Supplementary Information

Modeling of Drained and Undrained Cropping Systems

We used the Agricultural Production systems simulation (APSIM), an open-source, field-scale, process-based modeling platform that operates on a daily time step, to simulate crop-soil-atmosphere processes[1]. The APSIM platform contains several crop models together with soil-atmospheric models and a flexible manager to simulate a variety of cropping systems. The platform is regularly used to predict and explain agronomic and environmental outcomes of production scenarios from field to regional scales[2,3].

The APSIM cropping systems model is capable of simulating shallow water table dynamics in fields with various drainage systems[4]. The model simulates root depth (and thus daily water and nitrogen uptake) as a function of soil moisture, temperature, soil constraints and plant cultivar factors. Nitrogen below the root zone can either be denitrified or leached to lower soil layers. The model has been calibrated and validated for maize response to N fertilizer and root response to water table depth in drained and undrained fields[5–7]. Currently, the prediction of root depth has an R^2 of 0.94 across 18 datasets from drained and undrained locations with a range in depth to water table[7], which indicates that final root depth, mass and length along the soil profile are emergent properties of the simulation process. APSIM simulates plant litter decomposition (including root) and formation of SOM as a function of potential decomposition rates for different chemical compounds (carbohydrates, cellulosic, lignin) along with soil water, temperature, and inorganic N availability as modifiers[8]. In each soil layer, part of the decomposed plant litter is incorporated into a fast decomposing soil organic matter (SOM) pool and part into the slow decomposing SOM pools while the remainder is lost to the atmosphere[9]. Based on current model function, plant litters and SOM pools in soil layers saturated with water will decompose very slowly due to lack of O_2. The model also simulates soil N mineralization and immobilization, nitrification, denitrification, and urea hydrolysis for each soil layer. Moreover, roots cannot enter soil layers that are saturated with water[10,11] so that the plant's ability to uptake water and N will be restricted in poorly drained treatments.

For this analysis, we tested APSIM performance using a variety of data collected at a field experiment in Iowa USA (41°11'38.3"N 91°28'56.0"W) that includes replicated plots (1.2-2.4 ha) with and without artificial subsurface drainage. In the drained plots, perforated polyethylene pipes were installed in 2007 at 1.2 m depth and 18 m spacing. The drainage intensity is 1.9 cm d^{-1} [12]. It is important to note that observed and simulated differences between drained and undrained plots should be considered conservative due to the unavoidable and pervasive effects of local and regional drainage systems on soil water dynamics in the undrained plots. In other words, 'undrained' plots have better drainage than they would in the absence of surrounding local and regional drainage systems[13,14]. As a result, the differences in key drained and undrained ecosystem properties and processes may be slightly underestimated.

The replicated plots contain continuous maize cropping systems that are managed in eight subplots at eight N fertilizer rates from 0-400 kg N ha^{-1} applied as urea-ammonium-nitrate. All other nutrients and pH are maintained for agronomic optimum. We used various data from this experiment to further test APSIM before its application to simulate the continuous maize cropping system in drained and undrained treatments across 18 years of weather data from the experiment location. We used 18 recent weather-years because this range is enough to capture the inter-annual variability in weather and also because previous research has demonstrated that, in the Midwest US, about 20 weather years encompass sufficient inter-annual weather variability for accurate simulations of average cropping systems processes and properties[15]. Data measured in 2016 and 2017 include tile drainage flow and N leaching in drained plots, root depth, soil nitrate and ammonium pools sampled from 0-30 cm periodically during the two growing seasons, sub-daily soil moisture and temperature, biomass production and partitioning to leaves, stems and grains, tissue N concentrations and plant N dynamics (Figure S1). Grain yield in each of the eight N fertilizer rates was measured in 2017. Daily depth to water table was measured from 2011-2013 (Figure S2). Periodic N_2O emissions were measured from 2013-2014 using a static chamber approach (Figure S3).

We used APSIM version 7.8 with the following models: the maize crop model, the coupled soil N and C cycling model[8], the SWIM water balance model with the Richard's equation[16], the soil temperature2 model that mechanistically simulates soil temperature using Campbell's equations[17], the SURFACEOM model that deals with surface and incorporated residue dynamics[18,19], and the following management activities: planting, harvesting, tillage, N fertilization and tile drainage. Pests were assumed to be effectively controlled. Recent improvements made to the model for Midwest cropping system conditions such as denitrification by depth[20] and root growth inhibition due to excessive moisture[7] were included. The simulations used drained and undrained continuous corn systems managed at eight different N fertilizer rates planted 1st week of May every year with a 110 day cultivar at 8 plants/m^2 and 76 cm row spacing. The model output consists of a number of variables per year that we used to calculate the agronomic optimum N fertilizer rate (AONR)[21] by fitting quadratic-plateau regression models to mean 18-year maize grain yield where the joint point of the model was the AONR[21] (Table S1) and probability density plots using the geom_density function of ggplot2 in R[22]. Figures S1-S3 illustrate model performance across a range of soil-crop-atmospheric variables.

