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Extreme weather-year sequences have nonadditive effects on environmental nitrogen losses

Javed Iqbal
Iowa State University, jiqbal@iastate.edu

Magdalena Necpalova
Universitätstrasse 2, Zürich

Sotirios Archontoulis
Iowa State University, sarchont@iastate.edu

Robert P. Anex
University of Wisconsin-Madison

Marie Bourguignon
Iowa State University

See next page for additional authors

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Abstract

The frequency and intensity of extreme weather years, characterized by abnormal precipitation and temperature, are increasing. In isolation, these years have disproportionately large effects on environmental N losses. However, multi-year sequences of extreme weather years (e.g., wet-dry vs. dry-wet) and annual crop rotation (legume-cereal vs. cereal-legume) may interact to affect cumulative N losses across the complete crop rotation sequence. We calibrated and validated the DAYCENT model with a comprehensive set of biogeophysical measurements from a maizesoybean rotation managed at three different N fertilizer inputs with and without a winter cereal rye cover crop in Iowa, USA. Our objectives were to determine: i) how two-year sequences of extreme weather years interact with annual crop rotation sequence to affect two-year cumulative N losses, and ii) if the inclusion of a winter cover crop between corn and soybean and N fertilizer management mitigate the effect of extreme weather on N losses. Using historical weather data (1951-2013), we created nine two-year weather scenarios with all possible combinations of the hottest and driest ('dry'), coolest and wettest ('wet'), and average ('normal') weather years. We analyzed the effects of these scenarios following a period of relatively normal weather. Compared to the normal-normal two-year weather scenario, two-year extreme weather scenarios affected two-year cumulative NO3- leaching (range: -28 to +295%) more than N2O emissions (range: -54 to +21%). Moreover, the two-year weather scenarios had non-additive effects on N losses: although dry weather decreased NO3- leaching in isolation, two-year cumulative NO3- losses from the dry-wet scenario were 89% greater than the normal-normal scenario. Cover crops reduced the effect of extreme weather on NO3- leaching, but not N2O emissions. As the frequency of extreme weather events is expected to increase, understanding of interactions between crop rotation and interannual weather patterns can be used to mitigate the effect of extreme weather on environmental N losses.

Keywords

Climate Change, Crop system, Crop phase, Extreme precipitation, Nitrous oxide, Nitrate

Disciplines

Agricultural Science | Agronomy and Crop Sciences | Climate | Environmental Sciences | Soil Science

Comments

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Authors

Javed Iqbal, Magdalena Necpalova, Sotirios Archontoulis, Robert P. Anex, Marie Bourguignon, Daryl Herzmann, David C. Mitchell, John E. Sawyer, Qing Zhu, and Michael J. Castellano

Extreme weather and crop rotation sequence interact to affect environmental nitrogen losses

Javed Iqbal[1], Magdalena Necpalova[3], Sotirios V. Archontoulis[1], Robert P. Anex[2], Marie Bourguignon[1], Daryl Herzmann[1], David C. Mitchell[1], John E. Sawyer[1], Qing Zhu[4], and Michael J Castellano[1]

Running head: Weather year sequence affects N loss

(1)Department of Agronomy, Iowa State University, Ames, IA 50010

(2) Department of Biological Systems Engineering, University of Wisconsin-Madison, Madison, WI 53706

(3) Department of Environmental Systems Science, Universitätstrasse 2, Zürich, Switzerland

(4) Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing, China

Corresponding author: Michael Castellano, castelmj@iastate.edu, 515-294-3963

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Abstract

The frequency and intensity of extreme weather years, characterized by abnormal precipitation and temperature, are increasing. In isolation, these years have disproportionately large effects on environmental N losses. However, multi-year sequences of extreme weather years (e.g., wet-dry vs. dry-wet) and annual crop rotation (legume-cereal vs. cereal-legume) may interact to affect cumulative N losses across the complete crop rotation sequence. We calibrated and validated the DAYCENT model with a comprehensive set of biogeophysical measurements from a maize-soybean rotation managed at three different N fertilizer inputs with and without a winter cereal rye cover crop in Iowa, USA. Our objectives were to determine: i) how two-year sequences of extreme weather years interact with annual crop rotation sequence to affect two-year cumulative N losses, and ii) if the inclusion of a winter cover crop between corn and soybean and N fertilizer management mitigate the effect of extreme weather on N losses. Using historical weather data (1951-2013), we created nine two-year weather scenarios with all possible combinations of the hottest and driest ('dry'), coolest and wettest ('wet'), and average ('normal') weather years. We analyzed the effects of these scenarios following a period of relatively normal weather. Compared to the normal-normal two-year weather scenario, two-year extreme weather scenarios affected two-year cumulative NO_3^- leaching (range: -28 to +295%) more than N_2O emissions (range: -54 to +21%). Moreover, the two-year weather scenarios had non-additive effects on N losses: although dry weather decreased NO_3^- leaching in isolation, two-year cumulative NO_3^- losses from the dry-wet scenario were 89% greater than the normal-normal scenario. Cover crops reduced the effect of extreme weather on NO_3^- leaching, but not N_2O emissions. As the frequency of extreme weather events is expected to increase, understanding of interactions between crop rotation and interannual weather patterns can be used to mitigate the effect of extreme weather on environmental N losses.

Introduction

In the U.S. Corn Belt, analyses of historical weather trends and climate model projections indicate increasing frequency of extreme weather years characterized by drought and precipitation surplus (IPCC 2013; Dai et al., 2015). From 1981 to 2015, annual precipitation in Iowa, USA exceeded the 95th percentile of the 1893-2015 record in twelve years (Anderson and Kyveryga, 2016). This global change increases the likelihood that two or more of what are now considered extreme weather years will occur in succession.

The annual sequence of extreme weather years may have non-additive effects on environmental N losses. In isolation, extreme weather years have disproportionately large effects on nitrogen (N) losses to air and water resources (Groffman et al., 2009; Wang et al., 2015). Nitrate leaching and nitrous oxide emissions often increase exponentially with precipitation (Puntel et al., 2016; Schwenke and Haigh et al., 2016; Zhao et al., 2016). However, the amount and pathway of N loss during years with precipitation surplus may differ if the preceding year was characterized by normal precipitation, surplus precipitation or drought.

In arable lands with crop rotations, the annual sequence of extreme weather years can interact with the annual sequence of crop rotation to affect cumulative N losses across the multi-year crop system (Iqbal et al. 2015). Differences in crop species and N fertilizer requirements can modulate the effect of extreme weather on environmental N losses (Bita and Gerats, 2013; Folberth et al., 2016). In cereal-legume crop rotations, which represent >75% of arable land in the United States corn belt (USDA-NASS 2014), surplus precipitation may have a greater effect on N losses if the surplus precipitation occurs in the N-fertilized cereal year (especially during the spring; Puntel et al., 2016) rather than the unfertilized legume year. Similarly, the effect of surplus precipitation on N losses may be greater following a drought year than an average precipitation year due to residual soil nitrate resulting from low crop uptake and harvest removal (Huang et al., 2015).

Process-based cropping system models that are calibrated and validated with empirical data provide an opportunity to understand and quantify how sequences of extreme weather years interact with multi-year crop rotations to impact cumulative measures of production and environmental quality across a full crop rotation (Abdalla et al., 2010; Deryng et al., 2011). Moreover, mechanistic models can be used to test climate change adaptation strategies, such as N fertilizer management and cover cropping during fallow. For such an analyses, the set-up of the simulation and the capacity of the model to capture complex multi-year dynamics in the soil-crop-atmosphere are important. Indeed, Basso et al. (2015) demonstrated that the set-up of the model (seasonal: same soil initial conditions every year but different climate vs sequential: different soil initial conditions every year depending on previous crop growth and different climate) affects the output and result interpretation.

However, the majority of model-based assessments of extreme weather year effects on environmental N dynamics and crop production have focused on seasonal analyses eliminating crop rotation and N carry-over effects from one year to another (Wang et al., 2015; Jin et al., 2016; Rosenzweig et al., 2016). Nevertheless, existing experimental data suggest the sequence of extreme weather years is important such that isolated seasonal estimates of N losses are not additive across years (Iqbal et al. 2015; Metre et al., 2016). Consistent with this concept, antecedent soil moisture is well known to effect soil N mineralization and nitrate leaching during intense precipitation events (Muhr et al., 2008; Goldberg and Gebauer, 2009; Castellano et al., 2013). In fact, elevated nitrate leaching following periods of dry weather is frequently observed (Creed and Band, 1998; van Verseveld et al., 2008).

We hypothesized that sequences of extreme weather years (e.g., drought-wet vs. normal-surplus) and crop rotation phase (corn vs. soybean) interact such that the effect of extreme weather on environmental N losses across a multi-year crop rotation depends on antecedent conditions. Further, we hypothesized that a cover crop grown between grain crops can mitigate the effect of extreme weather years on N losses. To test these hypotheses, we use a comprehensive cropping systems data set, 63 historical weather years, and the DAYCENT ecosystem model (Parton et al., 1998, 2001; Del Grosso et al., 2001) for an Iowa, USA maize-soybean rotation. We first calibrated and then validated the model following a sequential approach that accounts for inter-annual carry-over effects using comprehensive crop and soil measurements that covered all crops in rotation across multiple years (2 crop rotations x 3 N fertilizer treatments x 2 cover crop treatments x 5 soil variables x 3 years). Then, based on historical weather records, we created two-year weather sequences (scenarios) with nine combinations of drought, normal, and surplus precipitation years. We used the model with these two-year scenarios to identify patterns and trade-offs between productivity and environmental performance across the full crop rotation.

Materials and Methods

The research site was located at Iowa State University Agricultural Engineering and Agronomy Research Farm in Boone County, IA (42.02 N, 93.77W). Long-term average annual precipitation and temperature are 872 mm and 9.4°C. The soil is Clarion-Nicollet-Webster series (fine-loamy, mixed, superactive, mesic Typic Hapludolls) with a pH of 6.4, and total organic carbon and total N of 2.4% and 0.2% (0-15 cm). The experiment was established in 2008 to study the effect of winter cereal rye cover crop on the optimum N fertilizer input to corn following soybean in a no-till cropping system (Pantoja et al., 2015). The experimental design was a split-plot in four replications. Main factor was the rye cover crop and sub-factor six N fertilizer rates. However, only three N rates (0, 135, and 225 kg N ha^{-1}; onwards N0, N135, and N225, respectively) were selected in this study. Each year, corn was planted on half of the site, while soybean was planted on the other half, thus both crops were present each year. Nitrogen fertilizer was applied only to corn. Rye cover crop was planted every fall (drilled at 70 kg seed ha^{-1}) and terminated with glyphosate ((N-) phosphonomethyl) glycine) at 1-2 kg active ingredient ha^{-1} every spring between 0 – 20 d before planting of main crop. Nitrogen fertilization to corn was side-dressed at 9-26 days after corn planting, depending on soil conductions, and injected as urea ammonium nitrate solution (32% N) in bands to 0-15cm soil depth in every other inter-row. No N fertilizer was applied in soybean. Phosphorus (triple superphosphate, 0-46-0) and potassium (potash 0-0-

60) fertilizer were applied at recommended rates of 56 kg P ha^{-1} and 140 kg K ha^{-1} every 2 year. From 2011-2013, we measured soil nitrate, N2O emissions and crop production in the following cropping systems (all system present every year): CRS = corn-soybean with rye cover crop, CS = corn-soybean without rye cover crop, SRC = soybean-corn with rye cover crop, SC = soybean-corn without rye cover crop. Further management details can be found in Iqbal et al. (2015) and Pantoja et al. (2015).

Weather measurements

Daily precipitation and air temperature data were recorded on site from 1951 to present (Iowa Environmental Mesonet). The cumulative annual precipitation during the study years of 2011, 2012, and 2013 were 816, 637, and 852 mm, respectively (Fig. 1), and the intra-annual pattern of precipitation was variable across years (Fig. S1). The average air temperature during 2011, 2012, and 2013 were 10.1, 12.0, and 8.7ºC, respectively (Fig. 1).

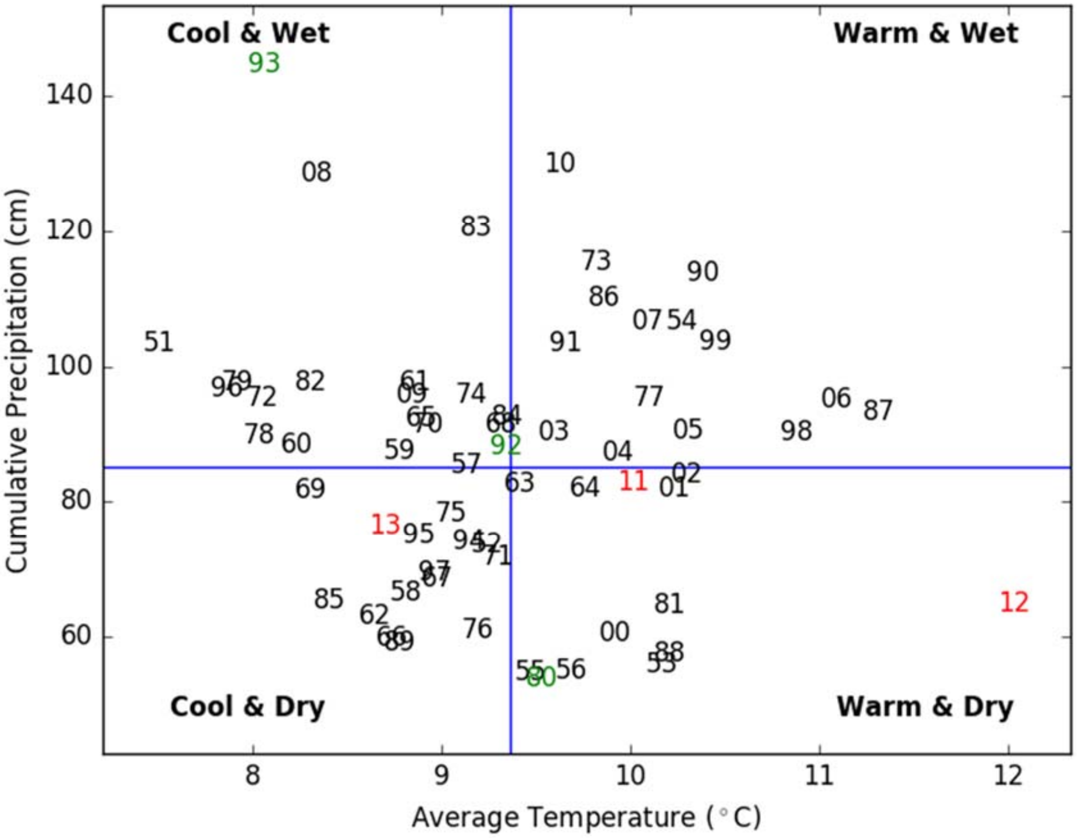

Fig. 1. Annual cumulative precipitation and annual average temperature from 1951-2013 at the study site location. Experimental years are displayed in red (2011-2013) and transposed extreme weather years are displayed in green (1980, 1992, 1993). Vertical and horizontal lines represent the annual average temperature and annual average cumulative precipitation from 1951-2013.

