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Measured and simulated effects of residue removal and amelioration practices in no-till irrigated corn (*Zea mays* L.)

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ABSTRACT

Reducing nitrous oxide (N_2O) emissions to the atmosphere is expected to provide substantial climate mitigation benefits. Herein, we measured soil N_2O emission and crop yield responses in a nine-year, no-till continuous corn system under contrasting management practices including irrigation (full; deficit), corn stover retention (100 % retention; maximum mechanical removal), and cover crop use (winter cereal rye, *Secale cereale* L.; no cover crop). Field-measured data were used to construct a structural equation model (SEM_{obs}) to explore the causal effects of management on soil N_2O emissions. We also used the Root Zone Water Quality Model 2 (RZWQM2) to simulate management effects on soil N_2O emission. Structural equation modeling was used for the field-measured data (SEM_{obs}) and the RZWQM2 simulated data (SEM_{sim}) to quantify management relationships with soil and determine whether relationships observed in field data were captured by RZWQM2 simulations. Our experimental field results showed that stover removal decreased annual N_2O emissions compared to stover retention, only for deficit irrigated soil (2.83 ± 1.31 *vs.* 4.49 ± 3.65 kg N ha^{-1} y^{-1}) and that deficit irrigation decreased annual N_2O emissions compared to full irrigation, only for soil with cover crops (3.31 ± 3.19 *vs.* 4.11 ± 3.80 kg N ha^{-1} y^{-1}). The SEM_{obs} and SEM_{sim} results showed similar direction and magnitude of relationships between daily soil N_2O emissions and various management and environmental drivers. Our study improved the mechanistic understanding for the effects of agricultural management on soil N_2O emissions and can help reduce N_2O emissions from agricultural systems.

1. Introduction

Agriculture contributes ~ 60 % of global anthropogenic emissions of nitrous oxide (N_2O), which has a global warming potential of 298 times larger than that of CO_2 (Stocker, 2014). Because ~ 70 % of global N_2O emissions arise from agricultural soils, agronomic conservation management practices offer great potential for N_2O reduction (Reay et al., 2012) while also enhancing soil organic carbon (SOC) sequestration to mitigate global warming (Chabbi et al., 2017). Some practices intended to increase SOC storage, however, also can increase soil N_2O emissions (Guenet et al., 2021). Therefore, evaluating the effects of agricultural operations on soil N_2O emissions is important for projecting and mitigating global warming.

Agricultural operations such as irrigation, stover retention, and winter cover crops are commonly employed to increase SOC sequestration and/or crop yield, but these practices can also affect soil N_2O emissions. Although irrigation can increase crop yield (Schmer et al., 2020; Sun et al., 2021), soil N_2O emissions can also increase after irrigation due to higher water-filled pore space, which controls the major biological processes that generate N_2O (Chen et al., 2019; Hui et al., 2018). Stover retention can reduce soil erosion and nutrient runoff and support SOC buildup (Battaglia et al., 2021; Ojekanmi and Johnson, 2021; Xu et al., 2019), but the effect of stover retention on soil N_2O emissions remains equivocal, with residue retention resulting in increased (Jin et al., 2014), decreased (Drury et al., 2020), or no change in emissions (Johnson and Barbour, 2019). Likewise, the effect of cover

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Table 1
The *p*-values of the main and interaction effects of stover retention (S), rye cover crop (R), irrigation (I), and year (Y) on corn grain and biomass.

	Grain yield	Aboveground biomass	Grain nitrogen	Biomass nitrogen	Annual N_2O emission
S	0.3644	0.4953	0.2074	0.8277	0.0002
R	0.9343	0.7877	0.7326	0.4161	0.6930
I	0.9360	0.6434	0.9730	0.9544	0.4457
Y	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
S × R	0.4808	0.6112	0.6962	0.5172	0.0635
S × I	0.9445	0.8927	0.5535	0.9223	**0.0439**
R × I	0.7133	0.7639	0.6361	0.5356	**0.0403**
S × Y	0.1549	0.0168	0.0605	0.0384	**< 0.0001**
R × Y	0.0114	0.0223	0.0719	0.1317	0.7692
I × Y	**0.0153**	**0.0004**	0.8410	0.2760	0.8023
S × R × I	0.0701	0.2154	**0.0134**	**0.0475**	0.9291
S × R × Y	**0.0012**	**< 0.0001**	**0.0001**	**0.0010**	0.7805
S × I × Y	0.8930	0.3586	0.6468	0.7545	0.7267
R × I × Y	0.6434	0.5811	0.9418	0.9937	0.3137
S × R × I × Y	0.5496	0.1004	0.5996	0.4654	0.1619

crops, a common amelioration practice recommended when removing stover, also has variable effects on soil N_2O emissions, with cereal rye cover crop increasing (Mitchell et al., 2013) or decreasing soil N_2O (Parkin et al., 2016). These research gaps need to be further elaborated.