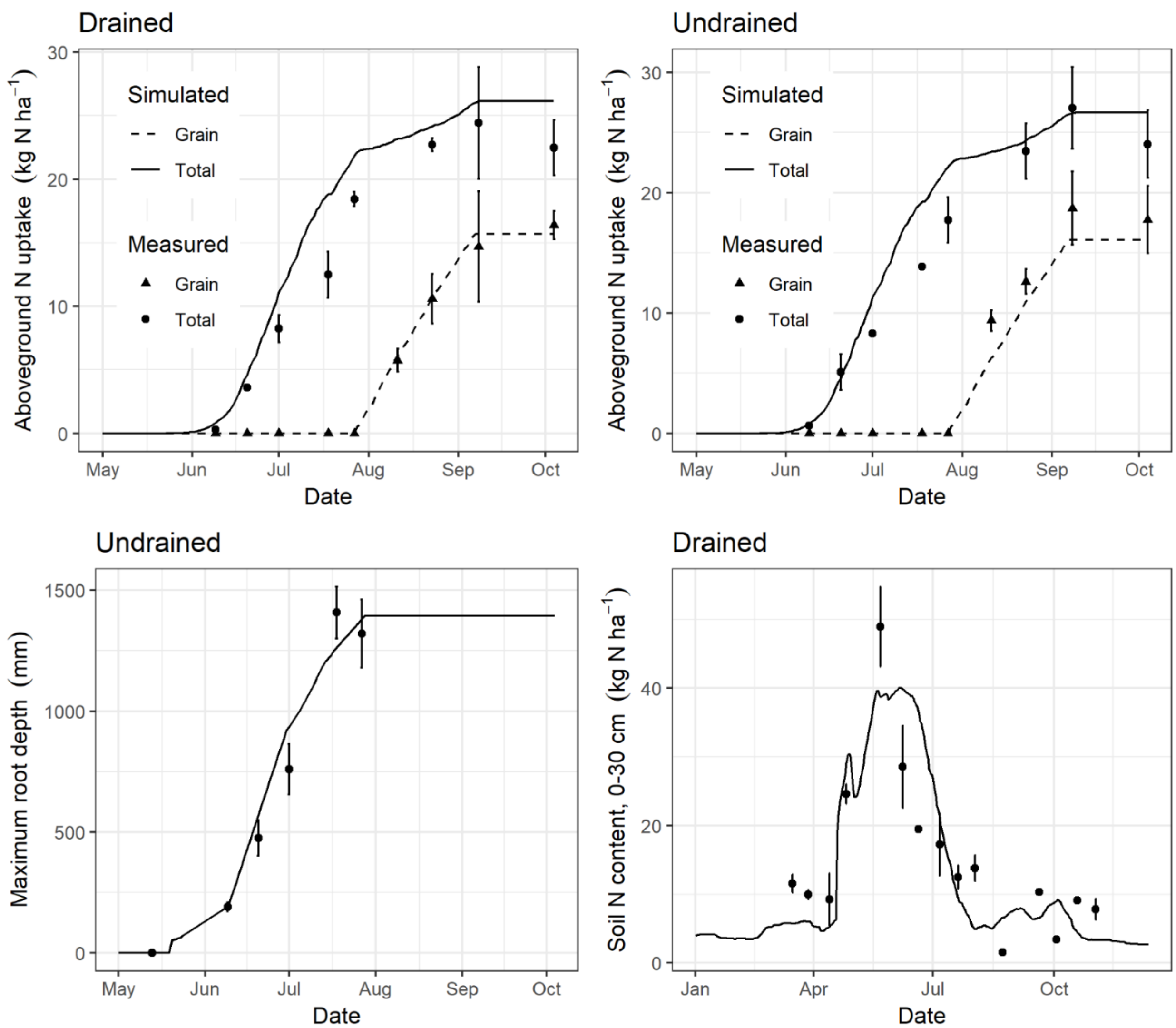

Figure S1. Simulated and measured data from maize in drained and undrained treatments managed at the optimum N fertilizer rate. Measured data (N = 3) presented with standard error. Upper two panels: simulated and measured aboveground nitrogen uptake in total biomass and the grain fraction from drained and undrained treatments in 2016. Lower left: root depth from the undrained treatment in 2016. Lower right: soil NO_3^- concentration from 0-30 cm in 2017.

