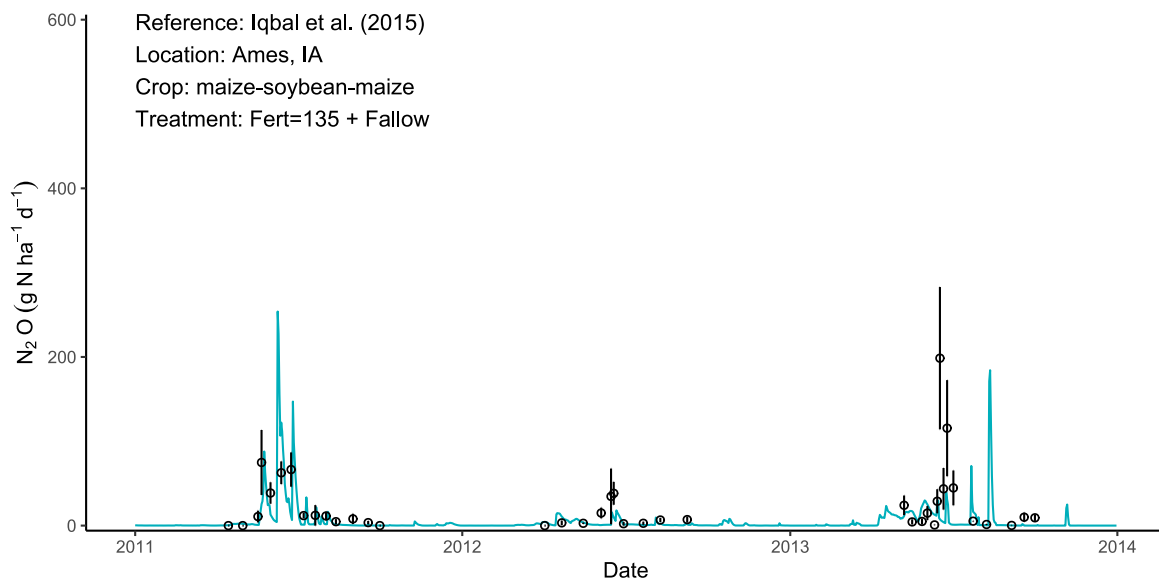
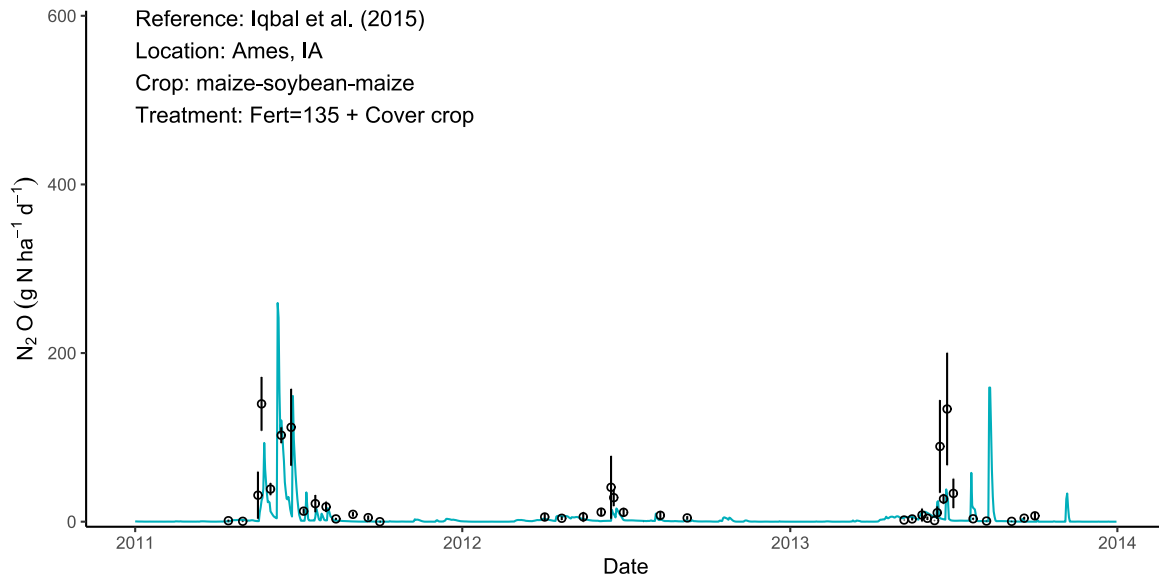
References for APSIM model evaluation

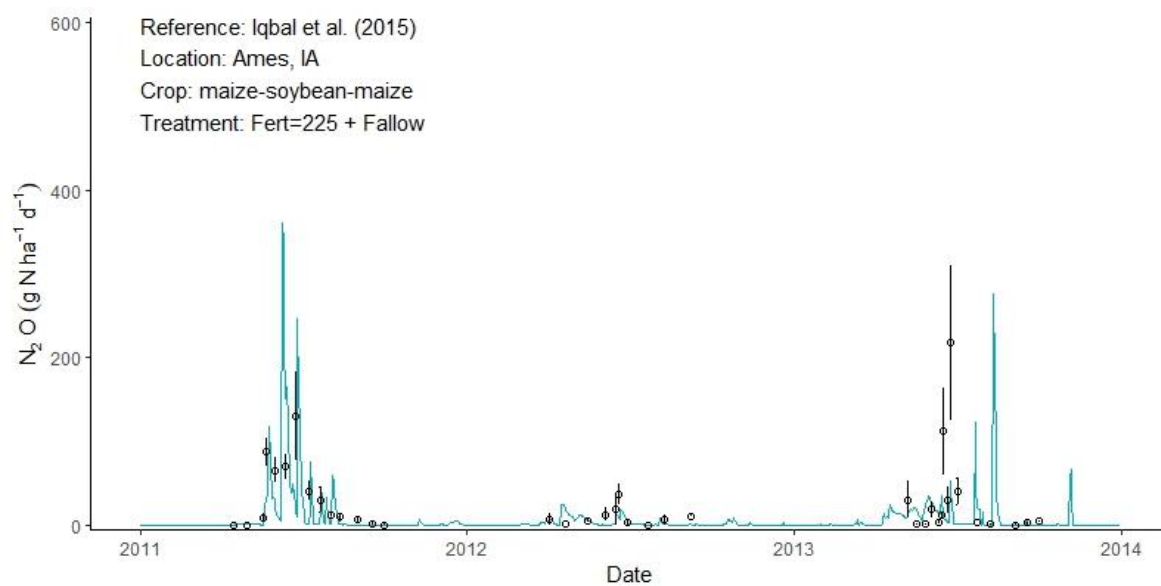