The Root Zone Water Quality Model 2 (RZWQM2), a process-based agroecosystem simulator developed and maintained by the USDA-Agricultural Research Service (Gillette et al., 2018; Malone et al., 2020), has been used to simulate N_2O emission as affected by winter rye cover crop, tillage, crop residue management, manure application, N application rate, as well as climate change (Gillette et al., 2017, 2018; Koehn et al., 2021; Malone et al., 2019; Wang et al., 2016). In particular, RZWQM2 adequately simulated N_2O emission from an irrigated continuous corn field under various crop residue and tillage management practices near our experimental site in Nebraska (Cheng et al., 2021). Most published studies use traditional metrics such as root mean squared error (RMSE) to evaluate RZWQM2 performance. These traditional measures of performance compare simulated *vs.* measured values and assume that the model is capturing simulated relationships if performance measures are adequate. Traditional performance measures, however, are unable to directly evaluate how well models capture the mechanistic relationships leading to the simulated values. Validating both modeled values as well as modeled relationships can provide effective tools to extrapolate management effects on sites outside the experimental locations and reduce the need for future work to assess long-term effects (Ahuja et al., 2000). A method of model evaluation based on mechanistic relationships is needed.

Therefore, our objectives are to (1) evaluate soil N_2O responses to the combined management practices of irrigation, stover retention, and cover cropping in a no-till continuous corn (*Zea mays* L.) production system in south central Nebraska; (2) test the RZWQM2 in simulating soil N_2O emission and crop yield under the management practices; and (3) evaluate the RZWQM2 performance in simulating N_2O responses to the management combinations. Our study can help clarify the effects of agricultural management on soil N_2O emissions and guide strategies of reducing N_2O emissions from agricultural operations.

2. Materials and methods

2.1. Site description and experimental design

The experimental site is located at the University of Nebraska-Lincoln's South Central Agricultural Laboratory (40.582°N, 98.144°W; 552 m asl), with a climate zone between subhumid and semiarid (Singh et al., 2021), mean annual temperature of 10.3 °C, and mean annual precipitation of 731 mm. The soil is a Hastings silt loam (fine, smectitic, mesic Udic Argiustolls) with a 0–2 % slope. For the top 30 cm soil depth, baseline soil bulk density for the site was 1.25 g cm^{-3}, soil pH (1:1 water) was 6.8, and SOC concentration was 16.2 g kg^{-1} (Blanco-Canqui et al., 2014). The site was previously in furrow-irrigated soybean [*Glycine max* (L.) Merr.] prior to study establishment in 2010. The site was tilled to the depth of 15 cm in April 2010 to level the soil surface prior to planting and has been maintained as a no-till continuous corn system through the present day.

Full details of experimental design and field management were reported in Schmer et al. (2020). The study reported here uses only a subset of treatments from the full experiment. Briefly, our experiment was a randomized complete block design with split-split plot. The whole plot represented irrigation management at two levels: deficit and full irrigation. The deficit irrigation was 60 % of the full irrigation. See specific timing and amount of irrigation and precipitation in Fig. S1. The split plot represented the use of winter cover crop to ameliorate the impact of corn stover removal at two levels: with cereal rye (*Secale cereale* L.) cover crop and no cover crop. The cover crop was planted at 112 kg ha^{-1} after stover harvest in late October/early November and chemically terminated prior to corn planting in late April or early May. The split-split plot represented stover management at two levels: 100 % stover retention and maximum mechanical removal corresponding to ~ 59 % removal of standing non-grain biomass after grain harvest (Schmer et al., 2020). Nitrogen fertilizer (urea ammonium nitrate solution; 32-0-0) was applied at 200 kg N ha^{-1} at V4-V6 corn growth stage [V(n), vegetative stage with "n" leaf collars present] using a sidedress coulter injection system. These treatments resulted in eight combinations: (1) DCM, deficit irrigation-cover crop-stover removal; (2) DCR, deficit irrigation-cover crop-stover retention; (3) DXM, deficit irrigation-no cover crop-stover removal; (4) DXR, deficit irrigation-no cover crop-stover retention; (5) FCM, full irrigation-cover crop-stover removal; (6) FCR, full irrigation-cover crop-stover retention; (7) FXM, full irrigation-no cover crop-stover removal; (8) FXR, full irrigation-no cover crop-stover retention. Each combination had four field replicates.

2.2. Sample collection and analyses

Soil N_2O emissions were sampled from April 2010 to August 2018 for a total of 3632 individual flux observations. Soil gas samples were collected about every two weeks during the growing season (May to September). Non-growing season measurements were collected monthly. Full details for soil gas collection, analysis, and calculation were reported in Jin et al. (2017). Briefly, headspace gas samples were collected with syringes from static vented chambers and then injected into evacuated vials at four evenly spaced time points across 30 min. Sample N_2O concentrations were analyzed using a headspace autosampler (CombiPAL; CTC Analytics, Zwingen, Switzerland) connected to a gas chromatograph (450-GC; Varian, Middelburg, Netherlands) equipped with an electron capture detector. Along with soil gas

Table 2
Measured and simulated means.