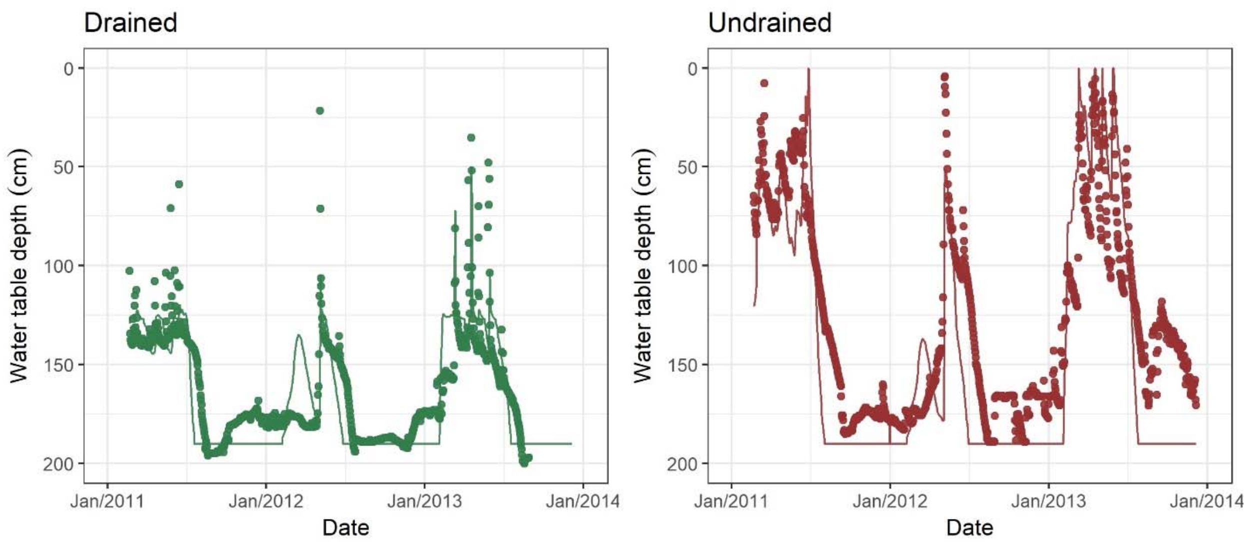

Figure S2. Simulated and measured water table depth from drained (left) and undrained (right) treatments in 2011-2013 managed in continuous maize at the optimum nitrogen fertilizer rate.

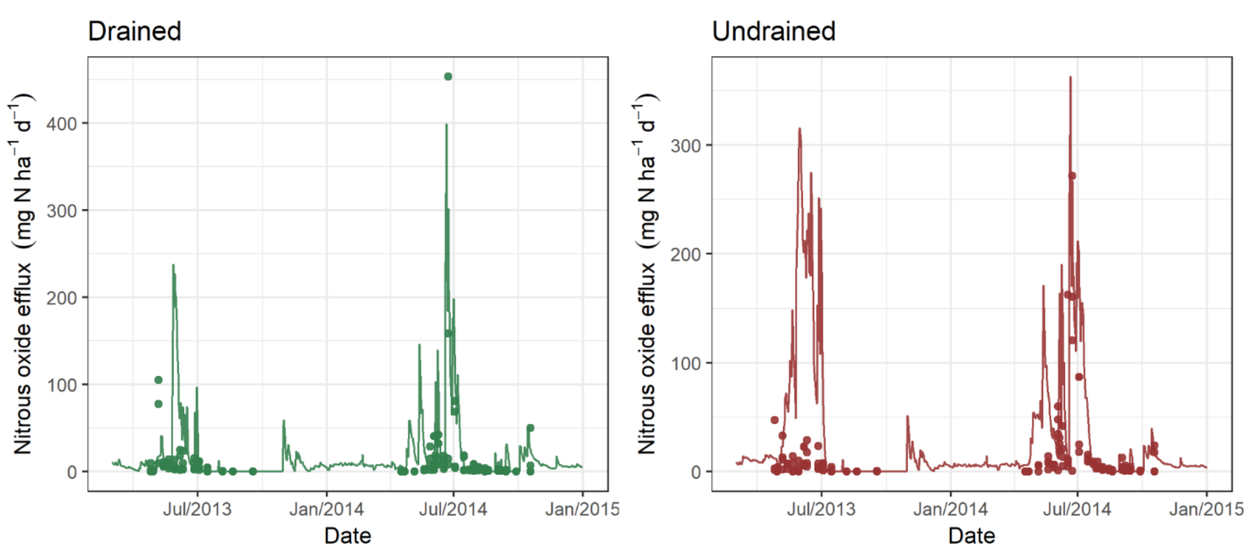

Figure S3. Simulated and measured N_2O emissions from drained (left) and undrained (right) treatments in 2013 and 2014.