Gas measurements

Nitrous oxide and CO_2-C emissions from soil were measured approximately fortnightly between 08:00 to 14:00h from planting to harvest of the corn and soybean crop areas. More frequent measurements were performed following N fertilizer application and rainfall events. Gas sampling was performed in polyvinyl chloride and aluminum rectangular static chambers installed over the area covering the fertilizer band and the inter row space which did not receive N fertilizer in corn. In soybean and corn plots not receiving N fertilizer, chambers were installed in positions equivalent to fertilized corn. Inside the chambers, changes in N_2O-N and CO_2-C gas concentrations over time were measured in-situ with a 1412 Photoacoustic Infrared Gas Analyzer (Innova Air Tech Instruments) or by gas chromatography. These two techniques provide statistically identical results (Ambus and Robertson, 1998; Iqbal., 2013; Tirol-Padre et al. 2013). Changes in gas concentration over time was best fit with linear regression. Detailed description of gas sampling and measurements can be found in Mitchell et al. (2013) and Iqbal et al. (2015).

Soil temperature, moisture and NO_3^--N measurements

At each gas sampling event, soil temperature and moisture were measured at 0-5 cm depth with a digital soil thermometer (AcuRite:±0.05) and a TH300 theta probe (Dynamax Inc.:±3% volumetric water content), respectively. Soil was sampled at each gas sampling point with a 2 cm diameter probe at 0-10cm depth nearby each chamber in a fertilizer band and an equivalent position in non-fertilized plots. Soil sampling in fertilizer bands was chosen because previous research has shown that fertilizer bands are the main source of N_2O-N emissions (Mitchell et al., 2013). Soil samples were analyzed for NO_3-N following Hood-Nowotny et al. (2010).

Crop measurements

Corn and soybean grain yields at harvest were recorded using combine harvesters. Rye above ground biomass and tissue N concentration were recorded at termination day (area = 0.54 m^2). The rye biomass was dried at 60°C, weighed, ground and analyzed for total C and N using elemental analyzer (LECO CHN-2000 analyzer, LECO Corp.). Rye N uptake was calculated by multiplying N concentration and dry matter yield. Data (either grain or biomass) are presented as kg C ha^{-1} at 0% moisture content.

DAYCENT model overview

DAYCENT is a daily time step ecosystem model capable of simulating soil C and N cycling and emissions, water balance, and plant growth of crops in rotation across multiple years (Parton et al., 1998, 2001; Del Grosso et al., 2001, 2002, 2005, 2008). Plant growth in the model is driven by temperature and the rate of increase is regulated by soil moisture, temperature and nitrogen stresses, as well as crop-specific parameters (Del Grosso et al., 2009). Soil C and N pools are regulated through various processes in key sub-models (Parton et al., 1994, 1998, 2001). Daily denitrification rates are calculated for each soil layer based on soil NO_3^- concentration distributed throughout the soil profile, heterotrophic respiration, soil water content, texture, and temperature; while nitrification rates are calculated based on soil NH_4^+ concentration, water content, texture, and temperature in the top 15 cm (Del Grosso et al., 2001, 2008). Water flow is simulated with the tipping-bucket approach and applies Richards' equation for water re-distribution after the drainage from saturation to field capacity. The proportion of NO_3^- subjected to downward transport with water flow is a function of sand content. Inputs to the model are agronomic management, weather variables including daily precipitation, minimum and maximum temperature, and soil profile parameters (see table S1). Model outputs include crop dry matter and partitioning to different plant tissues, N uptake dynamics, soil moisture, soil temperature, soil C and N mineralization, NO_3^- leaching, and nitrification and denitrification gas emissions. The reliability of the DAYCENT model to simulate the impact of a range of cropping systems and agronomic management practices on crop production and environmental C and N emissions has been well documented in the literature (Del Grosso et al., 2001, 2005, 2008, 2009; Parton et al., 2001; Stehfest et al., 2007).

Model set-up, calibration and validation

In this study we used DAYCENT version 4.5 to simulate net primary productivity (NPP), crop yields, soil organic carbon (SOC), soil temperature, moisture, soil NO_3^--N, NO_3^- leaching, and soil CO_2-C and N_2O-N emissions. The SOC conceptual pools were brought to an equilibrium linearly proportional to C inputs using a "spin-up" simulation of native prairie (C_3 warm and cold species mix, and symbiotic nitrogen fixing plants) and naturally occurring disturbances from year 0 to 1799. This proceeded with a "base" simulation of historical land use cover with less intensive (i.e. six year corn-wheat-fallow, two year corn and soybean rotations with low fertilizer input) followed by more intensive (i.e. two year corn-soybean or soybean-corn rotations with high yielding varieties and higher fertilizer application) site specific crop management until the year 2009 (Necpalova et al., 2015). The simulations in 2010 to 2013 were driven by 2010-2013 recorded agronomic management events such as rye cover crop planting and termination, herbicide and fertilizer inputs, and corn and soybean planting and harvesting dates as described in our recent paper (Iqbal et al., 2015).

All model runs were driven by repeated 1951-2013 weather data (i.e. daily precipitation, low and high temperature) downloaded from the Iowa Environmental Mesonet (https://mesonet.agron.iastate.edu/) weather data observing network. The simulations were driven by 13 soil layers (0-180cm) containing site specific soil profile variables, including soil texture, soil pH, soil bulk density and soil organic matter (SOM) measured at a depth of 0-10, 10-20, 20-40, and 40-60cm. The saturated hydraulic conductivity, wilting point, and field capacity for each layer were calculated on the basis of soil texture and soil organic matter content using pedotransfer functions (Saxton and Rawls, 2006) embodied in the Soil Water Characteristics Calculator software (SWCC), version 6.02.74 (USDA Agricultural Research Service, Washington).

We used six datasets (two crop rotations and three N fertilizer treatments) with cover crop to calibrate the model and the other six datasets (two crop rotations and three N fertilizer treatments) without cover crop to test the calibrated model's performance. Each dataset contained information on soil CO_2-C, N_2O-N, NO_3^--N, water, temperature, SOC, and crop yield for 3 years (2011-2013) each, which allowed us to test different aspects of the system. We sequentially calibrated to improve the model capacity in simulated soil water, plant and soil carbon, inorganic nitrogen, temperature, and N_2O-N and CO_2-C emissions by altering 11 parameters (see table S2). Model performance was evaluated with the coefficient of determination (R^2), root mean square error (RMSE) (see equations in Archontoulis and Miguez, 2015) and visual inspection of model error.

Model application and scenarios analysis

We used two metrics to investigate the impact of crop sequence and climate scenarios on N_2O-N emissions and NO_3^- leaching across the complete 2-year crop rotation. In the first, we used simulated values of N_2O-N emissions and NO_3^- leaching for 2011-2013 years to estimate yield-scaled N_2O-N emissions and yield-scaled NO_3^- leaching in corn and soybean crops by dividing simulated N_2O-N emissions and NO_3^- leaching by measured corn and soybean yields. In the second, we created weather files with nine different combinations of extreme site specific weather years and then ran the model for these weather scenarios to investigate the impact on N loss (N_2O-N emissions and NO_3^- leaching). We explored 63 years (1951-2013) of historical weather data and selected three extreme years (Fig. 1): (1) hottest and driest ('Dry') year of 1980, (2) average ('normal') year of 1992, and (3) coolest and wettest ('Wet') year of 1993. Precipitation and air temperature data from these three extreme years were placed into years 2006-2007 (corn 2006-soybean 2007) using the following nine combinations: (1) Dry-Dry, (2) Dry-Normal, (3) Dry-Wet, (4) Normal-Dry, (5) Normal-Normal, (6) Normal-Wet, (7) Wet-Dry, (8) Wet-Normal, and (9) and Wet-Wet years. To avoid any bias of preceding year N fertilizer carry over into transposed year, we placed extreme precipitation weather data into crop rotation years following several years of near-average precipitation. In this case, the years 2001, 2002, 2003, 2004, and 2005 had about normal precipitation (80.7, 82.9, 89.0, 86.1, and 89.4 cm respectively) which allowed us to transpose combinations of 1980 (dry), 1992 (normal) and 1993 (wet) weather into 2006-2007 (corn 2006-soybean 2007). In this way, 54 weather input files were developed using the above nine weather scenarios (9 scenarios × 3 N fertilizer rates × 2 cover crop levels).

Statistical Analysis

Yield-scaled N_2O-N emissions and yield-scaled NO_3^- leaching were log transformed to meet the normal distribution assumption before analysis using SAS 9.4 (SAS Institute Inc.). Differences in yield-scaled N_2O-N emissions and yield-scaled NO_3^- leaching across years, fertilizer rates, cover crop treatment and their interactions were analyzed through PROC MIXED ANOVA. Significant differences between cover crop and N fertilizer treatments were identified using pdiff option at $P \leq 0.05$.

Results

Model performance in simulating soil-crop parameters

Overall the model captured the measured temporal dynamics in soil nitrate, CO_2-C, N_2O-N emissions, water and temperature, across years and crop sequences during both calibration and validation phases. For example, figure 2 illustrates model simulations over time for one of the 12 crop and fertilizer datasets used in this study (Figs S2- S6). In terms of accuracy across all available datasets used for calibration and validation, the model simulated CO_2-C emissions with RMSE of 18.6 and 14.5 kg ha^{-1} d^{-1} respectively (Fig. 2 and Fig. S2). Simulated soil temperature was well correlated with observed soil temperature during calibration and validation with RMSE of 2.92°C and 3.18°C, respectively (Fig. 2 and Fig. S3). Simulated and observed soil moisture were also well correlated during calibration and validation with RMSE of 6.77% and 6.41%, respectively (Fig. 2 and Fig. S4). The model underestimated soil NO_3^--N in N-fertilized corn treatments in all three years and the simulated error, RMSE values, were high during calibration (85.7 mg kg^{-1} soil) and validation (81.7 mg kg^{-1} soil) (Fig. 2 and Fig. S5). This error is associated with the banded rather than broadcast application of N fertilizer (see discussion). In contrast to corn phases, simulated and observed soil NO_3^--N were similar in the soybean phase (no fertilization application) of the rotation in all years (Fig. 2 and Fig. S5). The model captured the magnitude of N_2O-N emission over time across calibration and validation datasets (RMSE of 23.5 and 26.0 g ha^{-1} d^{-1}, respectively) but missed some high fluxes in a few datasets (Fig. 3). In the N135 treatment, the model underestimated N_2O-N emissions in the 2011 and 2013 corn phase of the rotation in corn-soybean rotation with cover crop (CRS) and the 2013 corn phase of the rotation in corn-soybean rotation without cover crop (CS) (Fig. 3).