	Treatment	Grain yield (Mg ha^{-1})	Aboveground biomass (Mg ha^{-1})	Grain nitrogen (kg ha^{-1})	Biomass nitrogen (kg ha^{-1})	Daily N_2O emission (g N ha^{-1} d^{-1})	Annual N_2O emission (kg N ha^{-1} y^{-1})	Soil water (cm^3 water cm^{-3} soil)	Soil temperature (°C)
Measured	DCM	12.15 ± 3.31	22.10 ± 2.31	163.87 ± 29.11	237.62 ± 38.67	13.92 ± 22.78	2.34 ± 0.52	0.24 ± 0.03	17.39 ± 8.28
	DCR	12.14 ± 2.04	22.70 ± 2.88	164.15 ± 27.73	243.31 ± 41.99	16.95 ± 22.73	3.84 ± 1.03	0.25 ± 0.03	17.09 ± 8.27
	DXM	12.26 ± 2.61	22.10 ± 3.45	167.48 ± 35.63	236.56 ± 41.02	14.41 ± 18.87	2.93 ± 0.26	0.24 ± 0.03	17.76 ± 8.30
	DXR	11.81 ± 2.98	22.27 ± 2.11	154.85 ± 31.12	230.27 ± 38.81	22.23 ± 39.22	4.97 ± 1.18	0.25 ± 0.03	17.02 ± 7.93
	FCM	12.49 ± 2.07	22.85 ± 2.62	168.33 ± 27.49	236.41 ± 31.65	20.52 ± 34.11	4.13 ± 0.94	0.25 ± 0.03	17.33 ± 8.22
	FCR	11.68 ± 2.18	22.01 ± 3.04	157.11 ± 28.10	232.46 ± 37.35	19.93 ± 31.90	4.20 ± 1.35	0.26 ± 0.03	17.05 ± 8.00
	FXM	11.96 ± 2.46	21.93 ± 2.93	159.01 ± 29.75	229.34 ± 33.23	16.33 ± 26.60	3.08 ± 0.61	0.25 ± 0.03	17.54 ± 8.29
	FXR	12.34 ± 2.47	22.98 ± 3.12	167.83 ± 34.11	246.54 ± 38.47	21.09 ± 32.45	4.18 ± 0.94	0.26 ± 0.03	17.17 ± 7.98
Simulated	DCM	12.01 ± 1.75	20.04 ± 2.77	165.46 ± 27.44	196.88 ± 27.08	16.70 ± 18.76	6.72 ± 1.24	0.26 ± 0.05	15.58 ± 8.78
	DCR	12.17 ± 1.83	20.62 ± 2.76	176.20 ± 23.84	209.89 ± 22.69	21.77 ± 19.88	7.88 ± 0.73	0.26 ± 0.05	15.59 ± 8.79
	DXM	12.46 ± 1.62	21.25 ± 2.35	173.56 ± 25.39	206.30 ± 24.61	17.06 ± 20.40	6.45 ± 1.47	0.27 ± 0.05	15.55 ± 8.77
	DXR	12.54 ± 1.65	21.34 ± 2.37	177.28 ± 23.92	210.48 ± 23.02	18.47 ± 21.05	6.78 ± 1.32	0.27 ± 0.05	15.54 ± 8.78
	FCM	12.67 ± 1.42	21.56 ± 2.28	165.49 ± 27.53	196.85 ± 27.47	15.71 ± 17.45	6.66 ± 1.29	0.29 ± 0.05	15.50 ± 8.74
	FCR	13.31 ± 1.50	22.00 ± 2.38	176.99 ± 23.12	209.40 ± 23.00	20.27 ± 18.45	7.79 ± 0.34	0.27 ± 0.05	15.51 ± 8.73
	FXM	13.08 ± 1.32	22.29 ± 1.85	173.05 ± 26.33	205.39 ± 25.78	16.87 ± 20.32	6.68 ± 1.39	0.29 ± 0.05	15.47 ± 8.74
	FXR	13.27 ± 1.34	22.48 ± 1.91	177.42 ± 24.37	209.89 ± 23.80	18.43 ± 21.01	7.04 ± 1.23	0.29 ± 0.05	15.50 ± 8.75

The means were calculated by averaging values of all replicates across all years. Results were reported as mean ± standard deviation. DCM, deficit irrigation-cover crop-stover removal; DCR, deficit irrigation-cover crop-stover retention; DXM, deficit irrigation-no cover crop-stover removal; DXR, deficit irrigation-no cover crop-stover retention; FCM, full irrigation-cover crop-stover removal; FCR, full irrigation-cover crop-stover retention; FXM, full irrigation-no cover crop-stover removal; FXR, full irrigation-no cover crop-stover retention.

collection, soil temperature at 0–15 cm depth was measured by a stem thermometer (Model 9878E; Taylor, Oak Brook, IL, USA) and volumetric water content (VWC) was measured by a handheld time domain reflectometer (FieldScout TDR 300; Spectrum Technologies, Aurora, IL, USA) which was manually calibrated for site-specific soil characteristics. Daily soil N_2O fluxes were calculated as a linear or quadratic change in headspace gas concentration over time within the enclosed chamber volume (Venterea et al., 2020) corrected for suppression of the surface-atmosphere concentration gradient (Venterea, 2010), and reported as g N_2O-N ha^{-1} d^{-1}. Total annual N_2O emissions (kg N_2O-N ha^{-1} yr^{-1}) were estimated by linear interpolation of flux rates between sampling dates, then summing over crop year (*i.e.*, trapezoidal integration method).

Grain and aboveground biomass collection and measurement were reported in Schmer et al. (2020), and are reported as Mg ha^{-1} (dry matter, or 0 % moisture content). Grain and biomass N contents were analyzed by dry combustion (Flash EA 1112; Thermo, Waltham, MA, USA), and are reported as kg N ha^{-1}. Baseline soil data used for RZWQM2 parameterization were collected in October 2010 using a 4 cm-diameter soil probe for the depths of 0–7.5, 7.5–15, 15–30, 30–60, 60–90, 90–120, and 120–150 cm. Soil bulk density was calculated by dividing the mass of oven-dried soil (105 °C) by core volume. Particle size distribution (PSD) was measured by the sieving and sedimentation method (Kettler et al., 2001). Soil pH was measured by the 1:1 soil-water slurry method.