Table S1. Quadratic plateau model fitted to simulated grain yield response to N fertilizer (0-400 kg N ha^{-1} y^{-1}) in drained and undrained treatments of continuous corn systems across 18 weather-years.

	Yield at Zero N (Mg/ha)	Regression Parameters			Plateau N Rate (kg/ha)	Yield at Plateau N Rate (kg/ha)	Optimum N Rate (kg/ha)	Grain Yield at Optimum N Rate	Model	
Dataset		a	b	c	kg/ha	Mg/ha	kg/ha	Mg/ha	R2	P>F
Drained	5.24	5.24	0.0615	-0.000148	207.5	11.62	**188.6**	**11.57**	0.77	<0.001
Undrained	4.78	4.78	0.0576	-0.000121	237.2	11.61	**214.1**	**11.54**	0.71	<0.001

In addition to simulating the continuous maize system with and without drainage, we simulated an annual rotation of maize-soybean. In this case, the soybean model was calibrated and validated with a wide array of data from Iowa experiments (data not shown). However, unlike the continuous maize systems, we did not have a side-by-side replicated drained vs. undrained experiment with which we could calibrate and validate the model for maize-soybean rotation.

Results from the maize-soybean rotation were consistent with results from the continuous maize simulation (Figures S4 and S5). In both the maize and soybean phases of the rotation, proportional changes in N mineralization, denitrification, N_2O emissions and GWP were similar to continuous maize. However, because soybean receives no N fertilizer and the optimum N fertilizer input to maize rotated with soybean is lower than the optimum N fertilizer input to continuous maize (in both drained, 154 kg N ha^{-1}, and undrained systems, 179 kg N ha^{-1}), the absolute changes in these processes were smaller than in continuous maize.