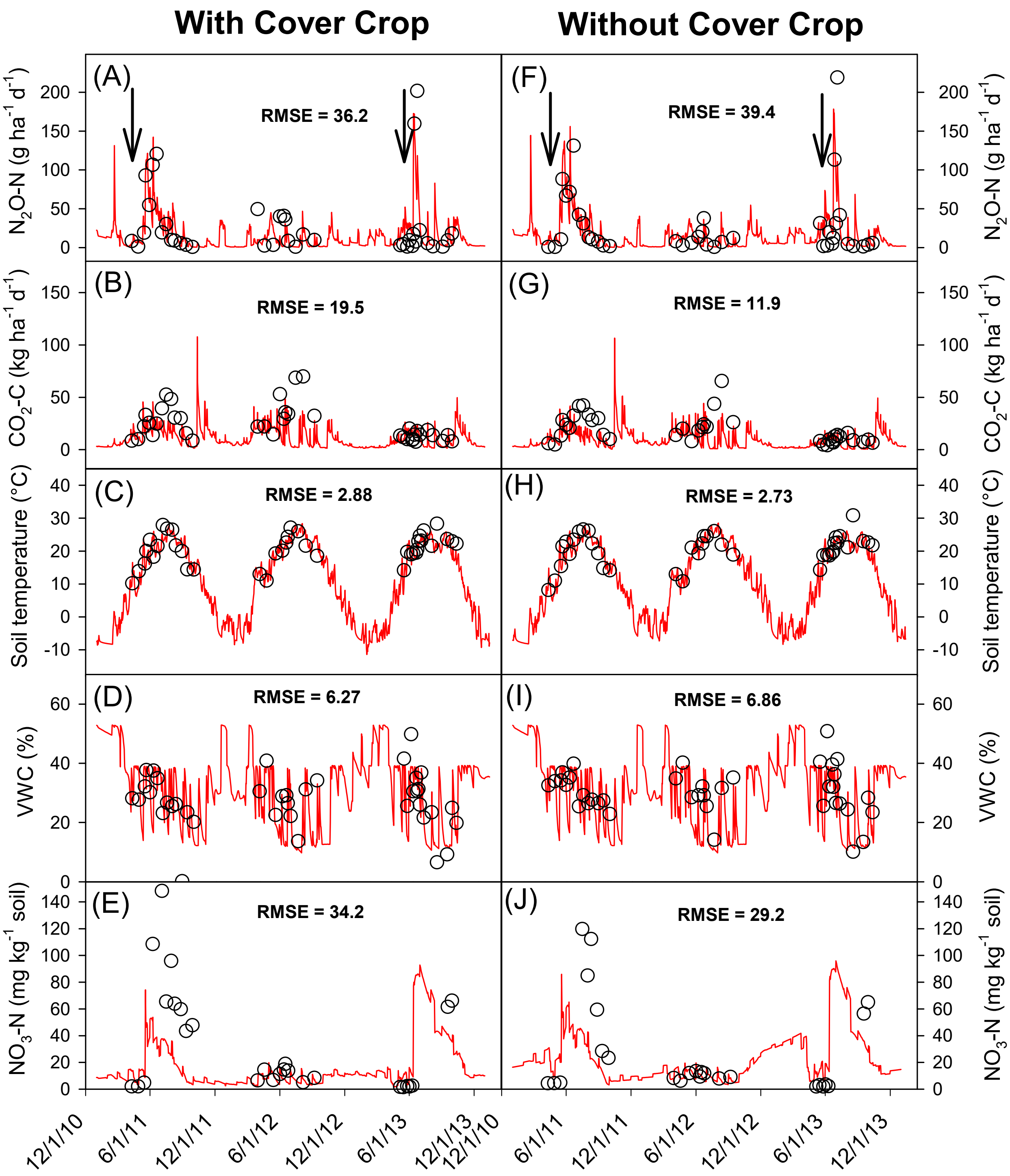

Fig. 2. An overview of experimental variables measured (open circles) and simulated (red lines) during 2011 to 2013: The model ran sequentially and the crop sequence was: corn-rye-soy (left, calibration) and corn-soy (right, validation). Arrows in A and F indicate the date of N fertilizer application to corn. RMSE is the root mean square error and has the same unit as the variable shown.

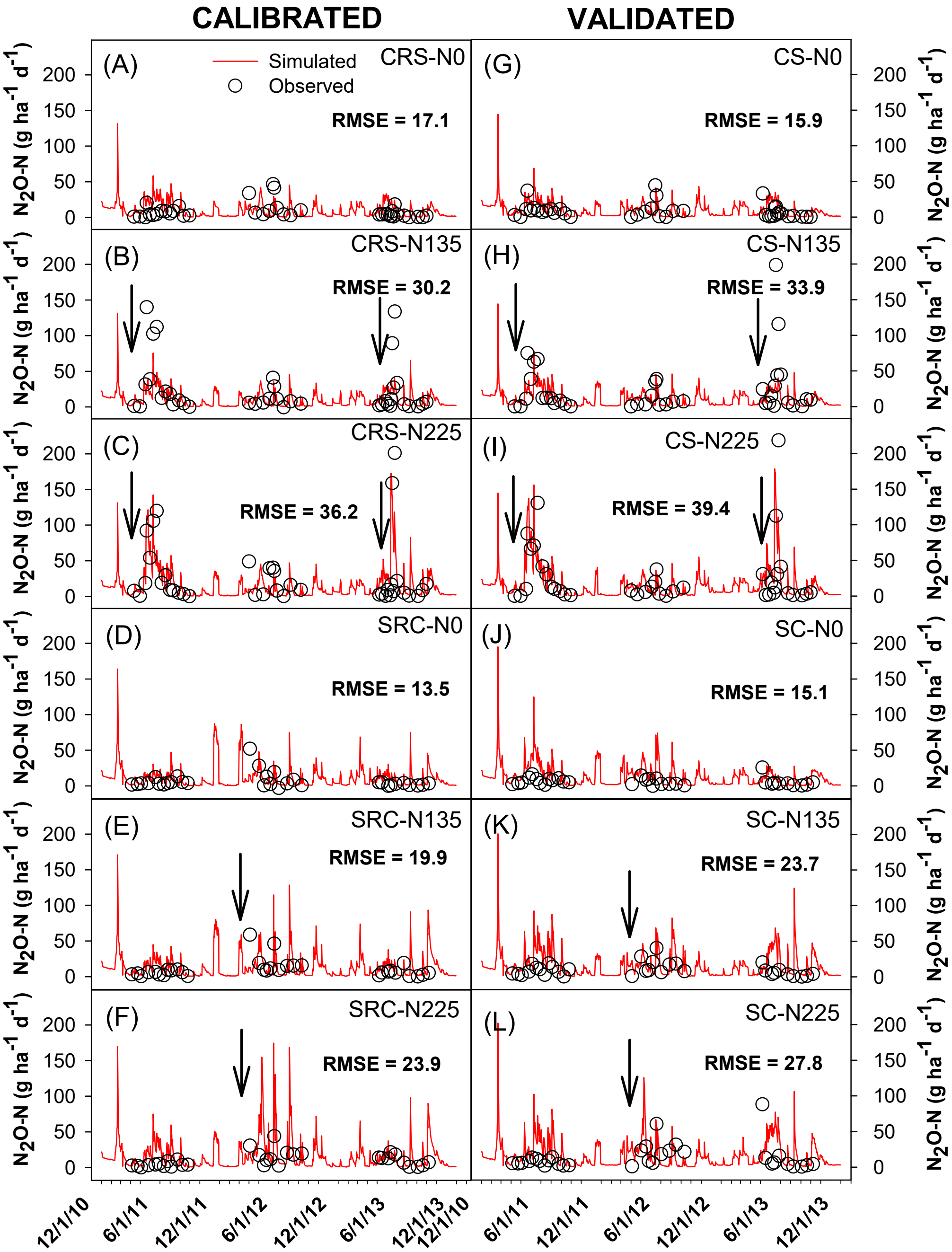

Fig. 3. Measured (open circles) and simulated (red lines) soil N_2O-N emissions during calibration (A,B,C,D,E,F) and validation (G,H,I,J,K,L) at 0 (N0), 135 (N135) and 225 (N225) kg fertilizer N ha^{-1}. CRS = Corn-Soybean with rye cover crop, CS = Corn-Soybean without rye cover crop, SRC = Soybean-Corn with rye cover crop, SC = Soybean-Corn without rye cover crop. RMSE is the root mean square error and has the same unit as the variable shown. Arrows indicate the date of N fertilizer application to corn.

In contrast to multiple soil measurements per year, only end-of-season net primary productivity data (crop yields and cover crop biomass) were available to evaluate simulated productivity. Overall DAYCENT simulations were in good agreement with observations for the calibration datasets (see values near 1:1 line; RMSE of 44 g C m^{-2}; Fig. 4). However, the model's ability to simulate the measured variability in crop yield decreased during validation (RMSE increased to 96 g C m^{-2}).

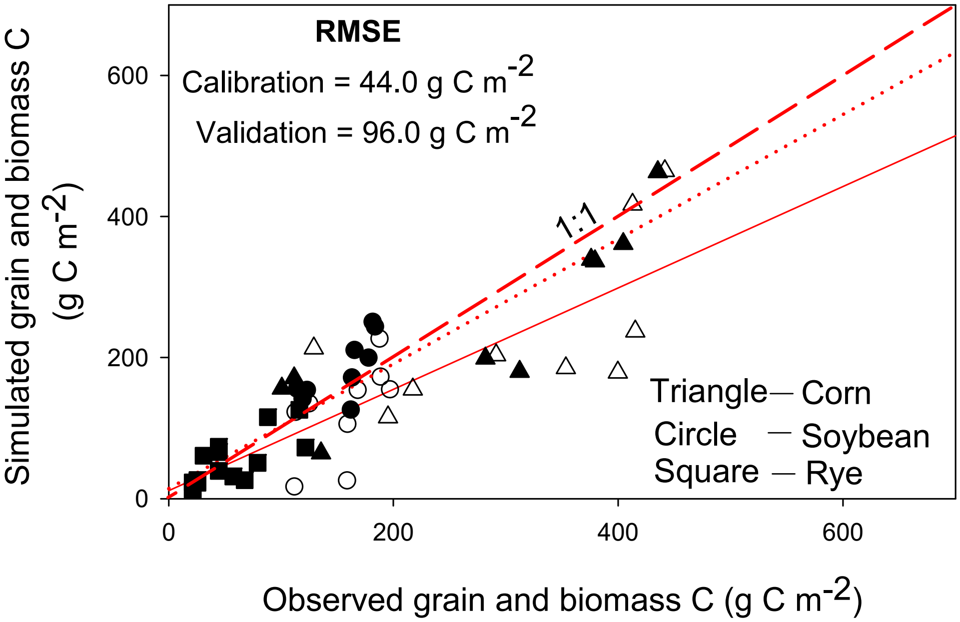

Fig. 4. Measured and simulated grain carbon at harvest and aboveground rye cover crop carbon at termination during calibration (closed symbols, n=34) and validation (open symbols, n=18). Dotted line is regression line for calibration (y=0.88+14.16x), solid line is regression line for validation (y=0.72+44.43x), and segmented line is 1:1 line.

Yield-Scaled N losses

The cover crop did not consistently reduce yield-scaled N_2O emissions from soybean (Table 1, Fig. 5). Moreover, there was no effect of N fertilizer rate to the previous corn crop on yield-scaled N_2O emissions from the following soybean crop. Similarly, in the corn phase of the rotation, the cover crop had no effect on yield-scaled N_2O emissions. However, N fertilizer rate had a large effect on yield-scaled N_2O-N emissions from corn. These yield-scaled emissions were lowest at the recommended N fertilizer rate (N135); yield-scaled N_2O emissions with zero (N0) and excessive N fertilizer (N225) rates were 114 and 37% higher.

Table 1: Analysis of variance of yield-scaled N_2O-N (kg Mg^{-1} grain C) and yield-scaled NO_3^--N leaching (kg Mg^{-1} grain C) in corn and soybean crops with N fertilizer and cover crop (CC) treatments during 2011-2013.

Source	**Corn**		**Soybean**	
	N_2O-N	**Leached NO_3^--N**	**N_2O-N**	**Leached NO_3^--N**
Year	0.25	<0.01	<0.01	<0.01
N rate	<0.01	<0.01	0.17	<0.01
Year x N rate	0.01	<0.01	<0.01	<0.01
CC	0.15	0.05	0.10	0.01
Year x CC	0.02	<0.01	0.06	<0.01
N rate x CC	0.30	0.32	0.31	0.44
Year x N rate x CC	<0.01	<0.01	<0.01	<0.01

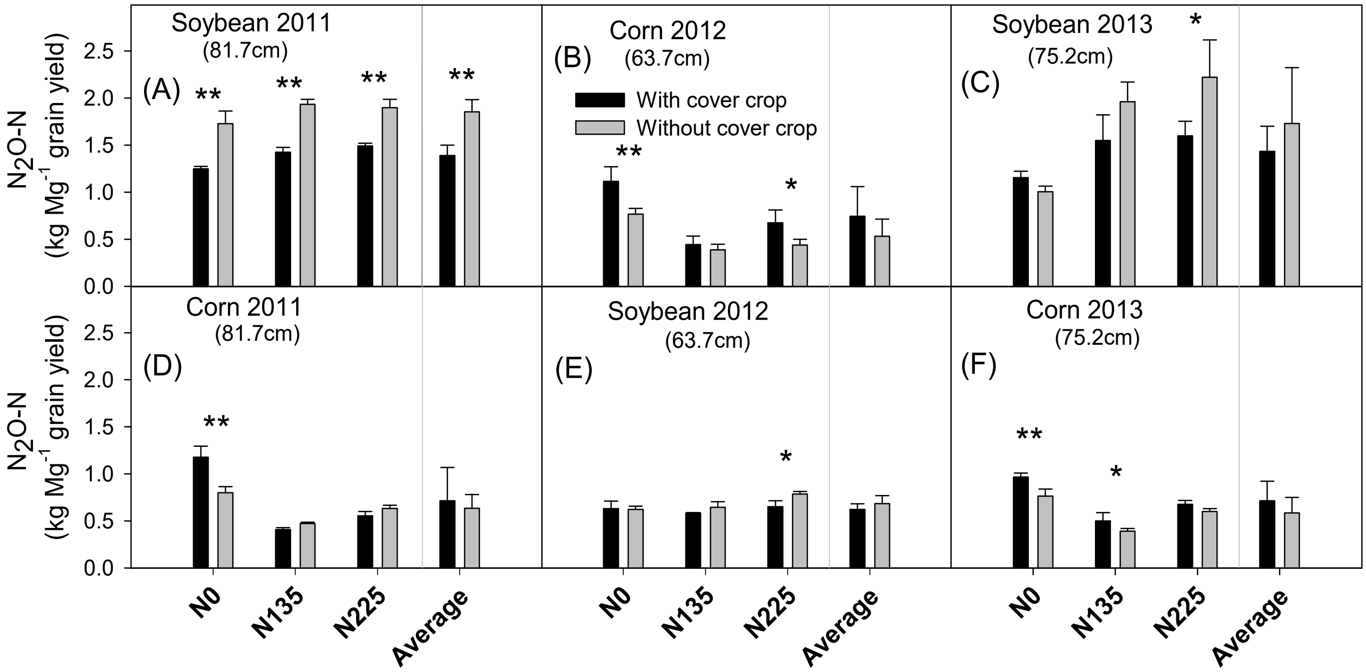

Fig. 5. Predicted yield-scaled N_2O-N emissions from Soybean-Corn (A,B,C) and Corn-Soybean (D,E,F) rotations with rye cover crop (black bars) and without rye cover crop (grey bars) at 0 (N0), 135 (N135) and 225 (N225) kg fertilizer N ha^{-1}. Yield data are measured and N_2O-N is predicted from the model. Annual cumulative precipitation is shown in each panel. Asterisks represent a significant mean comparison between with cover crop and without cover crop ($*P \leq 0.05$, $**P \leq 0.01$).