2.3. RZWQM2 input and calibration

The RZWQM2 (USDA-ARS; Fort Collins, CO, USA) was used to simulate soil N_2O emissions, VWC, temperature, crop yield, and grain and biomass N contents. The treatment of full irrigation-no cover crop-stover retention was used for calibration considering that it represented the optimal water and C supplies. The other treatments were used for subsequent validation. Specifically, the average of all four field replicates were used for model input. Meteorology data were obtained from the weather station (station ID: HARVARD 4SW) located ~ 1.5 km from the experimental site. Initial soil bulk density, PSD, and pH were set to measured values for six soil depth increments: 0–15, 15–30, 30–60, 60–90, 90–120, and 120–150 cm (Table 1). Soil porosity was calculated from bulk density and particle density (2.65 g cm^{-3}). Saturated hydraulic conductivity (K_{sat}) at each horizon was obtained from the Web Soil Survey (USDA-NRCS). The other hydraulic parameters were calibrated based on measured soil VWC. Soil nutrient pools were initialized by the RZWQM2 Initialization Wizard, with fast, intermediate, and slow humus pools being 1 %, 9 %, and 90 %, respectively. Model was run with default microbial population. The N_2O fraction in nitrification was calibrated to 0.044. The other parameters were set as RZWQM2 default values. Management practices (*i.e.*, planting, harvest, irrigation, fertilizer and pesticide application) were set according to Schmer et al. (2020) and Sindelar et al. (2019a).

2.4. Statistical analyses and model performance

A four-way mixed model ANOVA was used to determine the main and interaction effects of irrigation, cover crop, stover retention, and year on corn grain yield, aboveground biomass, grain and non-grain N contents, and annual soil N_2O emissions, with year as a repeated measure (Glimmix procedure; SAS 9.4, SAS Institute Inc., Cary, NC, USA).