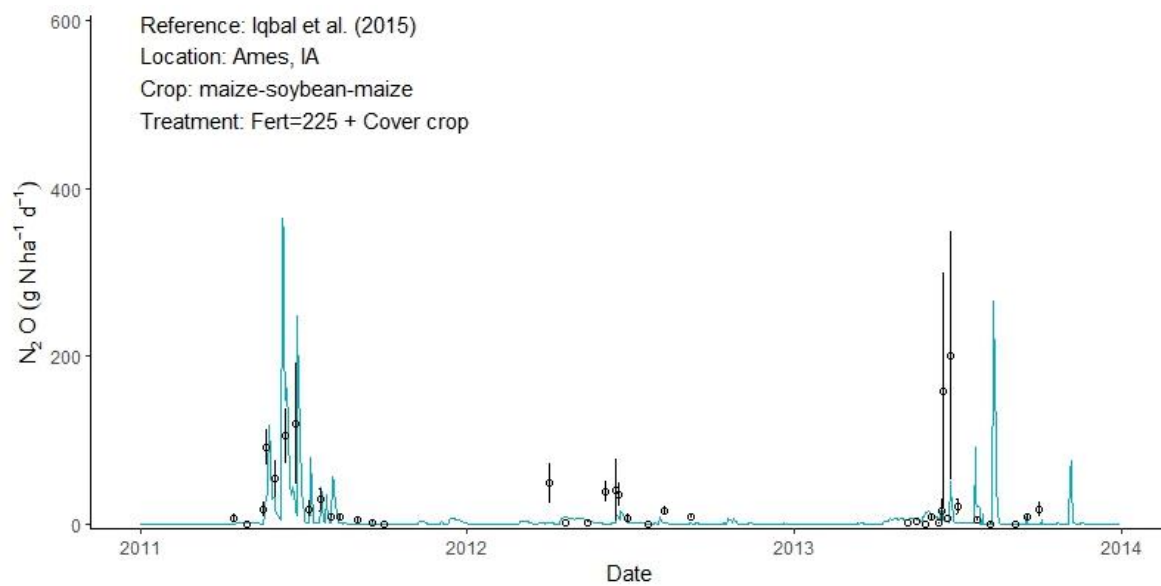
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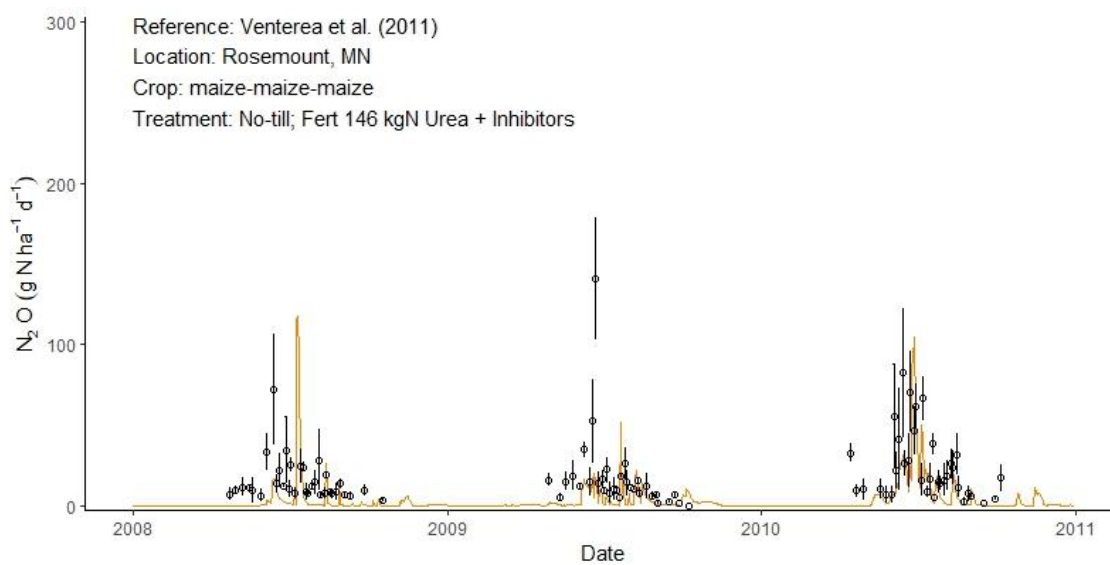