In contrast to yield-scaled N_2O, cover crops significantly reduced yield-scaled NO_3^- leaching in corn and soybean (Table 1, Fig. 6). Across all treatments and years, cover crop reduced yield-scaled NO_3^- leaching by 190% in corn and by 246% in soybean. Nitrogen fertilizer rate to corn had a significant effect on yield-scaled NO_3^- leaching in both phases of the crop rotation. In the corn phase, yield-scaled NO_3^- leaching was lowest at the recommended N fertilizer rate (N135). However, in the soybean phase, yield-scaled NO_3^- leaching was lowest at zero N fertilizer and increased with N fertilizer rate to the previous corn crop.

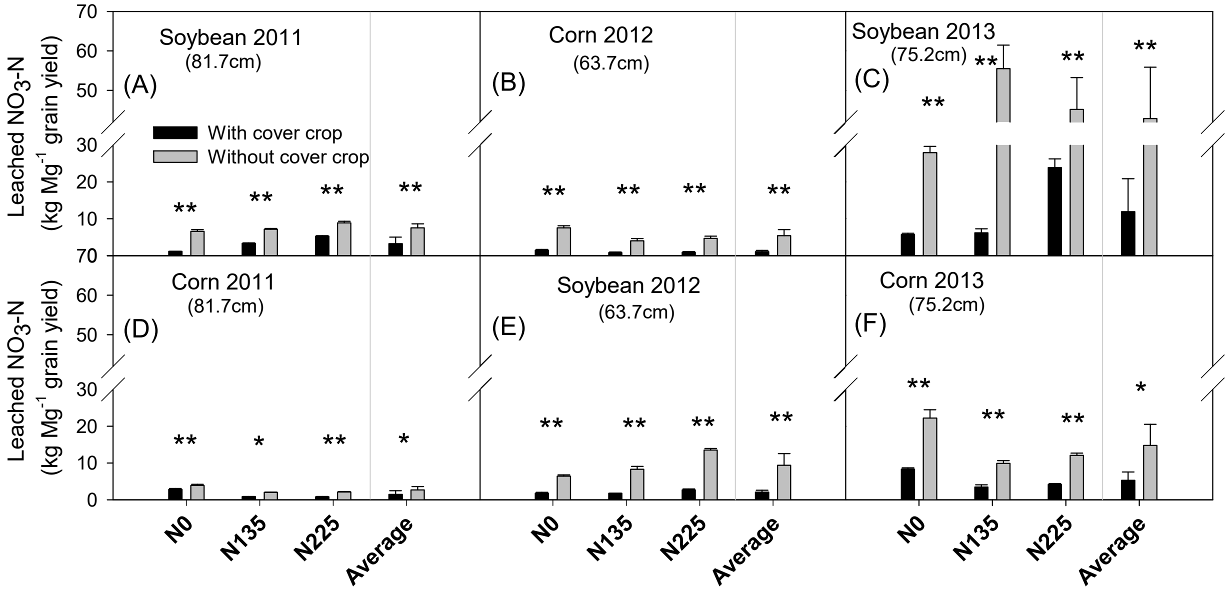

Fig. 6. Predicted yield-scaled NO_3^--N leaching from Soybean-Corn (A,B,C) and Corn-Soybean (D,E,F) rotations with rye cover crop (black bars) and without rye cover crop (grey bars) at 0 (N0), 135 (N135) and 225 (N225) kg fertilizer N ha^{-1}. Yield data are measured and NO_3^--N leaching is predicted from the model. Annual cumulative precipitation is shown in each panel. Asterisks represent a significant mean comparison between with cover crop and without cover crop ($*P \leq 0.05$, $**P \leq 0.01$).

The magnitude of yield-scaled NO_3^- leaching was comparable across all years except 2013 soybean following the 2012 drought. In this year, NO_3^- leaching from soybean was approximately 500% greater than NO_3^- leaching from soybeans in 2011 and 2012.

Model scenario analyses – Extreme weather and crop sequence

We present results regarding the effect of two-year extreme weather scenarios on two-year cumulative N_2O emissions and NO_3^- leaching from the corn-soybean sequence with and without cover crops at the recommended N fertilizer rate (Fig. 7). Analyses of extreme weather scenarios on N losses at zero and excessive N fertilizer inputs are reported in supplementary materials (Fig. S11).

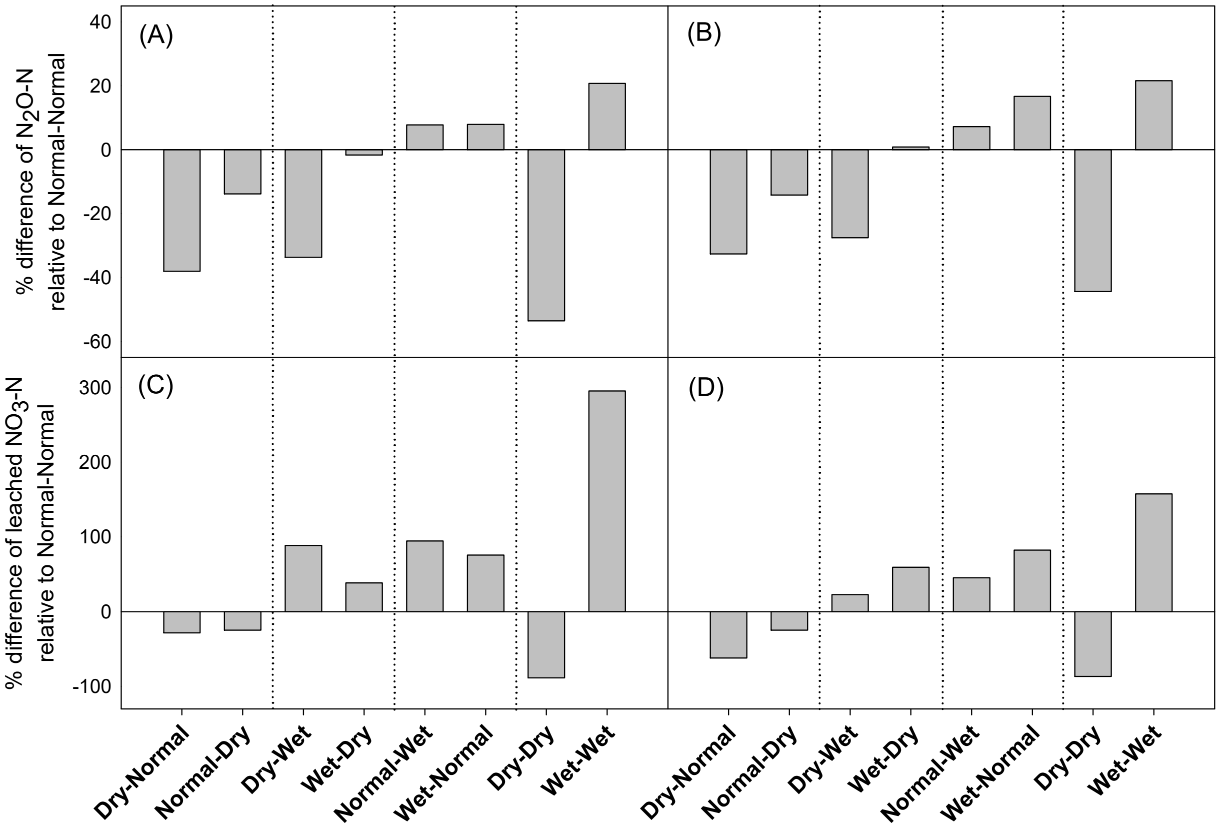

Fig. 7. The effect of extreme weather year sequence on predicted two-year cumulative N_2O emissions and NO_3^- leaching from the Corn-Soybean rotation without cover crop (A and C) and with cover crop (B and D) at the recommended nitrogen fertilizer input (135 kg N ha^{-1} to corn only) for nine two-year weather scenario combinations of dry, normal and wet years (see Figure 1). The predicted two-year cumulative soil N_2O-N emissions and NO_3^--N leaching in Normal-Normal scenario for panel A (1.35 g m^{-2}), B (1.18 g m^{-2}), C (6.62 g m^{-2}), and D (5.72 g m^{-2}) were used as control to benchmark % change (y axis) in the other eight scenarios in each panel. The dotted vertical lines separates scenarios for pairwise comparisons. Results from 0 and 225 kg N ha^{-1} fertilizer inputs are in supplementary materials (Figure 11S).

Relative to the normal-normal weather scenario without a cover crop, the two-year extreme weather scenarios without a cover crop changed two-year cumulative N_2O emissions from -54 to +21%. Drought interacted with crop phase to affect N_2O emissions. Drought in the corn phase of the rotation resulted in a much greater reduction in two-year cumulative N_2O emissions than drought in the soybean phase of the rotation. With the exception of the dry-dry two-year weather scenario, two-year cumulative N_2O emissions were reduced by 34-38% when drought occurred in the corn phase, but only 2-14% when drought occurred in the soybean phase. In contrast to the interaction between drought and crop rotation phase, the effect of a wet weather year on two-year cumulative N_2O emissions was similar in the corn and soybean crop phases; corn-wet/soybean-normal and corn-normal/soybean-wet scenarios both increased N_2O emissions by 8%.

In the normal-normal weather scenario, the cover crop reduced two-year cumulative N_2O emissions by 13% (Fig. 7). However, cover crops did not mitigate the impact of extreme weather on N_2O emissions. Without a cover crop, two-year cumulative N_2O emissions in the extreme weather scenarios differed from the normal-normal scenario by -54 to +21%; with a cover crop two-year cumulative N_2O emissions in the extreme weather scenarios differed from the normal-normal scenario by -44 to +22% (Fig. 7).

Relative to the normal-normal weather scenario without a cover crop, the two-year extreme weather scenarios without a cover crop changed two-year cumulative NO_3^- leaching from -28 to +295%. All extreme weather scenarios including a wet year increased two-year cumulative NO_3^- leaching with increases ranging from 28% in the corn-wet/soybean-dry scenario to 295% in the corn-wet/soybean-wet scenario. Dry weather in the corn phase of the rotation reduced two-year cumulative NO_3^- leaching when it was followed by a dry soybean year (-88%) or a normal soybean year (-28%). However, when dry weather in the corn phase was followed by wet weather year in the soybean phase, two-year cumulative N_2O-N emissions increased by 88%.

The cover crop mitigated the effect of extreme weather scenarios on NO_3^- leaching. The two-year extreme weather scenarios without a cover crop changed two-year cumulative NO_3^- leaching by -28 to +295%, however, the two-year extreme weather scenarios with a cover crop changed two-year cumulative NO_3^- leaching by just -87 to +157% (Fig. 7). Without a cover crop, the dry-corn/wet-soybean weather scenario increased NO_3^- leaching from the normal-corn/normal-soybean baseline by 88%, however, with a cover crop this weather scenario increased NO_3^- leaching from the normal-corn/normal-soybean rotation with a cover crop by only 23%. Although the wet-corn/wet-soybean weather scenario increased NO_3^- leaching with and without a cover crop, inclusion of the cover crop reduced this increase by ~50%.

Discussion

The interaction between crop and weather-year sequences could have important effects on watershed-scale nitrogen trading programs and regional estimates of annual reactive N losses, particularly as economic conditions impact the ratio of corn:soybean area in the US Corn Belt. We used a combination of experimental data and ecosystem process modeling to reveal that: i) the effect of extreme weather years on reactive N losses is modulated by the specific crop in rotation as well as the weather in the previous or subsequent years, ii) drought can increase cumulative reactive N losses across multi-year cropping systems when followed by years of precipitation surplus, and iii) cover crops can mitigate the effect of extreme weather on NO_3^- leaching, but not N_2O-N emissions (Figs 5-7).

Modeling N losses

The fact that the model simultaneously simulated well the temporal dynamics in N_2O and CO_2-C along with soil nitrate (e.g. Fig. 2) and crop yields across multiple years indicates that DAYCENT has the capacity to assist environmental N assessments in the US Corn Belt. Our modeling approach which included carry-over effects from previous year/crop increased the complexity of the simulation process, but we were able to reveal the emergent consequences of extreme weather years on N losses (Fig. 7). To our knowledge the majority of climate extreme impact studies used different weather files (either historical or future) but the same initial conditions of soil water, nitrogen and residue amount and quality to perform assessments. In this study we showed (Fig 2-3 and Figs S2-S6) that initial soil conditions are extremely variable from year to year, which can substantially affect the simulation results. These results are consistent with Basso et al. (2016), which demonstrated a substantial yield difference between simulations by continuous and annually re-initialized pre-season soil conditions.

Compared to literature studies, the RMSE values were comparable with other modeling studies of the same processes (Shen et al., 1998; Garrison et al., 1999; Li et al., 2005). However, a major challenge faced in this study was the simulation of soil NO_3^- after N fertilizer application. The model captured soil NO_3^- temporal dynamics well in the soybean phase, but underestimated soil NO_3^- in the corn phase after N fertilizer application. This underestimate likely resulted from the inability of DAYCENT and simulation biogeochemical ecosystem models in general to capture 'banded' N fertilizer which is applied and concentrated in a small area rather than uniformly distributed across the soil volume (Del Grosso et al., 2008; Fang et al., 2015). This is a critical challenge for ecosystem models because most N fertilizer in North American cereal crops is banded and the placement of N fertilizer is known to affect N_2O emissions (Venterea et al. 2005).

Underestimates of soil NO_3^- in the corn phase had led to the underestimation of some N_2O emissions from corn in 2011 and 2013 (Fig. 3). The N fertilizer bands may have produced high N_2O emissions that the model did not capture (Fig. 3; Venterea et al., 2012). Nevertheless, despite some underestimations of N_2O emissions during the time of N application in corn our results in general are similar to previous reports (Parton et al., 2005, Ahmed et al., 2007; Del Grosso et al., 2008; Thorp et al., 2008; Abdalla et al., 2010; Liu et al., 2011) and accurate N_2O emission estimation during most periods over the three years and two crop rotations confirmed that the model has a satisfactory ability to predict N emissions in these systems.