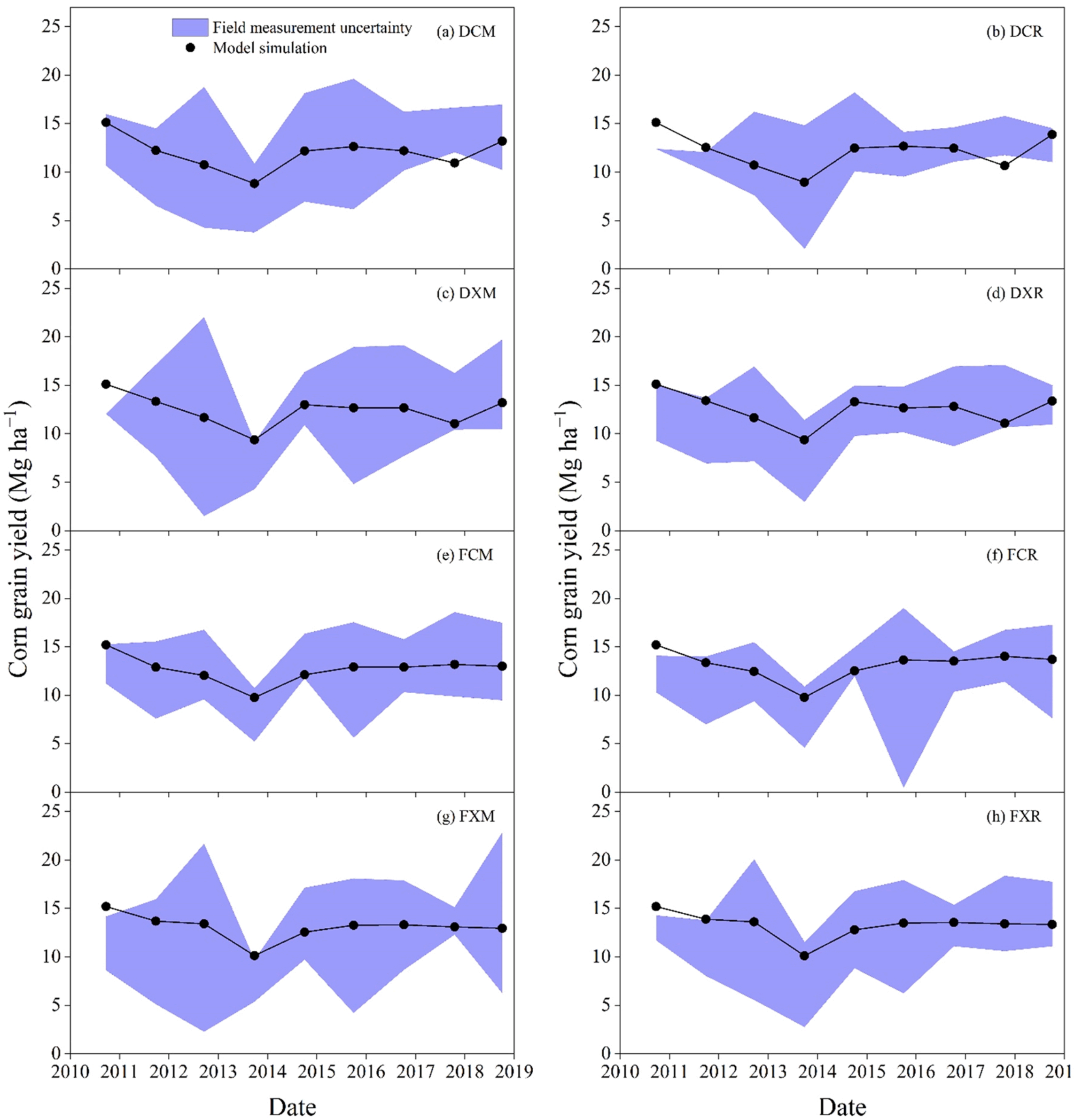

Fig. 1. Corn grain yield with field measurement uncertainty. The field measurement range was calculated by means ± 3.9 × standard deviations. (a) DCM, deficit irrigation-cover crop-stover removal; (b) DCR, deficit irrigation-cover crop-stover retention; (c) DXM, deficit irrigation-no cover crop-stover removal; (d) DXR, deficit irrigation-no cover crop-stover retention; (e) FCM, full irrigation-cover crop-stover removal; (f) FCR, full irrigation-cover crop-stover retention; (g) FXM, full irrigation-no cover crop-stover removal; (8) FXR, full irrigation-no cover crop-stover retention.

Post-hoc Least Squares Means for treatments were compared when there were significant main effects or interaction effects among the factors. Least Squares Means were compared by Fisher's Least Significant Difference. Data were log-transformed to achieve normal distribution when necessary. The univariate procedure was used for checking normality of residuals. Normality was determined by the Shapiro-Wilk's test. Equal variance was determined by the Levene's test. Significance was set at $p \leq 0.05$. Results were reported as untransformed mean ± standard deviation.

Root mean squared error (RMSE) (Table S2) and normalized RMSE (RMSE/measured mean) were used to evaluate how well RXWQM2 simulated crop and soil responses. The simulated and the measured data were compared within measurement uncertainty boundaries because it is not appropriate to disregard measurement uncertainty in model evaluation (Harmel and Smith, 2007). This novel method can enhance model evaluation by providing a more realistic uncertainty estimation based uncertainty distribution (Harmel and Smith, 2007). The uncertainty boundaries were calculated by field measurement means ± 3.9 × standard deviations, encompassing 99 % of the normal probability distribution.

Structural equation modeling (SEM; AMOS 27; IBM Corporation, Meadville, PA, USA) was applied to the field measurements to quantify the observed effects of management practices on daily soil N_2O emissions, SVW, and soil temperature and illustrate how these variables interact with each other to produce the overall effect (SEM_{obs}). The SEM was also applied to the RZWQM2 simulations to evaluate how the simulated N_2O emissions related to management and environmental drivers (SEM_{sim}) and whether these simulated relationships captured those shown in SEM_{obs}. Path coefficients were tested by maximum likelihood estimation at $p \leq 0.05$. Multivariate normality was evaluated by Kurtosis value ≤ 7. The SEM model fit was evaluated by (1) the minimum discrepancy divided by its degrees of freedom (CMIN/DF) in the range of 1–3 (Carmines and McIver, 1983), (2) the goodness of fit index (GFI) close to 1 (Tanaka and Huba, 1985), (3) the comparative fit