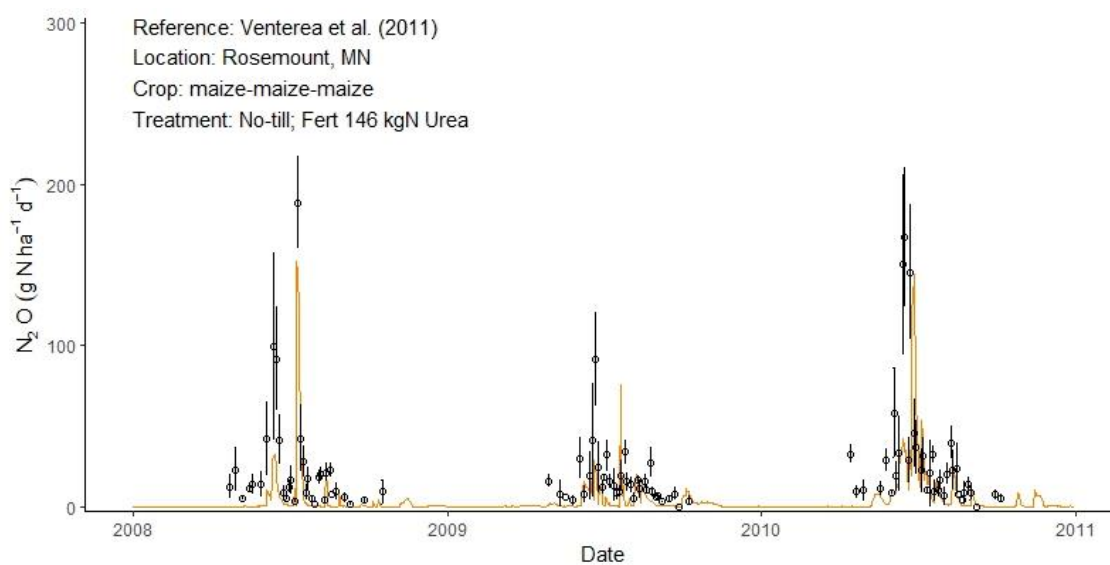
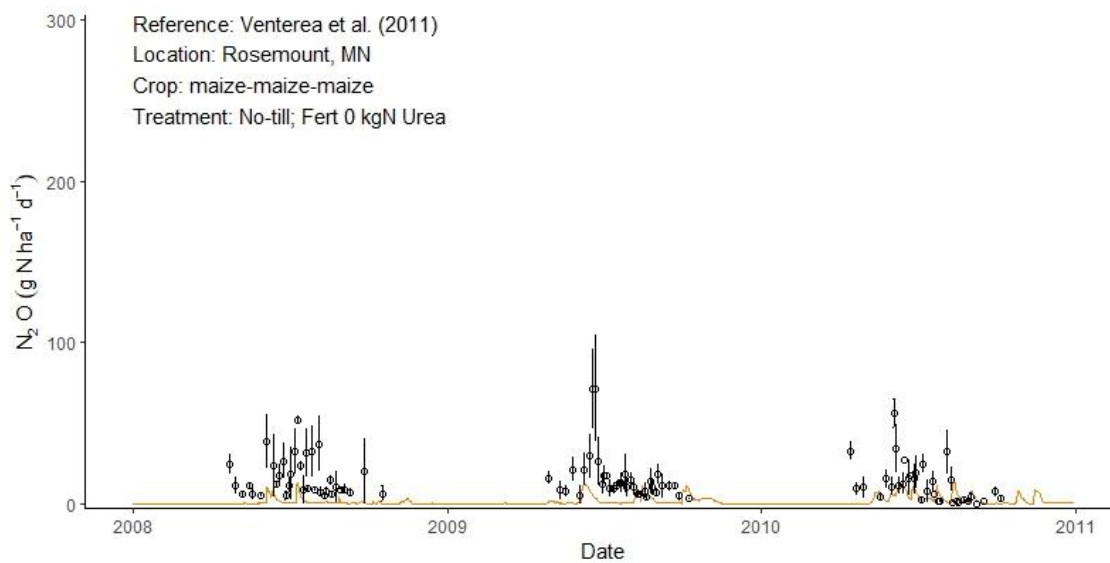
Fig. S5 | APSIM simulated (lines), and field measured (dots $\pm$ 1 SE) daily N_2O emissions. The following figures show examples of the data used during model evaluation process. References of the study, location and treatment are stated on each figure.