Yield-scaled N_2O-N emissions and NO_3 leaching:

Our consideration of the two-year crop rotation revealed that N fertilizer rate to corn did not affect yield-scaled N_2O losses and increased yield-scaled NO_3^- leaching from the following soybean crop. In contrast to this result from a non-fertilized legume crop, there is growing consensus that the magnitude of yield-scaled N_2O emissions and NO_3^- leaching from N-fertilized cereal crops are minimized at the optimum N fertilizer input such that yield-scaled N losses are greater with insufficient or excessive N fertilizer inputs (van Groenigen et al., 2010; Zhao et al., 2016). Although our yield-scaled N losses for the corn phase are consistent with this concept, our yield-scaled N losses from the soybean phase indicate that this concept may not transfer to a multi-year crop rotations (Figs 5 and 6). In the northern Corn Belt, soybean yield is not affected by N fertilizer input to the previous corn crop (Poffenbarger et al. 2016) and our results are consistent with this widespread pattern; N fertilizer to the previous corn crop increased N losses during the soybean phase (Table 1), but did not increase soybean yield. Comparison of yield-scaled N losses across different crops or multi-year rotations is challenging because crops are not selected simply for maximum biomass production; for example, soybean is grown for protein.

Although N fertilizer rate affected yield-scaled N_2O emissions from corn, cover crops did not affect yield-scaled N_2O emissions from either crop (Table 1, Fig. 5). A recent meta-analysis of cover crop effects on N_2O emissions determined that non-legume cover crops have no effect on N_2O emissions (Basche et al. 2014). However, this study highlighted that current N_2O research is largely limited to emissions from the soil surface. Cover crops have significant potential to reduce NO_3^- leaching and N_2O emissions can result from leached NO_3^- that is subsequently reduced to N_2O downstream (Turner et al., 2015; Parkin et al., 2016).

In fact, the cover crop consistently reduced yield-scaled NO_3^- leaching from both crop phases (Fig. 6). In corn, the reduction in yield-scaled NO_3^- leaching from the cover crop was greater than the reduction in yield-scaled NO_3^- leaching from application the recommended N fertilizer rate rather than the excessive rate. Consistent with this result, several studies have determined that N fertilizer management has limited potential to reduce NO_3^- leaching from rainfed annual crop rotations on soils with high organic matter (INRS, 2013; Gassman et al., 2015, McLellan et al., 2015). In these systems, a lack of synchrony between soil organic matter N mineralization and crop uptake is the primary cause of NO_3^- leaching.

The reduction in yield-scaled NO_3^- leaching due to cover crops was greater in soybean than corn. Two processes likely affected this result. First, cover crops have greater opportunity for growth (i.e., N uptake) prior to soybeans because soybean is planted later than corn (USDA, 2010). Second, cereal cover crops often reduce corn yield, but not soybean yield (INRS, 2013; Martinez-Feria et al., 2016). Cover crops also have significant potential to mitigate the effect of extreme weather on NO_3^- leaching when drought results in large amounts of residual inorganic N after an N-fertilized crop. In the 2013 soybeans that followed corn in the 2012 drought, the cover crop decreased yield-scaled NO_3^- leaching by almost 800% (Fig. 6).

Interactive effects of crop phase and extreme weather on N_2O-N emissions and NO_3^- leaching at a recommended N rate

Environmental N losses were path-dependent. The sequence of extreme weather years interacted with crop rotation sequence to affect environmental N losses, potentially creating a feedback with global climate change. For example, drought in corn followed by excess precipitation in soybean increased NO_3^- leaching by 88% relative to baseline leaching with average weather years. However, excess precipitation in corn followed by drought in soybean only increased NO_3^- leaching by 38%. This difference was due to residual N in the soil profile during the soybean phase that resulted from water limitation on corn N uptake and harvest (Huang et al., 2015; Iqbal et al., 2015). These simulated patterns at the field scale were manifest in the Mississippi River Basin: after the 2012 drought in the Midwest US, 2013 stream NO_3^- concentrations and loads in the Mississippi were exceptionally high (Metre et al., 2016).

In the upper Midwest United States, early spring precipitation is increasing while summer and fall precipitation are decreasing (Hatfield et al., 2011; Dai et al., 2015). Moreover, compared to the long-term weather record (>100 years), extremely wet and dry years are occurring more frequently (Anderson and Kyveryga, 2016). This shift in precipitation can have substantial effects on farming decisions, thus impacting crop yield (Hatfield 2010). The changing weather patterns can also stimulate N losses from the cropping system (Goldberg and Gebauer, 2009).

The two-year extreme weather scenarios did not always have the same effect on N_2O emissions and NO_3^- leaching. All two-year weather scenarios including a dry year reduced N_2O emissions whereas all two-year weather scenarios including a wet year increased NO_3^- leaching. As a result, the corn-dry/soybean-wet and corn-wet/soybean-dry weather scenarios had opposing effects on N loss pathways: they decreased N_2O emissions but increased NO_3^- leaching. These data suggest increased NO_3^- leaching in wet conditions may limit N_2O emissions. This could occur in at least two ways (Maggi et al. 2008; Castellano et al. 2013): i) rapid NO_3^- movement through the soil profile can exceed microbial uptake kinetics, and ii) high soil water content can promote more complete reduction of N_2O to N_2.

The cover crop mitigated the effect of extreme weather on NO_3^- leaching, but not N_2O emissions. Nitrate leaching was much more sensitive to extreme weather than N_2O emissions. In N-saturated agricultural systems, the physical process of NO_3^- leaching is a monotonic function of water: the greater the ratio of precipitation to evapotranspiration, the greater the NO_3^- leaching. Cover crops decrease this ratio. In contrast, N_2O emissions result from a complex interaction of biotic and abiotic processes during aerobic and anaerobic conditions (Venterea et al., 2007; Zhu et al., 2013). As a result of these processes, the magnitude of N_2O emissions is typically a Gaussian function of soil water content (Castellano et al., 2010) and cover crops can, in some situations, increase N_2O emissions (Mitchell et al., 2013; Basche et al., 2014).

Managing crop systems for extreme weather

Not all climate change adaptation strategies will mitigate the effects of extreme weather on environmental N losses. Here, we found that cover crops reduced the effect of extreme weather on NO_3^- leaching, but not N_2O emissions (Fig. 7). In contrast, the recommended N fertilizer rate minimized yield-scaled N_2O emissions from corn, but not soybean (Fig. 5). There are more mitigation strategies and combinations of those that could be evaluated and modeling provides a way to do that as we demonstrated in this study.

These results have practical applications. A cover crop following dry weather in the corn phase of the rotation will have a large impact on reducing NO_3^- leaching and retaining N in the soil for future crops. This result is particularly exciting because it demonstrates an opportunity to mitigate the effect of extreme weather after it occurs.

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Supplementary materials

Table S1. Site specific soil input parameters for the DAYCENT model.

Depth (cm)	Soil bulk density (g/cm3)	Sand (%)	Clay (%)	Soil organic matter (%)	Soil pH	Soil field capacity (%)	Wilting point (%)	Minimum volumetric content (%)	Soil saturated hydraulic conductivity, (cm/s)
0-2	1.174	36	21	3.8913	6.45	39.3	14.5	0.11	0.000579
2-5	1.174	36	21	3.8913	6.45	39.3	14.5	0.08	0.000579
5-10	1.174	36	21	3.8913	6.45	39.3	14.5	0.05	0.000579
10-20	1.546	37	25	3.6057	6.55	31.7	17	0.01	0.000367
20-30	1.479	34	27	2.6843	6.75	32.2	17.6	0	0.000247
30-45	1.479	34	27	2.6843	6.75	32.2	17.6	0	0.000247
45-60	1.506	37	26	1.55703	7.25	30.2	16.5	0	0.000205
60-75	1.506	37	26	1.55703	7.25	30.2	16.5	0	0.000205
75-90	1.506	37	26	1.55703	7.25	30.2	16.5	0	0.000205
90-105	1.506	37	26	1.55703	7.25	30.2	16.5	0	0.000205
105-120	1.506	37	26	1.55703	7.25	30.2	16.5	0	0.000205
120-150	1.506	37	26	1.55703	7.25	30.2	16.5	0	0.000205
150-180	1.506	37	26	1.55703	7.25	30.2	16.5	0	0.000205

Table S2. Crop and site specific DAYCENT model parameters adjusted during model calibration.

Parameter	Description	Calibrated value	Unit
dmpflux	The damping factor for soil water flux	0.000008	unitless
hours_rain	Duration of each rain event	4.1	hours
himax c	Harvest index maximum for corn (fraction of aboveground live C in grain)	0.521	fraction of C
himax s	Harvest index maximum for soybean (fraction of aboveground live C in grain)	0.45	fraction of C
prdx(1)c	Coefficient for calculating potential aboveground monthly production as a function of solar radiation outside the atmosphere for corn	1.95	g C/m^2/langleys of shortwave radiation
prdx(1)r	Coefficient for calculating potential aboveground monthly production as a function of solar radiation outside the atmosphere for rye	0.57	g C/m^2/langleys of shortwave radiation
prdx(1)s	Coefficient for calculating potential aboveground monthly production as a function of solar radiation outside the atmosphere for soybean	1.30	g C/m^2/langleys of shortwave radiation
prdx_g3n(1)	Coefficient for calculating potential aboveground monthly production as a function of solar radiation outside the	1.00	g C/m^2/langleys of shortwave radiation

	atmosphere for mixed grasses		
nit_amnt	Maximum daily nitrification amount	2.4	g N/m^2
dmp_st	Damping factor for calculating soil temperature by layer	0.0025	unitless
nitrified_n	Proportion of nitrified N that is lost as N_2O	0.78	fraction N

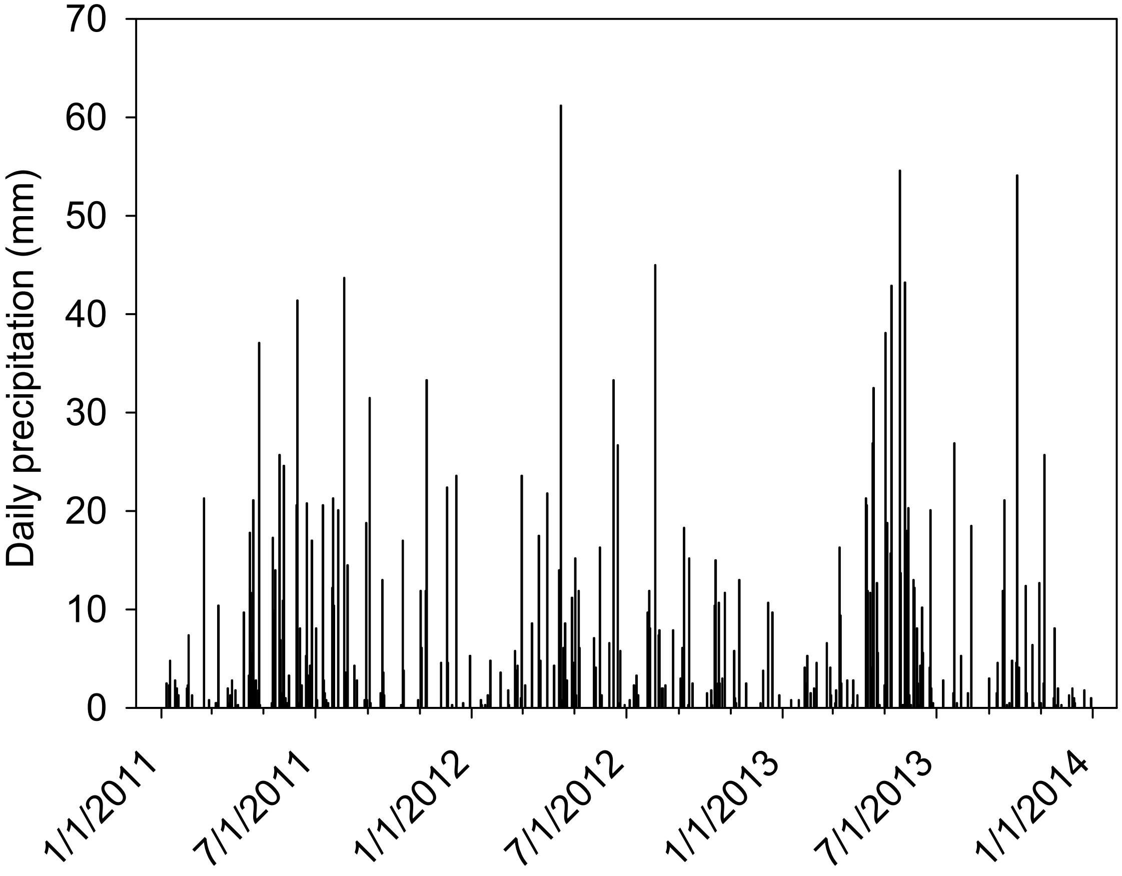

Fig. S1. Daily precipitation during the study period (2011-2013) at Boone County, IA.