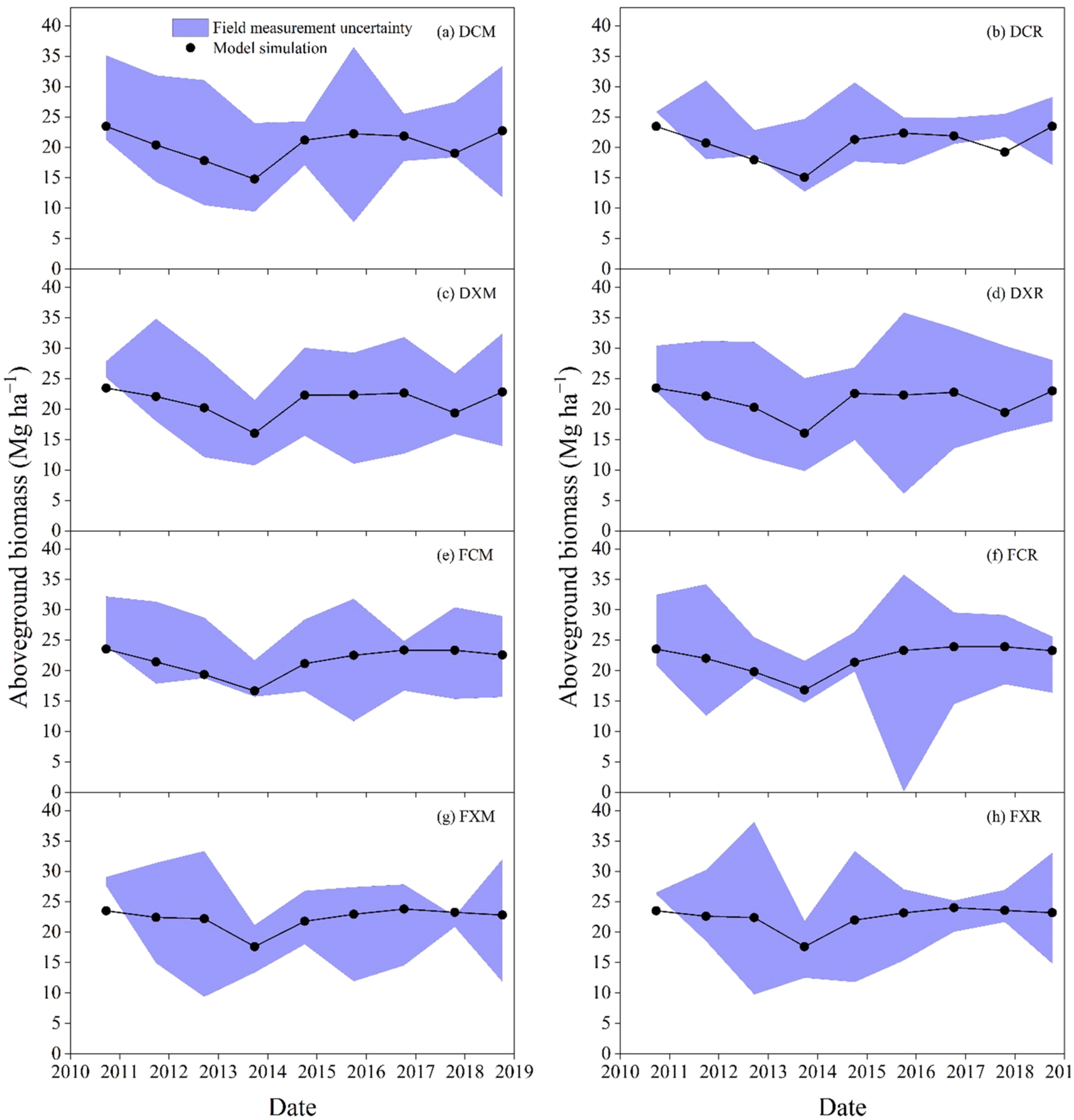

Fig. 2. Corn plant aboveground biomass with field measurement uncertainty. The field measurement range was calculated by means ± 3.9 × standard deviations. (a) DCM, deficit irrigation-cover crop-stover removal; (b) DCR, deficit irrigation-cover crop-stover retention; (c) DXM, deficit irrigation-no cover crop-stover removal; (d) DXR, deficit irrigation-no cover crop-stover retention; (e) FCM, full irrigation-cover crop-stover removal; (f) FCR, full irrigation-cover crop-stover retention; (g) FXM, full irrigation-no cover crop-stover removal; (8) FXR, full irrigation-no cover crop-stover retention.

index (CFI) close to 1 (Bentler, 1990), and (4) the root mean square error of approximation (RMSEA) less than 0.05 (Browne and Cudeck, 1993). We followed the procedures of developing and modifying a structural equation model in Byrne (2013) and Li et al. (2019). Briefly, we proposed a hypothesized model according to empirical research and scientific theory, tested if important pathways were left out and if the existing pathways were significant, and then revised the hypothesized model by adding missing pathways and dropping insignificant pathways in consideration of model fit and scientific rationality.

3. Results

3.1. Measured crop and soil variables

Measured corn grain yield and aboveground biomass was affected by the 3-way interaction effect of stover retention, cover crop, and year and the 2-way interaction effect of irrigation and year (p < 0.05 both; Table 1). No significant four-way interaction were detected. The 3-way interaction was limited to four of the nine crop years. Specifically, grain yield was higher under cover crop-stover retention than no cover crop-stover retention in 2014, but then reversed in 2015 with lower under cover crop-stover retention *vs.* no cover crop-stover retention (Fig. S2). Corn grain yield under no cover crop-stover removal was higher than cover crop-stover retention in 2018. Measured aboveground biomass was higher with cover crop-stover removal than cover crop-stover retention in 2015, while it was higher with cover crop-stover retention than no cover crop-stover removal in 2017 (Fig. S3). The two-way interaction of irrigation and year was limited to two of nine crop years. Measured corn grain yield was lower with full irrigation than deficit irrigation in 2015. Measured aboveground biomass was higher with full irrigation than deficit irrigation in 2012. Measured corn grain yield and aboveground biomass were respectively 12.1 ± 0.1 and 22.1 ± 0.3 Mg ha^{-1}, being averaged across treatments (Table 2). The lowest yield and biomass of 7.5 ± 0.1 and 17.6 ± 0.1 Mg ha^{-1} occurred in 2013