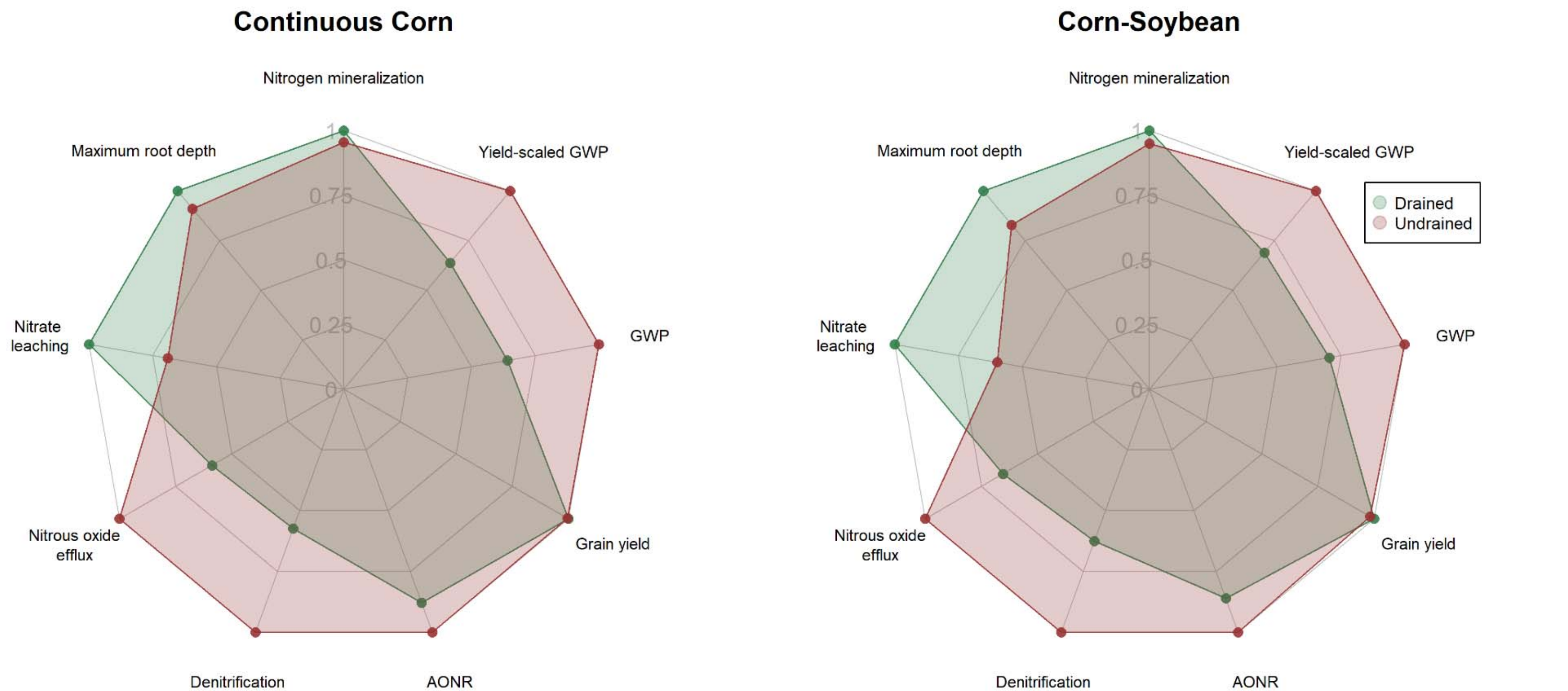

Figure S4. Relative differences in ecosystem properties and processes between drained and undrained continuous corn (left) and corn-soybean rotation (right) cropping systems. The differences between drained and undrained corn-soybean systems represent the mean difference across the two crops in rotation except for the AONR, which is only applicable to the corn phase of the rotation. All data represent the mean annual simulated value across 18 weather-years. GWP = global warming potential and AONR = agronomic optimum nitrogen fertilizer rate.