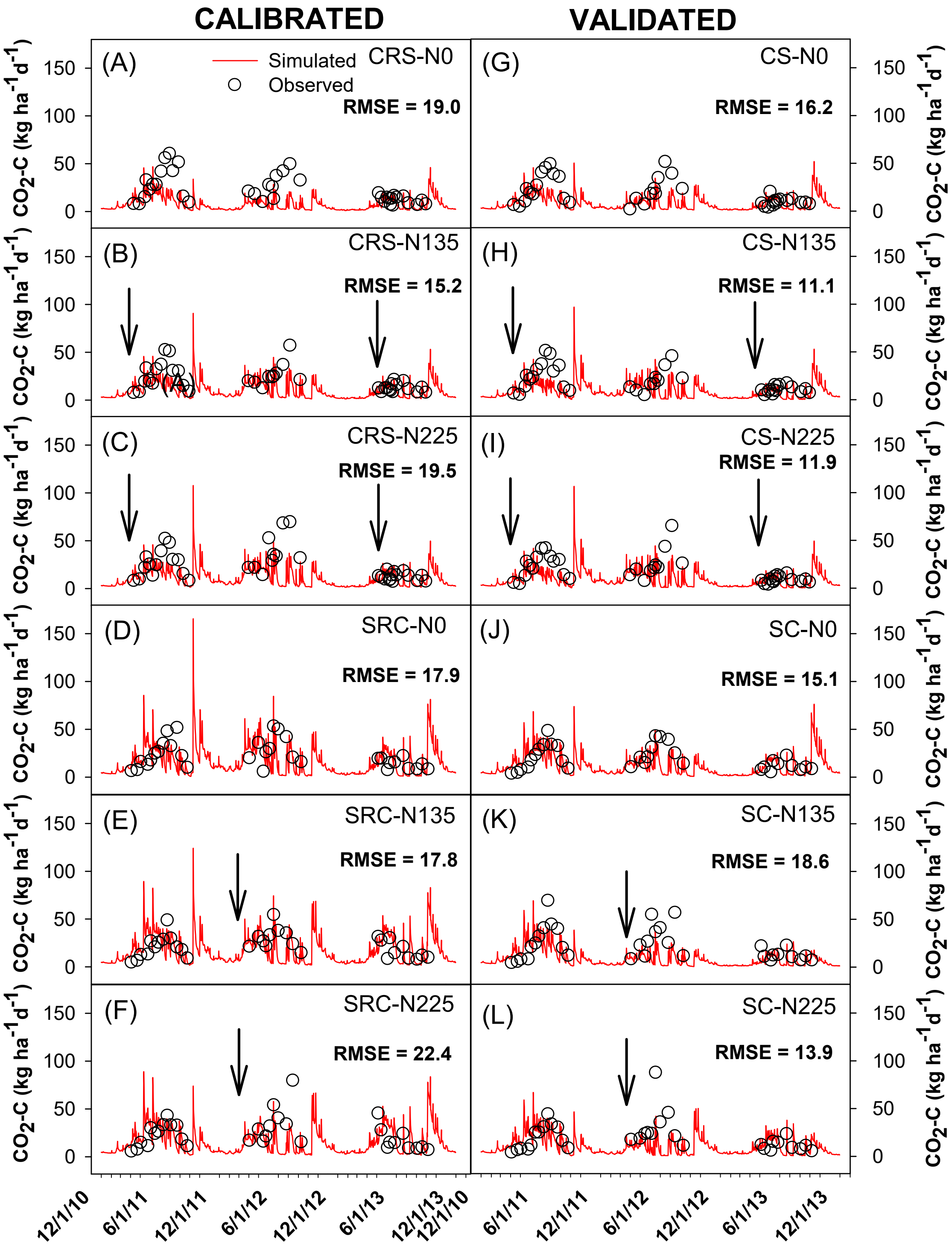

Fig. S2. Measured (open circles) and simulated (red lines) soil CO_2-C emissions in model calibration (A,B,C,D,E,F) and validation (G,H,I,J,K,L) at 0 (N0), 135 (N135) and 225 (N225) kg fertilizer N ha^{-1}. CRS = Corn-Soybean with rye cover crop, CS = Corn-Soybean without rye cover crop, SRC = Soybean-Corn with rye cover crop, SC = Soybean-Corn without rye cover crop. RMSE is the root mean square error and has the same unit as the variable shown. Arrows indicate the date of N fertilizer application to corn.

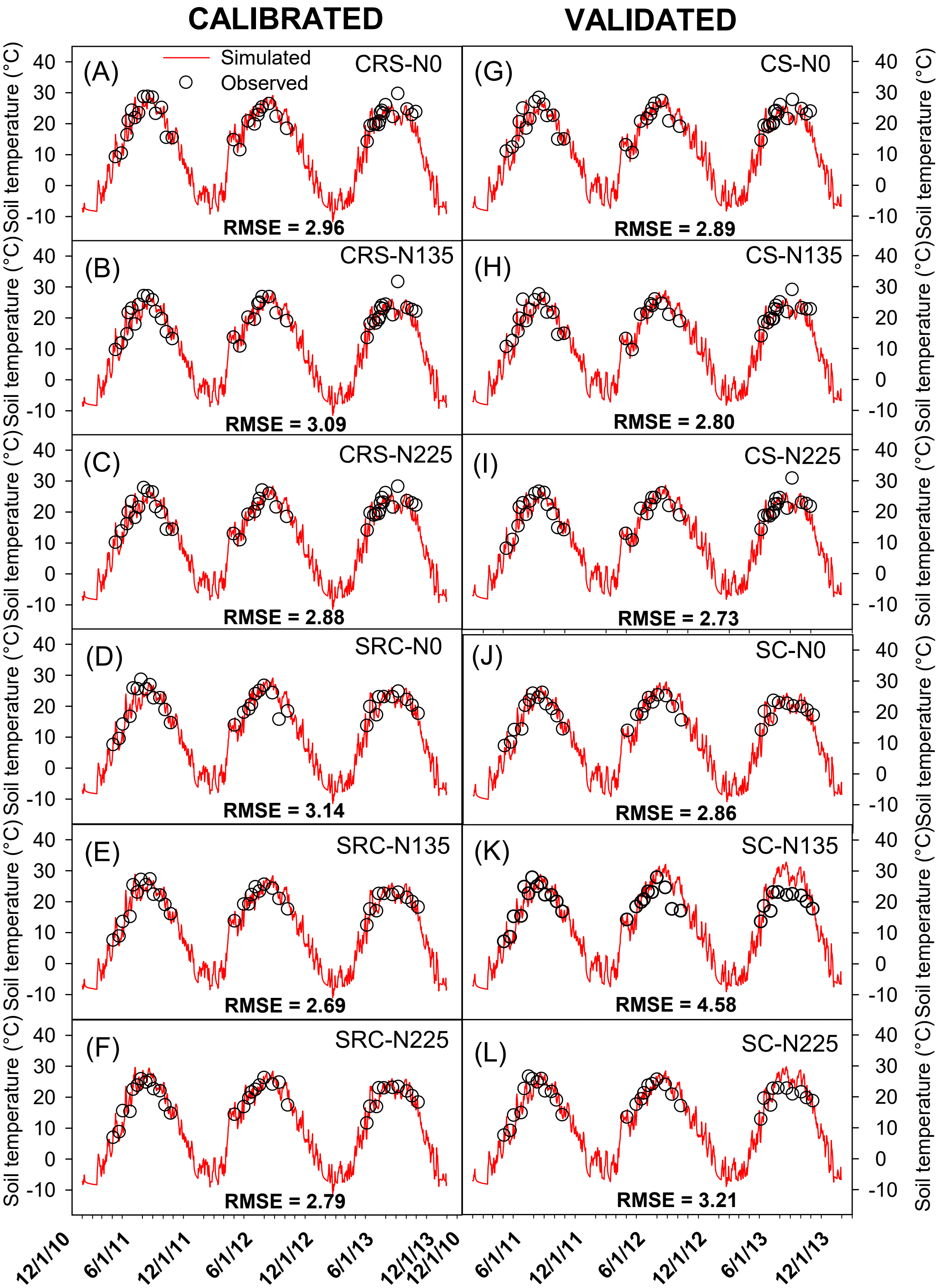

Fig. S3. Measured (open circles) and simulated (red lines) soil temperature at 5cm depth in model calibration (A,B,C,D,E,F) and validation (G,H,I,J,K,L) at 0 (N0), 135 (N135) and 225

(N225) kg fertilizer N ha^{-1}. CRS = Corn-Soybean with rye cover crop, CS = Corn-Soybean without rye cover crop, SRC = Soybean-Corn with rye cover crop, SC = Soybean-Corn without rye cover crop. RMSE is the root mean square error and has the same unit as the variable shown.

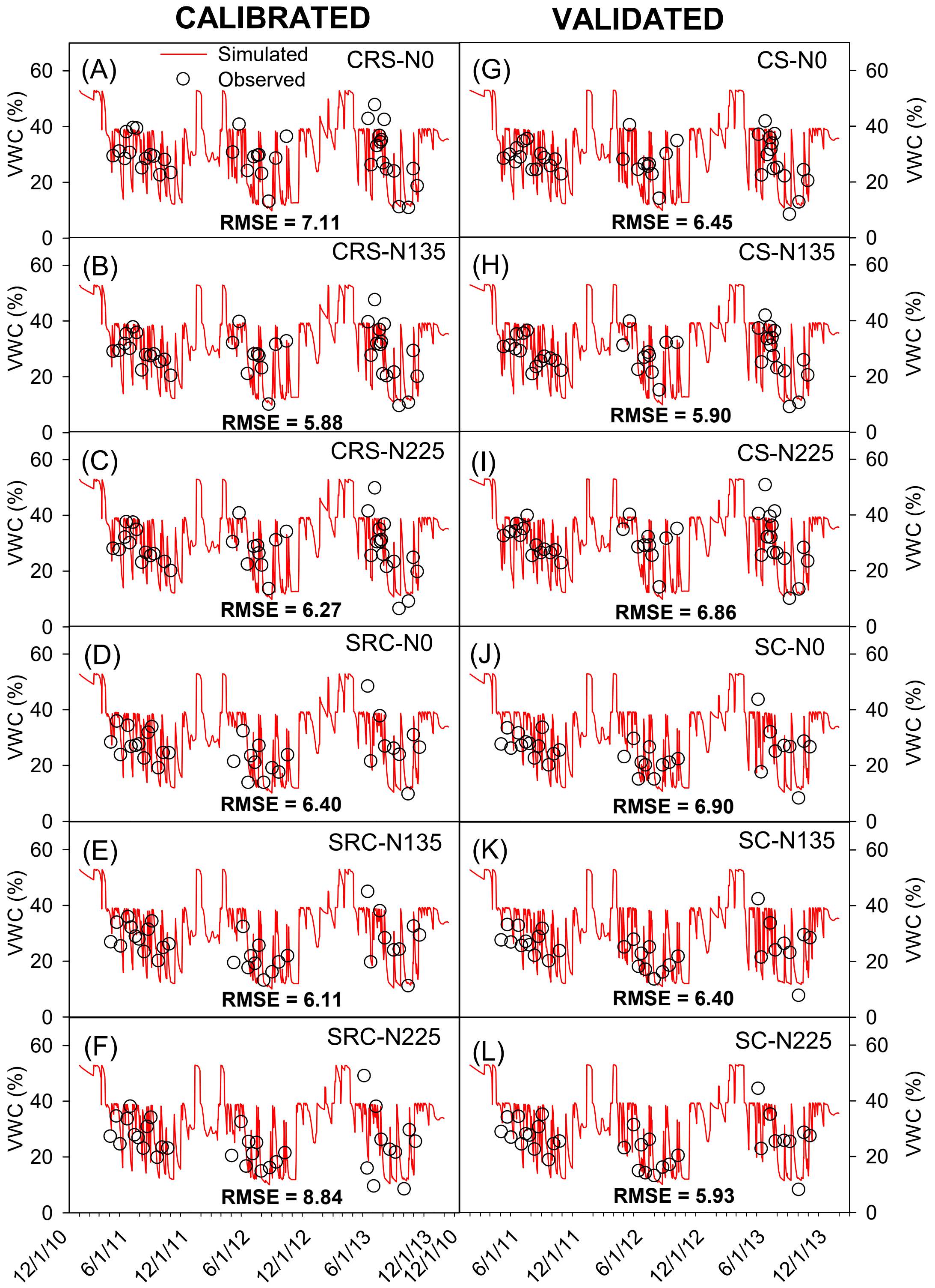

Fig. S4. Measured (open circles) and simulated (red lines) soil volumetric water content (VWC %) at 5cm depth in model calibration (A,B,C,D,E,F) and validation (G,H,I,J,K,L) at 0 (N0), 135 (N135) and 225 (N225) kg fertilizer N ha^{-1}. CRS = Corn-Soybean with rye cover crop, CS = Corn-Soybean without rye cover crop, SRC = Soybean-Corn with rye cover crop, SC = Soybean-Corn without rye cover crop. RMSE is the root mean square error and has the same unit as the variable shown.