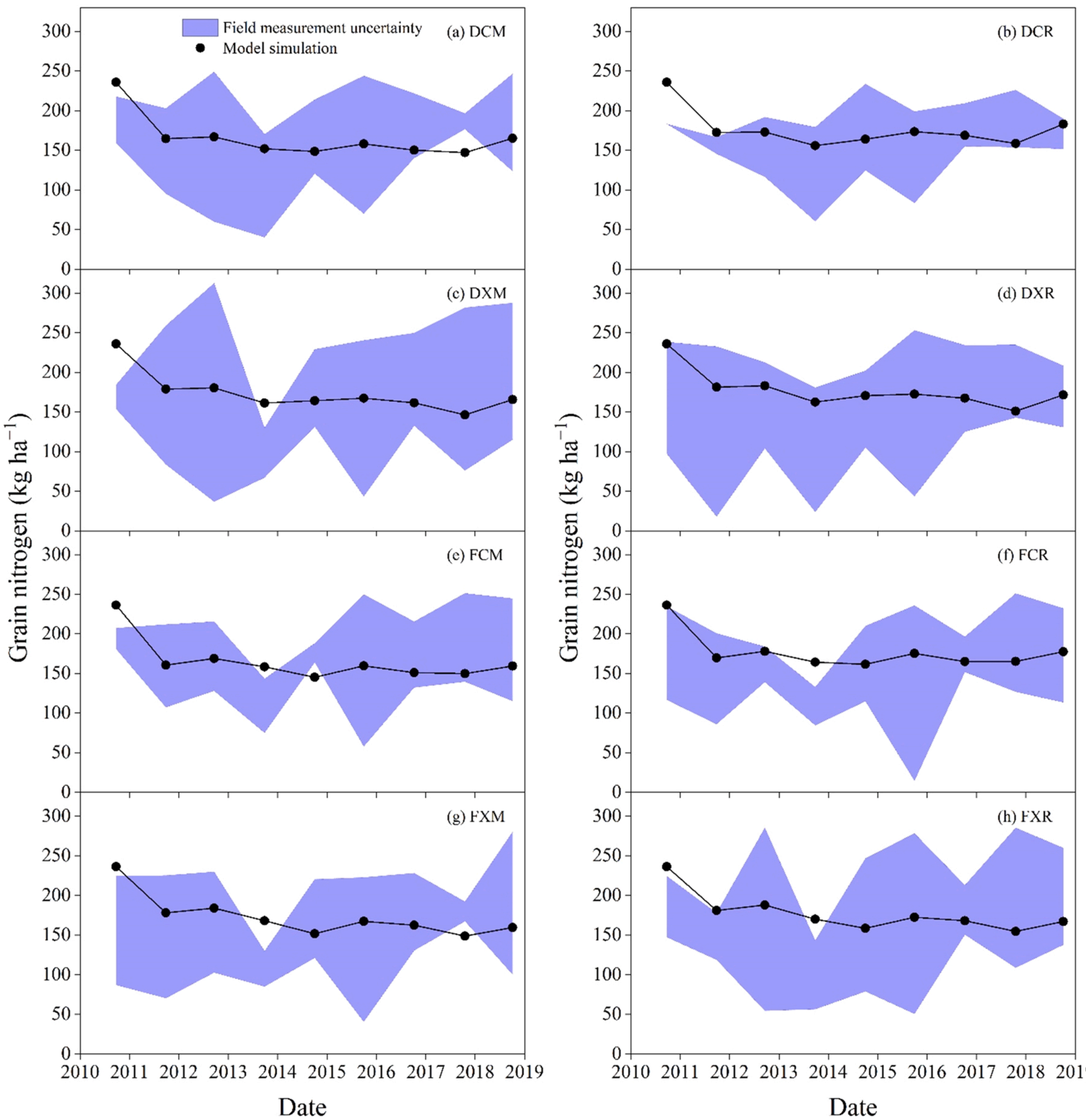

Fig. 3. Corn grain nitrogen with field measurement uncertainty. The field measurement range was calculated by means ± 3.9 × standard deviations. (a) DCM, deficit irrigation-cover crop-stover removal; (b) DCR, deficit irrigation-cover crop-stover retention; (c) DXM, deficit irrigation-no cover crop-stover removal; (d) DXR, deficit irrigation-no cover crop-stover retention; (e) FCM, full irrigation-cover crop-stover removal; (f) FCR, full irrigation-cover crop-stover retention; (g) FXM, full irrigation-no cover crop-stover removal; (8) FXR, full irrigation-no cover crop-stover retention.

with extreme weather (*i.e.*, abnormal drought).

Measured N contents of grain and aboveground biomass were affected by the interaction effect of stover retention, cover crop, and irrigation and the interaction effect of stover retention, cover crop, and year ($p < 0.05$, Table 1). Measured grain N was lower under deficit irrigation-no cover crop-stover retention than full irrigation-cover crop-stover removal (Fig. S4). Measured grain N was higher with no cover crop-stover removal than cover crop-stover retention in 2018 but showed no difference between these two treatments in the other years. Measured biomass N was lower under full irrigation-no cover crop-stover removal than deficit irrigation-cover crop-stover retention (Fig. S5). Measured biomass N was lower under no cover crop-stover removal than no-cover crop-stover retention in 2015 and 2017 but showed no difference between these two treatments in the other years. Measured N contents of grain and aboveground biomass were respectively 162 ± 3 and 234 ± 3 kg ha^{-1}, being averaged across treatments. Grain and biomass N contents were higher in 2010 compared to the subsequent years.

Measured annual N_2O emissions was affected by the 2-way interaction effects of irrigation and stover retention, irrigation and cover crop, and stover retention and year ($p < 0.05$, Table 1). Stover removal decreased annual N_2O emissions compared to stover retention, only for deficit irrigated soil (2.83 ± 1.31 *vs.* 4.49 ± 3.65 kg N ha^{-1} y^{-1}). Deficit irrigation decreased annual N_2O emissions compared to full irrigation, only for soil with cover crops (3.31 ± 3.19 *vs.* 4.11 ± 3.80 kg N ha^{-1} y^{-1}). Stover removal decreased annual N_2O emissions compared to stover retention, only in 2011 and 2013.

3.2. *Simulated crop and soil variables*

The normalized RMSE values for grain, biomass, and soil water and temperature ranged between 0.11 and 0.26 (Table S2), indicating good RZWQM2 performance. The simulated values are generally within the measurement uncertainty boundaries (Figs. 1–6), showing accurate model simulations. The RZWQM2 captured the decreases of grain and biomass in 2013 due to extreme weather (Figs. 1 and 2), the high N