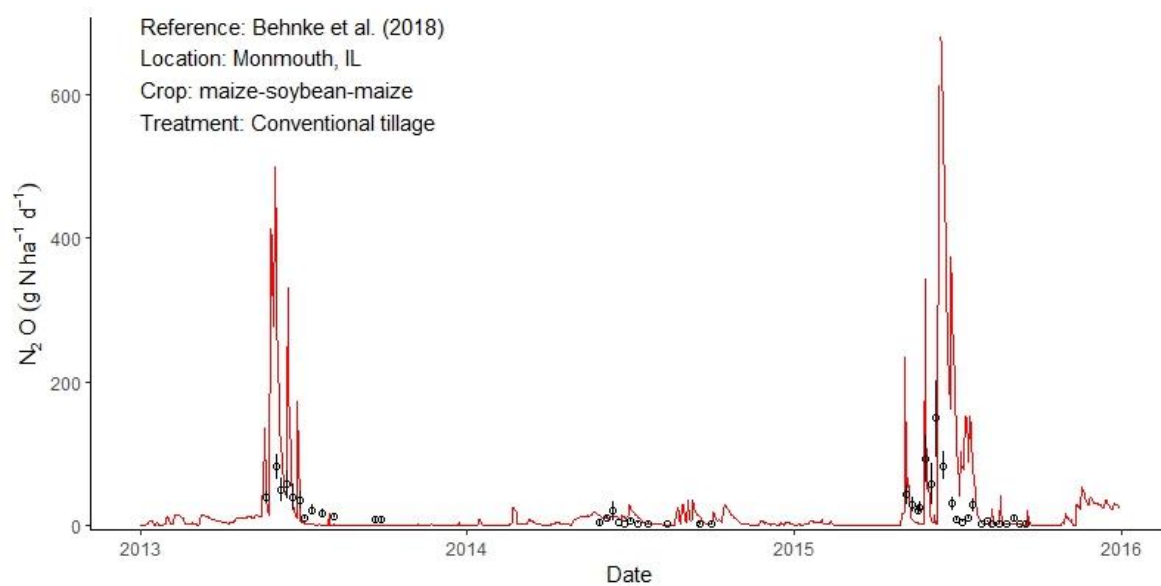
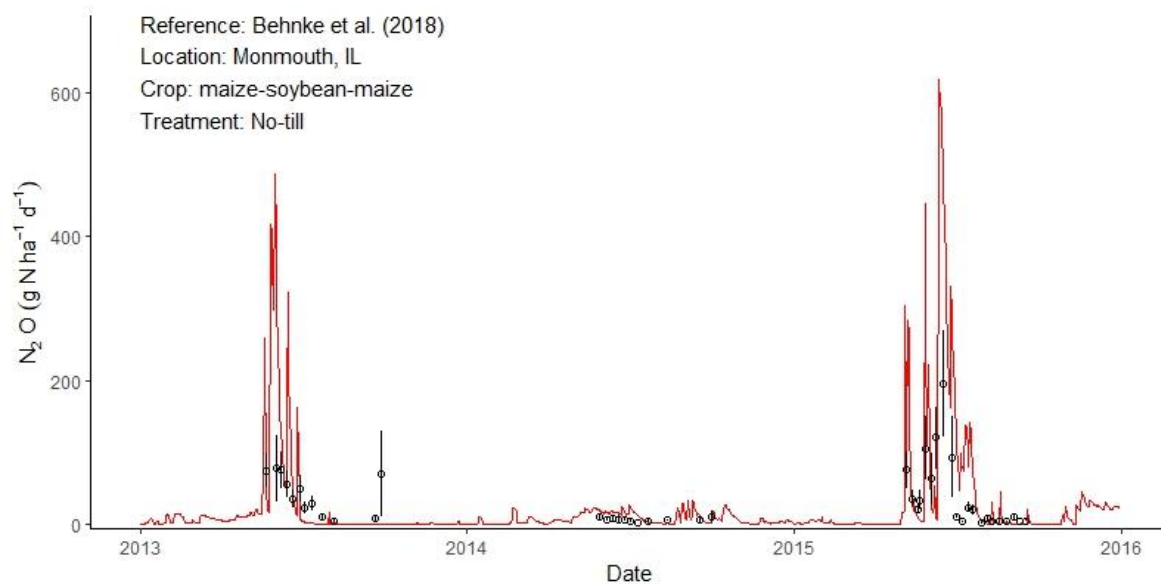


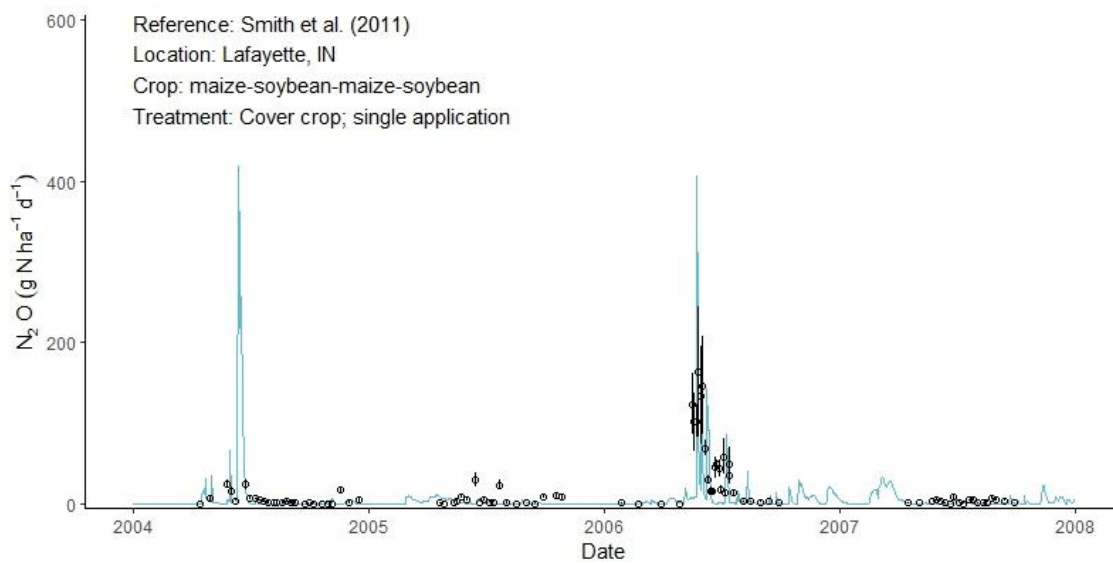
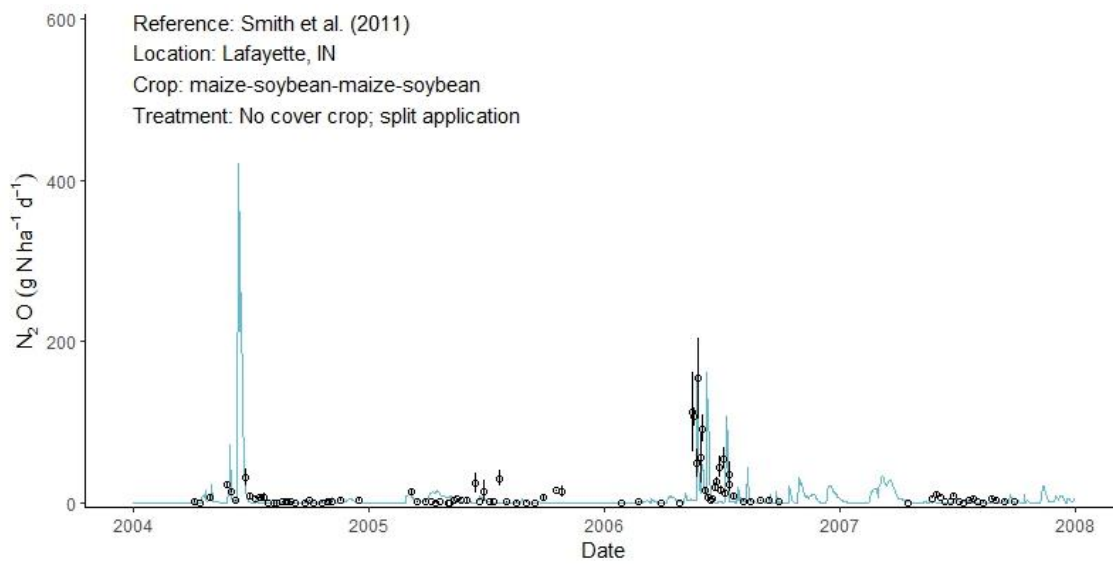
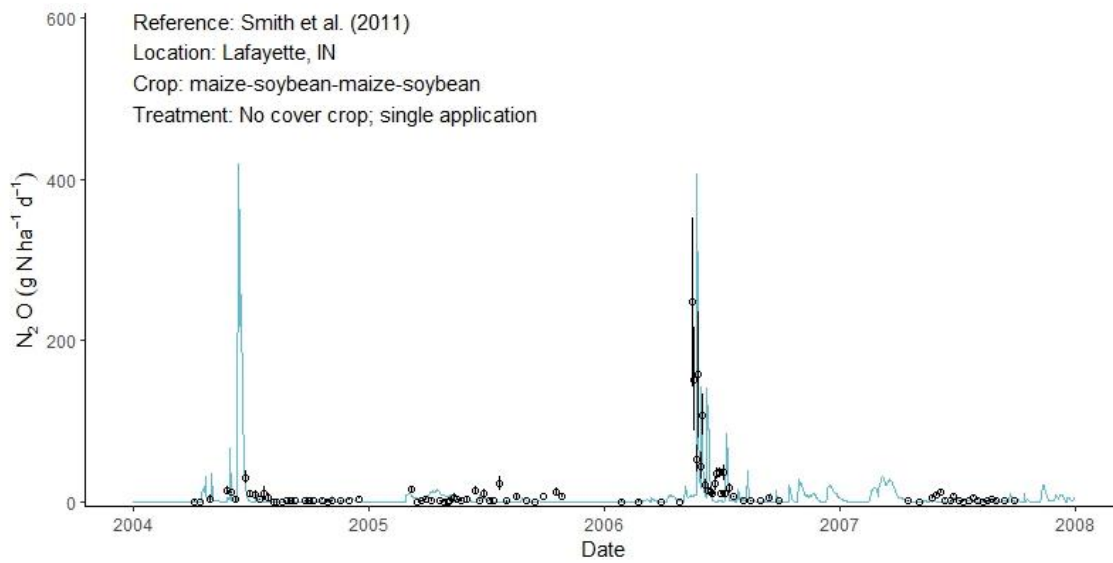












5. Life-Cycle-Assessment

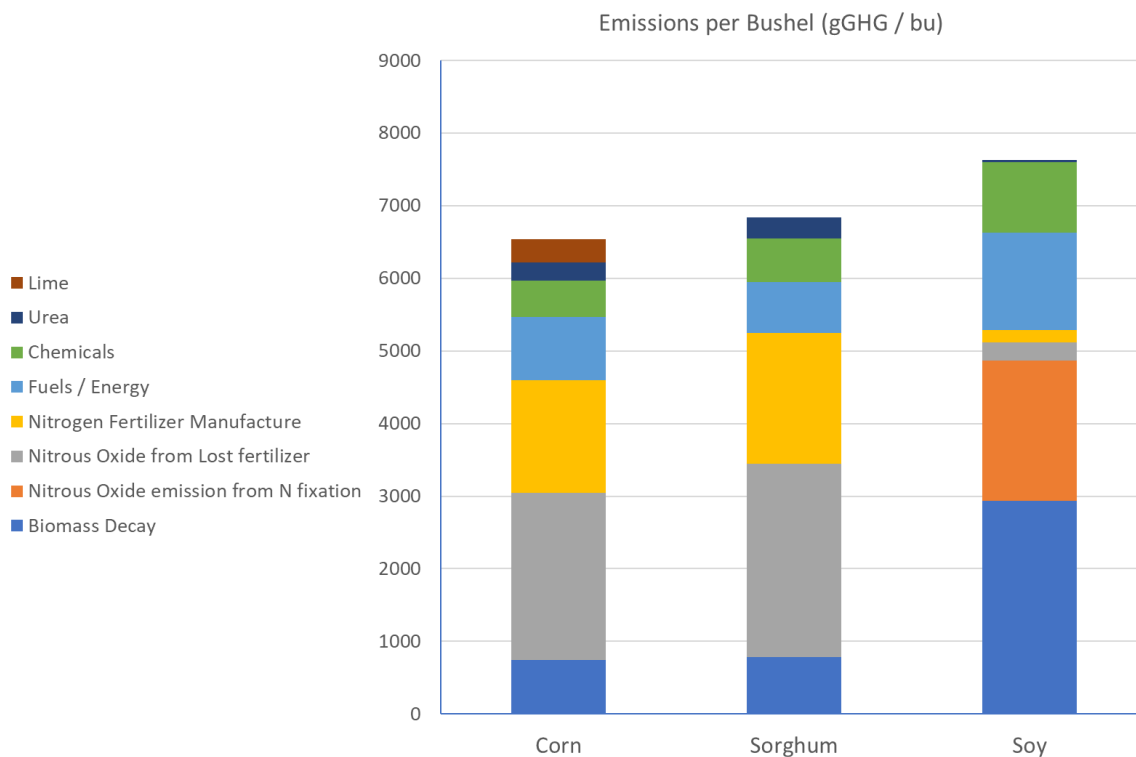


Fig. S6 | Default values from FD-CIC 2021 release showing the emissions categories