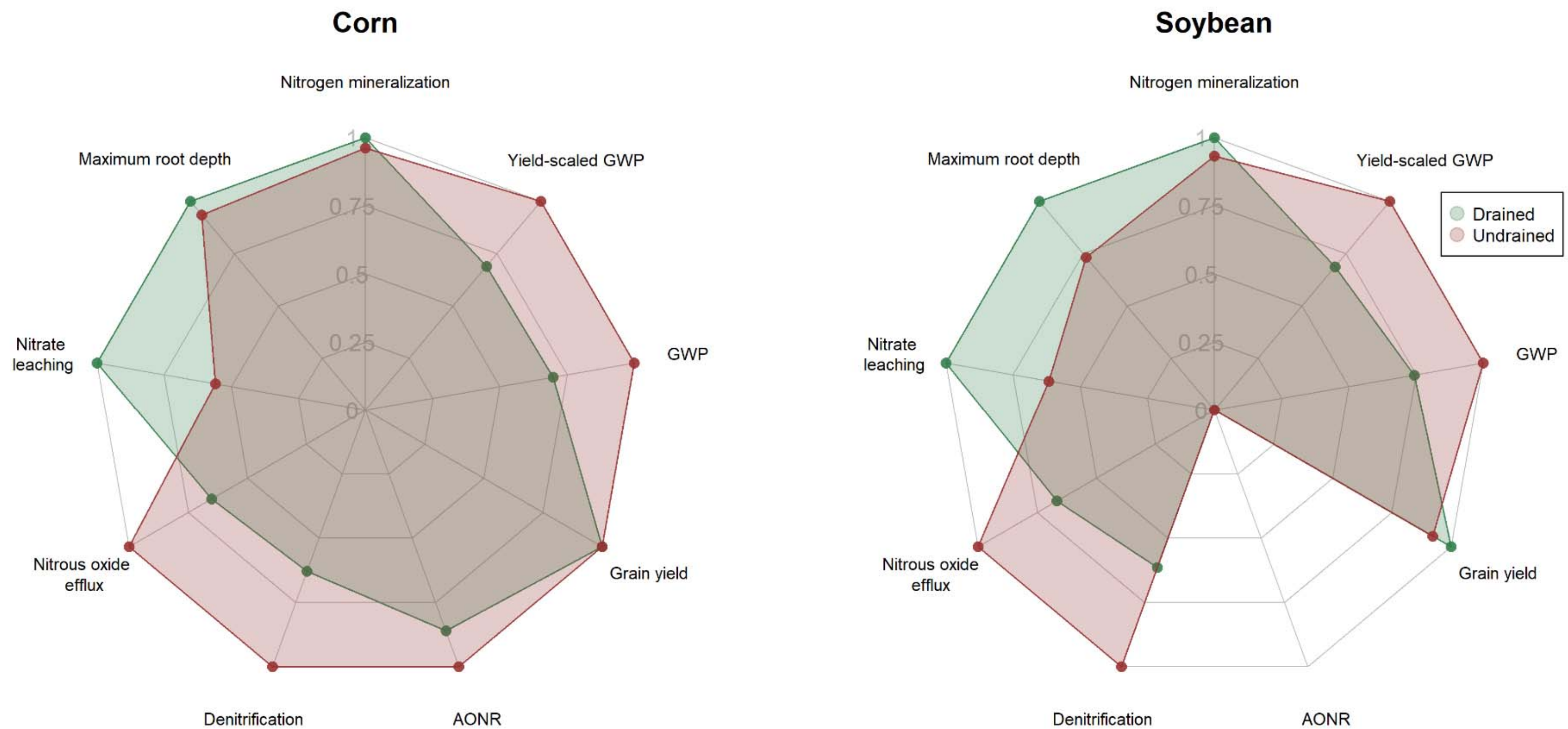

Figure S5. Relative differences in ecosystem properties and processes between drained and undrained corn (left) and soybean (right) phases of an annually rotated corn-soybean cropping system. All data represent the mean annual simulated value across 18 weather-years. GWP = global warming potential and AONR = agronomic optimum nitrogen fertilizer rate.

Global Warming Potential Calculations

Using the model simulation outputs, global warming potential was estimated as the sum of CO_2 equivalents (CO_2e) from the following processes: N_2O emissions from the soil surface, downstream N_2O emissions from NO_3^- leaching, and greenhouse gas emissions associated with the synthesis, delivery and application of N fertilizer (Table S2). Because N_2O has a long lifespan in the atmosphere, we used the 100-year warming potential where one kg of N_2O traps 298 times the heat of one kg of CO_2 (1 kg N_2O emission from the soil surface = 298 kg CO_2e[23]). To account for N_2O emissions that are produced from NO_3^- after it is leached from the field, we used the Intergovernmental Panel on Climate Change (IPCC) EF5 emission factor of 0.0075 kg N_2O-N kg^{-1} NO_3^-–N leached[23]. The synthesis, delivery and application of nitrogen fertilizers emits large amounts of greenhouse gases and we used a factor of 3.9 kg CO_2e kg^{-1} of N fertilizer input to account for these emissions [24]. However, we are aware of similar analyses that have used values as high as 4.5 kg CO_2e kg^{-1} of N fertilizer[25]. Our goal was to make a conservative estimate of GWP mitigation potential.

We also estimated the total amount of CO_2e that are emitted upon soil drainage from the oxidation of soil organic carbon (SOC). Changes in land use, such as drainage, lead to a new equilibrium SOC pool size. As a result, the GWP associated with SOC loss is finite whereas the GWP associated with N fertilizer use and losses accrue every year of crop growth. There are no reports of total SOC loss due to the drainage of mineral soils. However, a comprehensive meta-analysis of total SOC loss upon cultivation of soil (including tillage, drainage, changes in net primary productivity, etc.) indicates a mean loss of 27%[26]. Mineral soils in drained regions store ~100,000 kg C ha^{-1} to the depth of drainage[27]. Thus, we estimated a total loss of 27,000 kg C ha^{-1} or 100,000 kg CO_2e ha^{-1} (1 kg CO_2 = 0.27 kg C) with the installation of new drainage systems.

In contrast, to the installation of new drainage systems, the intensification of drainage systems is likely to create a much smaller loss of SOC. In this case, we arbitrarily selected what would be a relatively small SOC loss due to a change in management[26]: 2,727 kg C ha^{-1} or 10,000 kg CO_2e ha^{-1}. In most drained soils, this would be less than a 5% loss of SOC.

We excluded GHG emissions associated with potential effects of drainage on CH_4 emissions, surface albedo, and fuel use for farm operations because we are unaware of research to constrain the effect of drainage on these sources and sinks of greenhouse gases in mineral soils. Nevertheless, drainage would almost certainly mitigate GWP from all these sources because drainage is likely to cause or enhance soil CH_4 consumption[28], increase the albedo of bare soil[29], and reduce the energy required for field traffic due to lower rolling resistance. Thus, our estimates of reduction in GWP with drainage are conservative. We also excluded the effect of soil erosion on GWP because it is likely net neutral due to balancing effects[30].