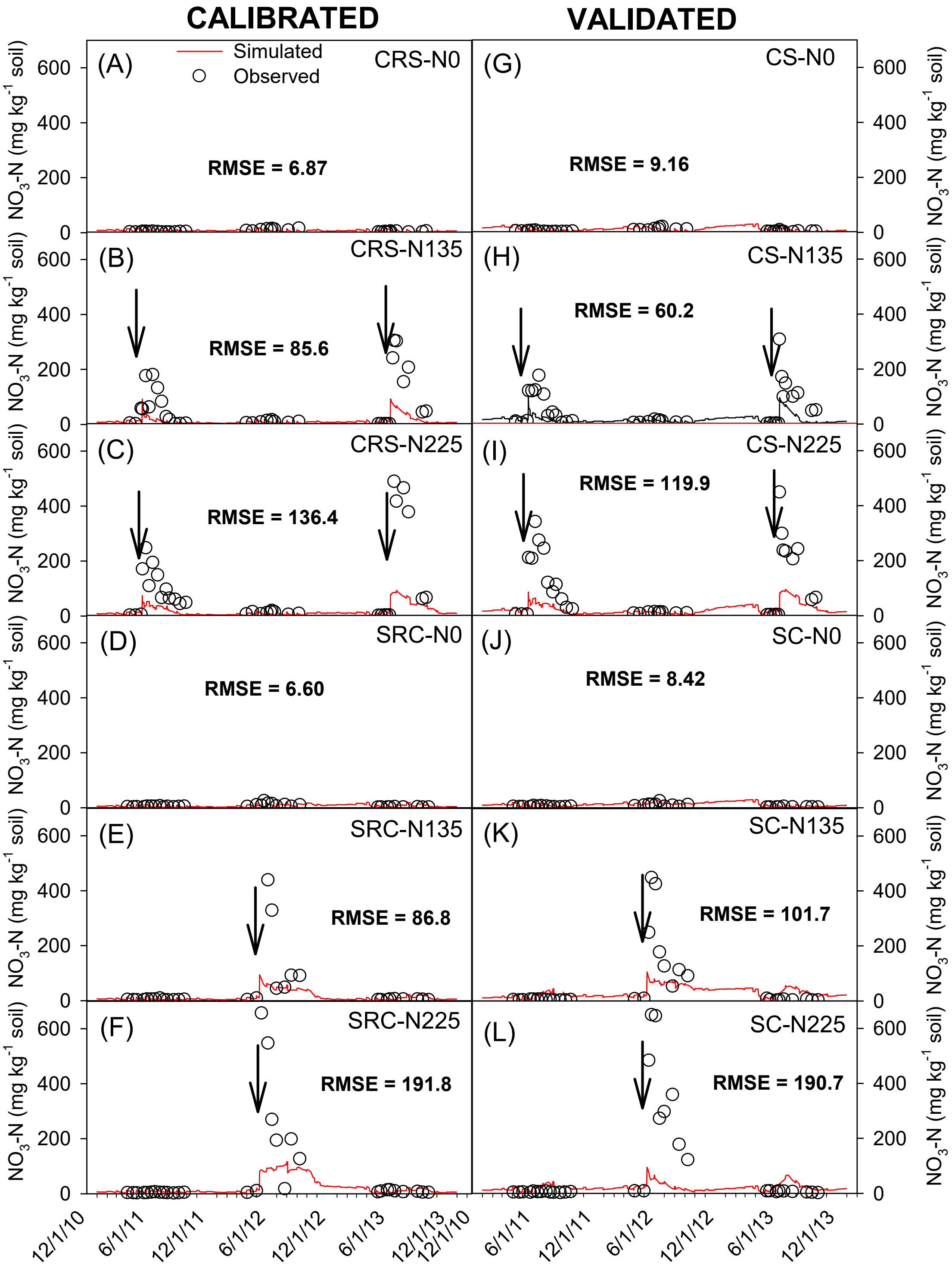

Fig. S5. Measured (open circles) and simulated (red lines) soil NO_3^--N in model calibration (A,B,C,D,E,F) and validation (G,H,I,J,K,L) at 0 (N0), 135 (N135) and 225 (N225) kg fertilizer N ha^{-1}. CRS = Corn-Soybean with rye cover crop, CS = Corn-Soybean without rye cover crop, SRC = Soybean-Corn with rye cover crop, SC = Soybean-Corn without rye cover crop. RMSE is the root mean square error and has the same unit as the variable shown. Arrows indicate the date of N fertilizer application to corn. For better visualization, soil NO_3^--N values with small scale are shown in Fig. S6.

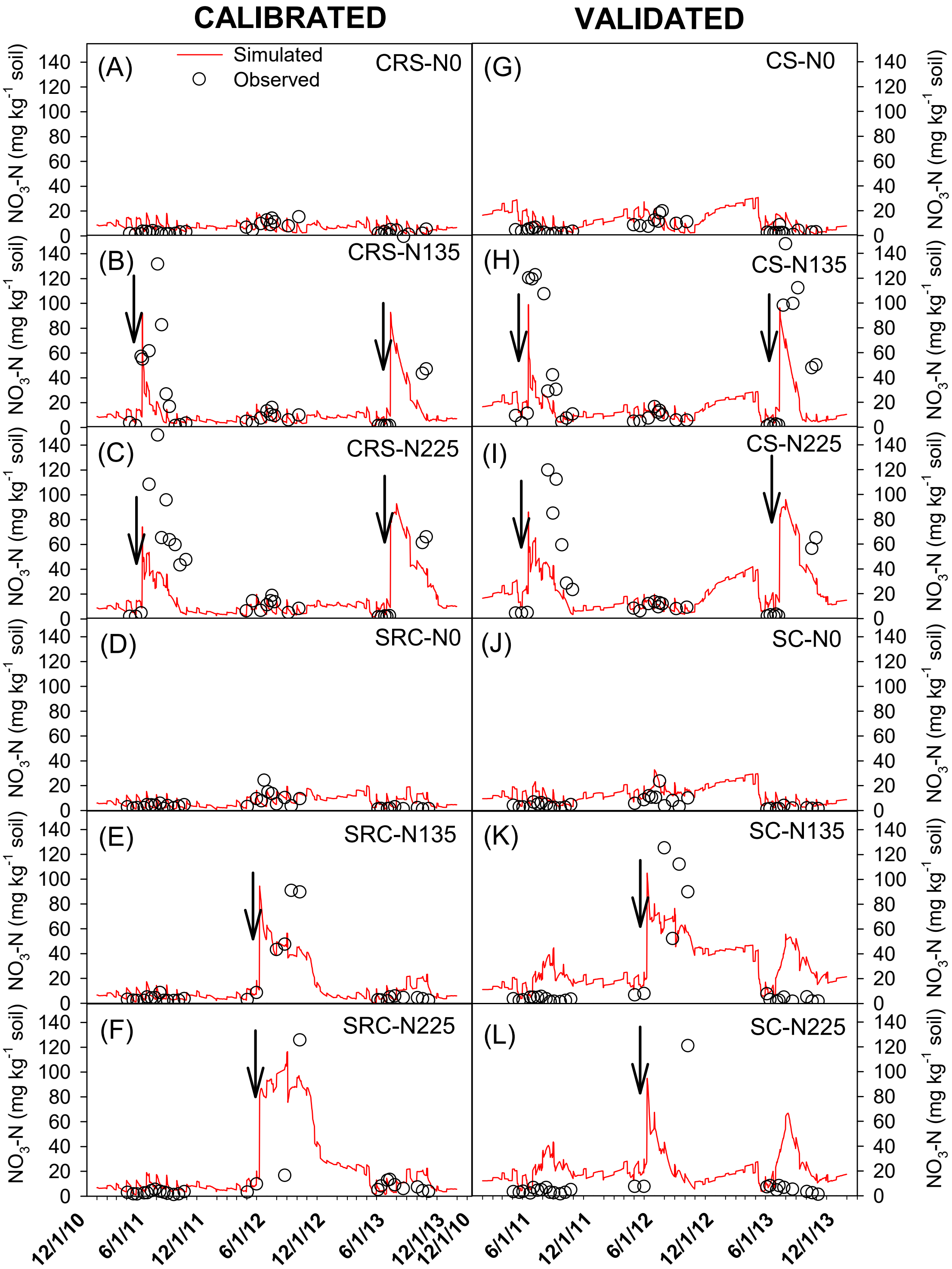

Fig. S6. Measured (open circles) and simulated (red lines) soil NO_3^--N in model calibration (A,B,C,D,E,F) and validation (G,H,I,J,K,L) at 0 (N0), 135 (N135) and 225 (N225) kg fertilizer N ha^{-1}. CRS = Corn-Soybean with rye cover crop, CS = Corn-Soybean without rye cover crop, SRC = Soybean-Corn with rye cover crop, SC = Soybean-Corn without rye cover crop. Arrows indicate the date of N fertilizer application to corn.

NOTE: This figure is a copy of figure S5, however scale for soil NO_3^--N is reduced to improve visualization.

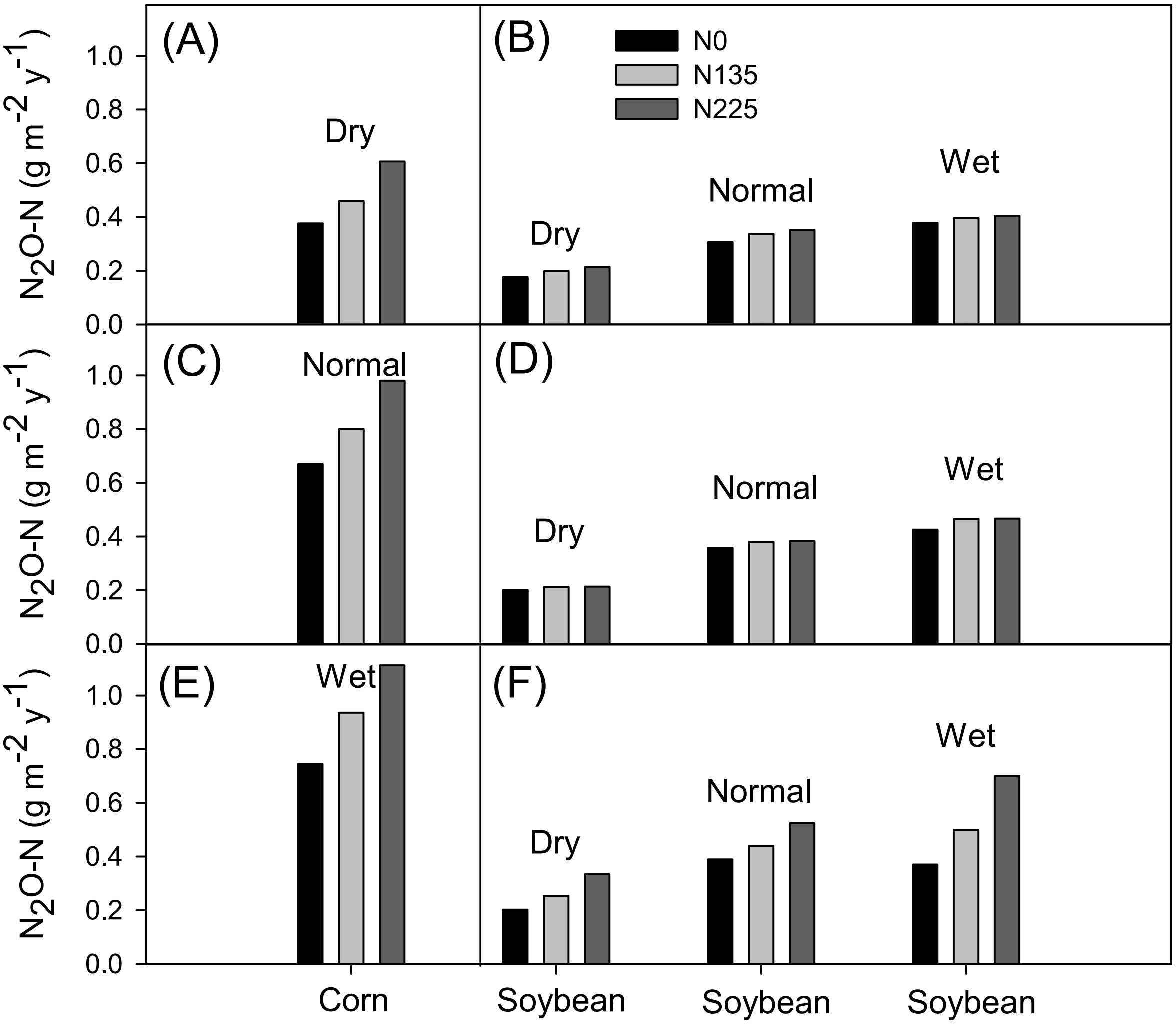

Fig. S7. Predicted soil N_2O-N emissions with possible precipitation combination of dry, normal and wet years of Corn (A,C,E) and Soybean (B,D,F) with rye cover crop at 0 (N0), 135 (N135) and 225 (N225) kg fertilizer N ha^{-1}.

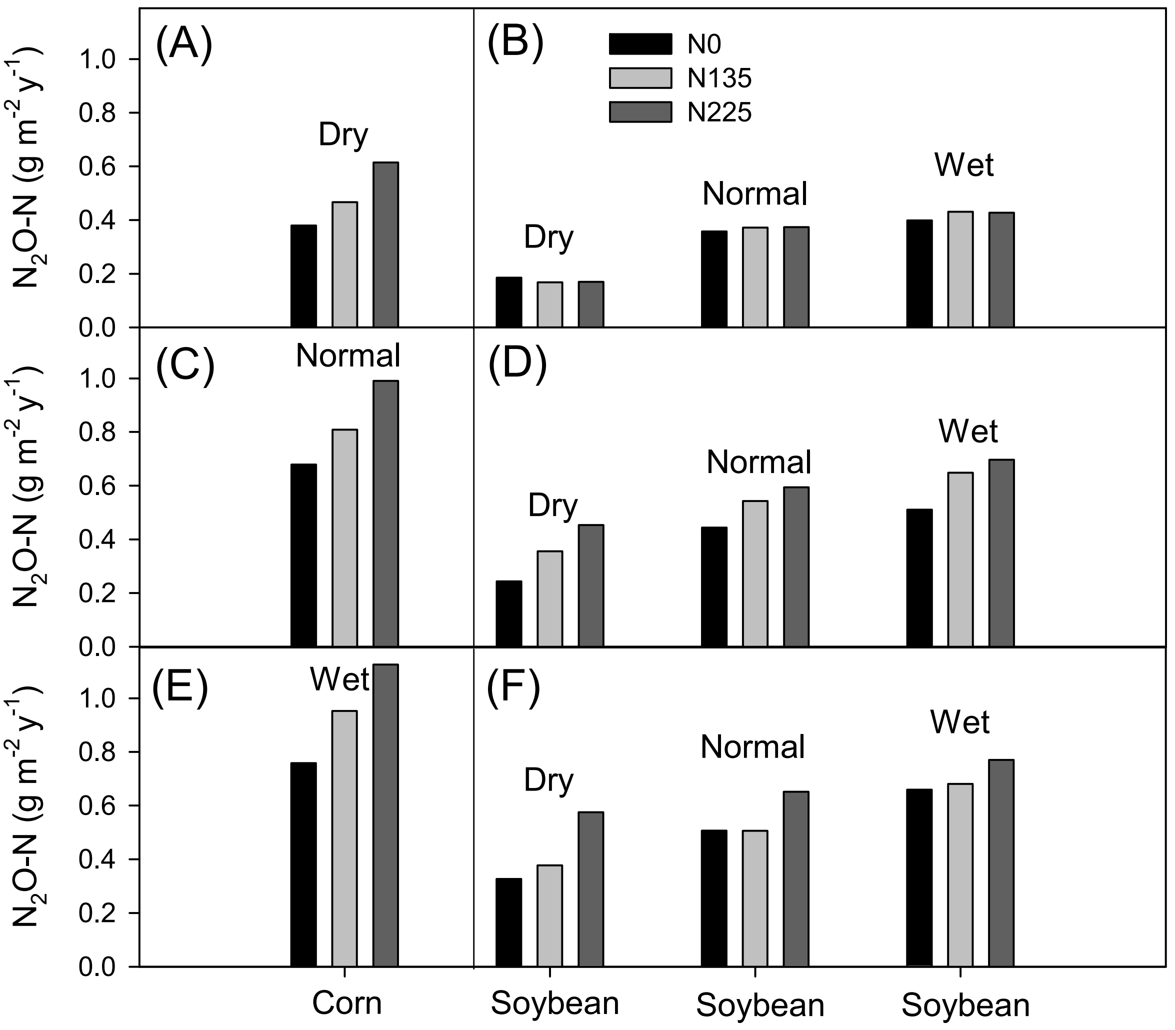

Fig. S8. Predicted soil N_2O-N emissions with possible precipitation combination of dry, normal and wet years of Corn (A,C,E) and Soybean (B,D,F) without rye cover crop at 0 (N0), 135 (N135) and 225 (N225) kg fertilizer N ha^{-1}.