for corn, sorghum, and soy (grams of CO₂ eq per U.S. bushel). Reflecting the similarity of corn and sorghum production systems, their emission categories are similar, and mostly comprised of emissions associated with nitrogen fertilizer. By contrast, soybeans do not typically receive nitrogen fertilizer, and the emissions come from biological sources of reactive nitrogen.

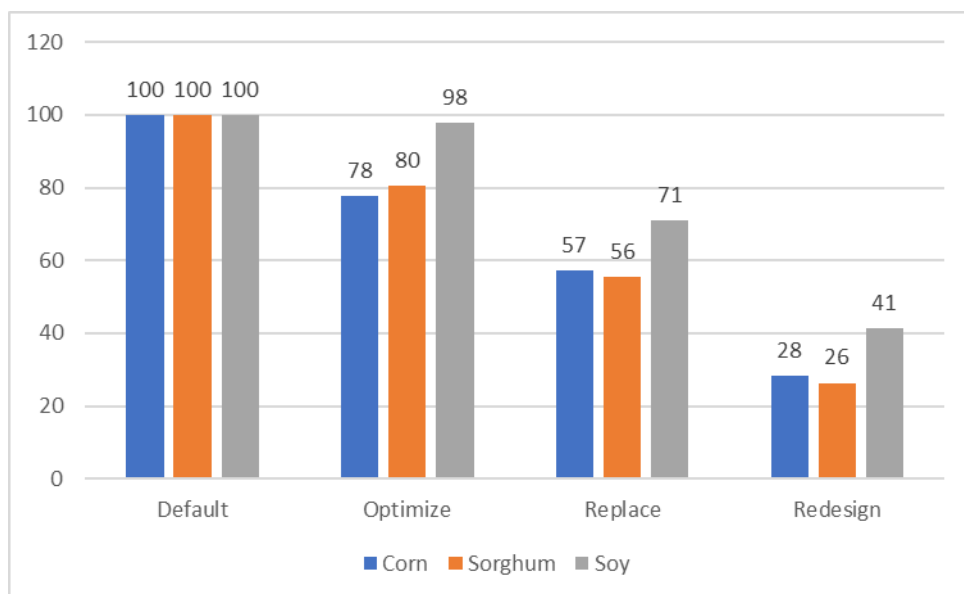


Fig. S7 | We used the FD-CIC tool and adjusted the default emission category for each crop using the reductions that are projected for each phase of technology adoption (see Northrup et al. 2021 <https://doi.org/10.1073/pnas.2022666118>). The columns are the summed emissions for all categories at each technology phase normalized to the current default value in each technical regime. Notably, corn and sorghum, which receive significant quantities of N fertilizer, are easier to decarbonize via reduced inputs. By contrast the limited inputs that are applied to soybean present little opportunity for improvement prompting our search for additional emission reduction opportunities.