Table S2. Cropping systems processes and properties included in the calculations of global warming potential for undrained and drained continuous corn cropping systems. The agronomic optimum N rate (AONR) and thus emissions from N fertilizer is fixed at the average annual AONR across 18 simulated weather years.

		Grain Yield at AONR*	AONR	NO_3^- leaching	Downstream N_2O	Soil Surface N_2O	N Fertilizer
		($Mg\ ha^{-1}\ y^{-1}$)	-----(kg N ha^{-1})-----		----------(kg CO_2e ha^{-1} y^{-1})----------		
Undrained	Mean	11.2	214	15.8	55.56	4669	834.6
	SD	1.02	--	16.1	56.43	1398	--
Drained	Mean	11.2	189	22.9	80.53	2748	737.1
	SD	1.03	--	18.6	65.40	832.8	--

*15% moisture; AONR is agronomic optimum nitrogen rate

Sensitivity Analysis

We conducted a sensitivity analysis to demonstrate how different combinations of drainage-induced N fertilizer reductions and SOC losses affect net GWP over the duration of 50-year and 100-year drainage design-lives. Most drainage systems have a design-life of 100 years[31]. For this analysis, we simulated (see above) continuous corn in drained and undrained systems at five different N fertilizer inputs and five different SOC losses. For N fertilizer inputs, we used optimum N rates in undrained and drained systems (214 & 189 kg N ha^{-1}) as a baseline and increased and decreased these rates by 15 and 30% (for example, a 30% decrease results in N rates of 150 and 132 kg N ha^{-1} in the undrained and drained systems; Table S3). Simulations were repeated for 18 years and results were averaged to calculate N-rate impacts on various processes. All other factors were kept the same in the model. To estimate sensitivity due to SOC loss, we used SOC losses of 5, 15, 27, 35 and 45% which can also be interpreted as 5, 15, 27, 35 and 45 Mg C ha^{-1} assuming a baseline SOC stock of 100 Mg C ha^{-1} (Table S4). We used 27% as the median loss estimate because this was the mean SOC loss in a comprehensive meta-analysis of the effect of land conversion to agriculture[26] while 5 and 45% represent the potential range we estimate that might be attributed to drainage across a wide range of scenarios (e.g., improved and new drainage systems). To estimate the net mitigation of GWP for each combination of N fertilizer reductions and SOC losses, we subtracted the GWP generated from SOC losses from the product of the drainage system design life (50 or 100 years) and the annually recurring GWP mitigation due to lower N inputs in the drained system (Table S4).

Table S3. Reductions in global warming potential (GWP) due to lower N fertilizer inputs with drainage. The baseline N fertilizer input is the output from model simulations (Table S1). The GWP at each N fertilizer rate is the sum of CO_2e from N fertilizer inputs, N_2O emissions and downstream NO_3^- leaching.

	Undrained		Drained		
% Change in N fertilizer from baseline	N Fertilizer Rate (kg N ha^{-1} y^{-1})	GWP (CO_2e $ha^{-1}y^{-1}$)	N Fertilizer Rate (kg N ha^{-1} y^{-1})	GWP (CO_2e ha^{-1} y^{-1})	Net Reduction in GWP (CO_2e ha^{-1} y^{-1})
-30%	150	3351	132	1970	1381
-15%	182	4498	161	2686	1812
Baseline	214	6031	189	3473	2559
+15%	246	7423	217	4176	3248
+30%	278	8612	246	5135	3477

Table S3. Net global warming potentials (GWP) due to drainage system reductions in N fertilizer rate (mitigation of GWP) and reductions in soil organic carbon (source of GWP) over 50- and 100-year drainage design-lives. Note that the GWP source due to soil organic C loss does not change with length of design-life because the SOC loss occurs in the first 10-15 years following drainage installation or intensification, but the GWP mitigation due to a reduction in N fertilizer input increases with length of design-life because it is annually recurring. A negative net reduction represents a net increase in GWP. Mitigation is highest at +30% N fertilizer rates because the absolute difference between optimum N fertilizer rates in drained and undrained systems increases with fixed proportional increases from the baseline.