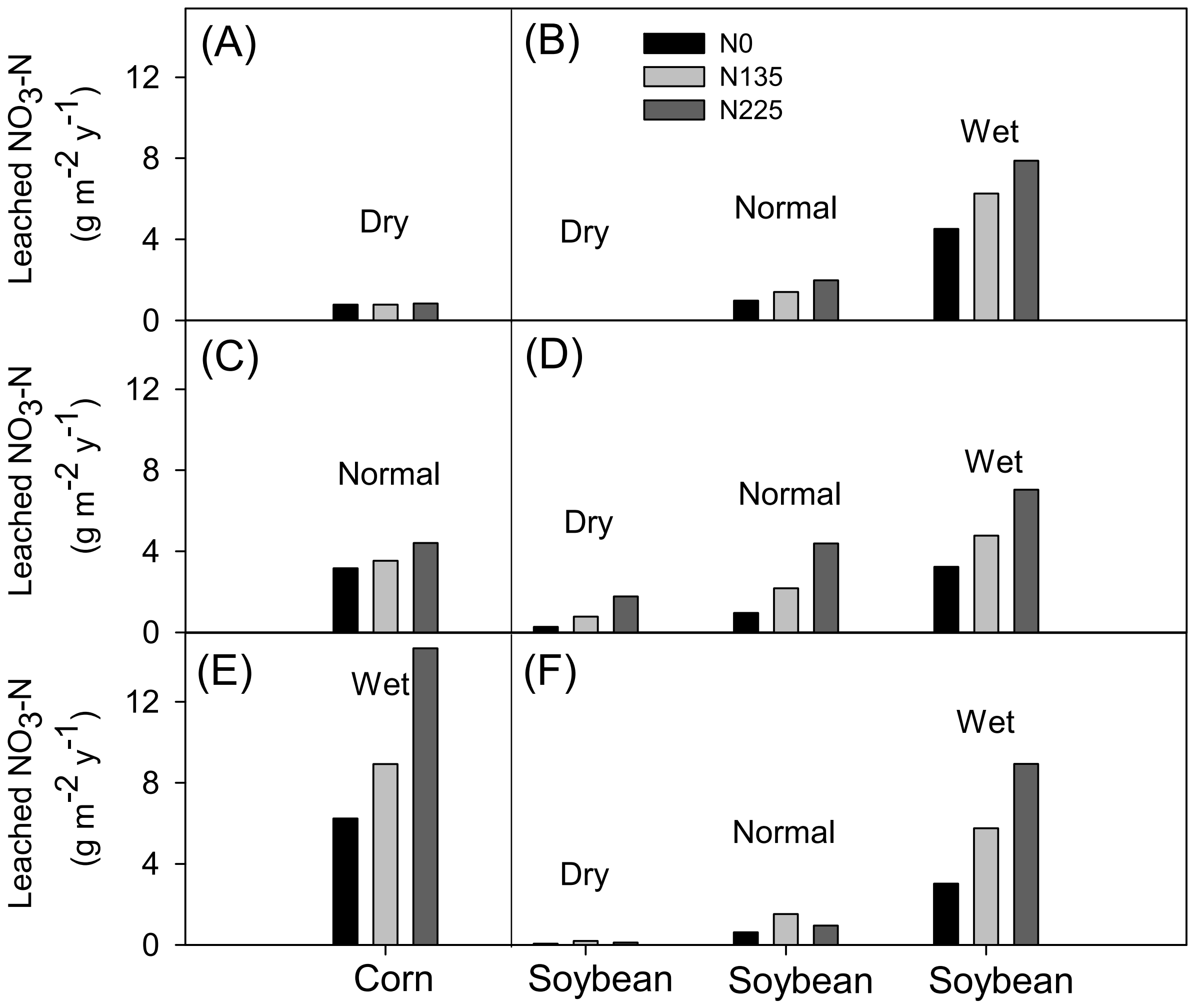

Fig. S9. Predicted soil NO_3^- leaching with possible precipitation combination of dry, normal and wet years of Corn (A,C,E) and Soybean (B,D,F) with rye cover crop at 0 (N0), 135 (N135) and 225 (N225) kg fertilizer N ha^{-1}.

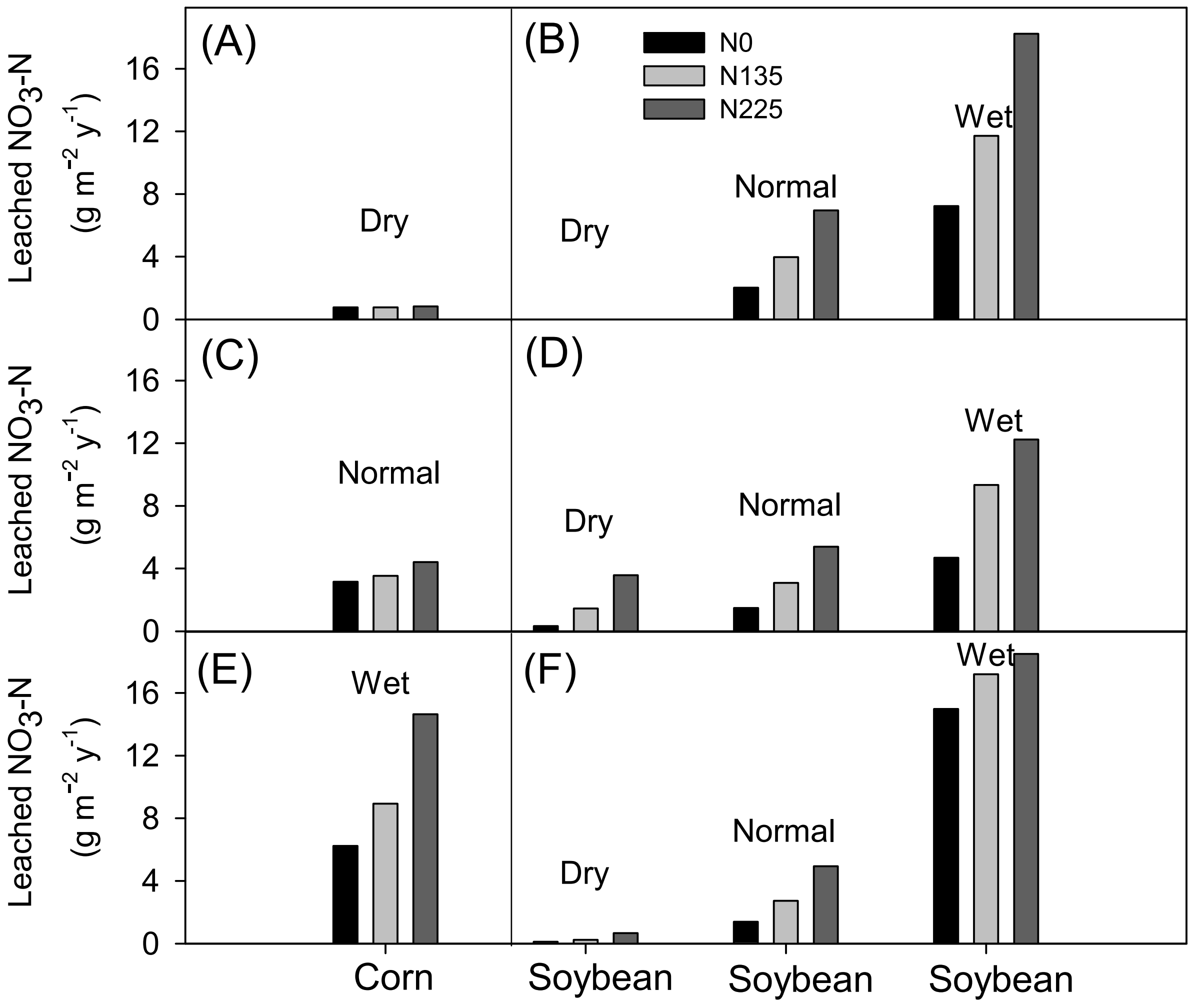

Fig. S10. Predicted soil NO_3^- leaching with possible precipitation combination of dry, normal and wet years of Corn (A,C,E) and Soybean (B,D,F) without rye cover crop at 0 (N0), 135 (N135) and 225 (N225) kg fertilizer N ha^{-1}.

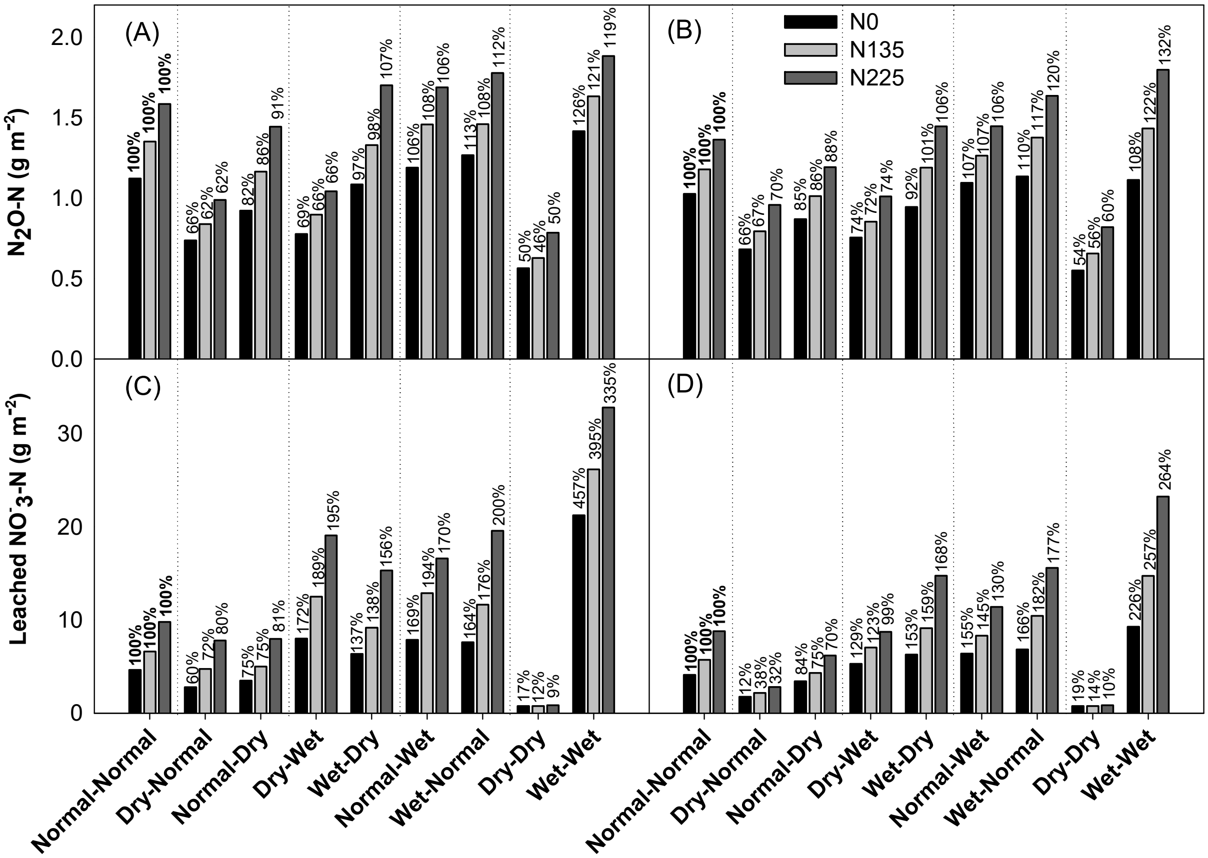

Fig. S11. Predicted two-year cumulative N$_2$O-N emissions and NO$_3^-$ leaching from the Corn-Soybean rotation without cover crop (A and C) and with cover crop (B and D) at 0 (N0), 135 (N135), and 225 (N225) kg N ha^{-1} to corn only for nine two-year weather scenario combinations of dry, normal and wet years (Figure 1). Among nine precipitation scenarios combinations, Normal-Normal years are considered as a control to compare with other eight scenarios. So, the values on top of each fertilizer bar in eight scenarios (Dry-Dry, Dry-Normal, Dry-Wet, Normal-Dry, Normal-Wet, Wet-Dry, Wet-Normal and Wet-Wet) indicate the percentage of values of respective fertilizer rates to Normal-Normal year. The dotted vertical lines separates scenarios for pairwise comparisons.