Net Reduction in Global Warming Potential Over 100 Years (1000s CO2e)

N Fertilizer Rate	Soil Organic Carbon Loss (% reduction)				
	5	15	27	35	45
-30%	120	83	39	10	-27
-15%	163	126	82	53	16
Baseline	238	201	157	128	91
+15%	306	270	226	196	160
+30%	329	293	249	219	183

Net Reduction in Global Warming Potential Over 50 Years (1000s CO2e)

N Fertilizer Rate	Soil Organic Carbon Loss (% reduction)				
	5	15	27	35	45
-30%	51	14	-30	-59	-96
-15%	72	36	-8	-38	-74
Baseline	110	73	29	0	-37
+15%	144	107	63	34	-3
+30%	156	119	75	46	9

Historical changes in crop systems and drainage

In the Midwest U.S. Corn Belt, the total area of cropland has remained relatively constant over the last 100 years[32]. However, there was a major change in cropping systems from 1960-1980. During that time, soybeans (*Glycine max)* replaced alfalfa (*Medicago sativa*) and small grains such as oats (*Avena sativa*). Now, two crops dominate Midwest land use: maize (*Zea mays*) and soybean[33] (Figure S6).

More recently, there has been a northward expansion of the U.S. Corn Belt into South Dakota and North Dakota. Unlike other intensively drained states in the Corn Belt (e.g., Iowa, Illinois, Indiana and Ohio), South Dakota and North Dakota require permits for most installations of field drains (Box 1). However, these records are not easily accessible because they must be collected from various municipal organizations. Finocchiaro[34,35] assembled these records for different periods in each state. We determined the increase in the area planted to maize and soybean in these states from 2000-2011 using the USDA National Agriculture Statistics Service online database [36]. We selected this period to match the report of wetland loss in these states due to land conversion to agriculture[37]. During this time, maize area increased from 2.2 Mha to 3.0 Mha while soybean increased from 2.5 Mha to 3.3 Mha.

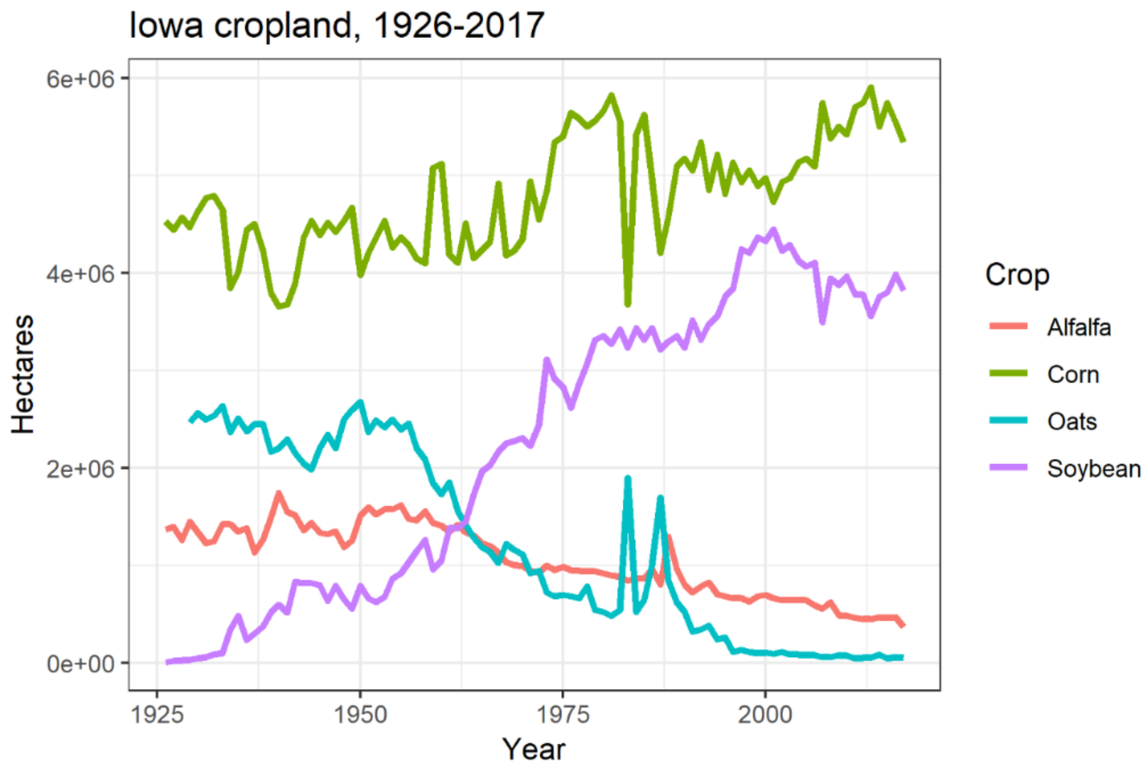

Figure S6. Historical cropping system change in Iowa USA as an example of general trends in the Midwest USA[36].

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