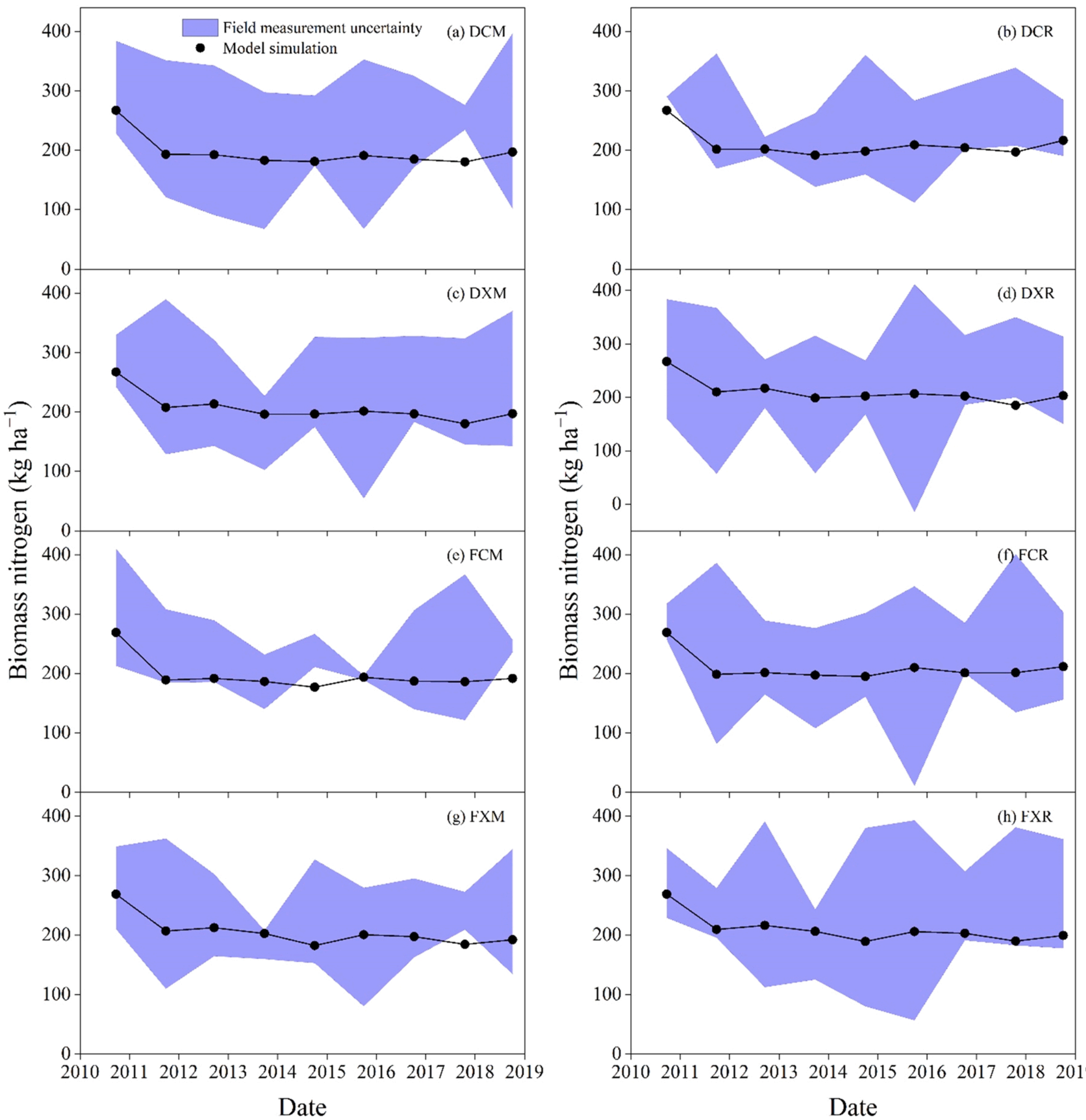

Fig. 4. Aboveground biomass nitrogen with field measurement uncertainty. The field measurement range was calculated by means ± 3.9 × standard deviations. (a) DCM, deficit irrigation-cover crop-stover removal; (b) DCR, deficit irrigation-cover crop-stover retention; (c) DXM, deficit irrigation-no cover crop-stover removal; (d) DXR, deficit irrigation-no cover crop-stover retention; (e) FCM, full irrigation-cover crop-stover removal; (f) FCR, full irrigation-cover crop-stover retention; (g) FXM, full irrigation-no cover crop-stover removal; (8) FXR, full irrigation-no cover crop-stover retention.

contents of grain and biomass in 2010 due to residual N from previous field management (Figs. 3 and 4), and the seasonal fluctuations of daily soil water and temperature (Figs. 5 and 6 and S6–S7). The daily N_2O simulations were less than ideal according to the normalized RMSE values (1.28–1.60, Table S2). However, the simulated daily N_2O values were largely within the measurement uncertainty boundaries (Fig. 7) and aligned with the measured seasonal variations (Fig. S8), suggesting acceptable RZWQM2 performance.

3.3. Structural equation modeling of observed field data (SEM_{obs})

The effects of irrigation, stover retention, and cover crop on measured soil N_2O emissions were evaluated using a structural equation model (SEM_{obs}; goodness-of-fit indices: CMIN/DF = 0.252, GFI = 0.999, CFI = 1.000, RMSEA = 0.000, Fig. 8a). The squared multiple correlation coefficient (R^2) of soil N_2O was 0.327, which would be interpreted as SEM_{obs} explaining 32.7 % of the variance in measured soil N_2O. Soil temperature had a direct positive effect on N_2O, with an effect size of 0.461 ($p < 0.05$). In other words, a 1.000-unit of increase in soil temperature would cause a 0.461-unit increase in soil N_2O emissions. Indirect effects of irrigation and stover retention on N_2O were mediated by soil water content, which positively affected N_2O. Full irrigation increased soil N_2O emissions by 9 % compared to deficit irrigation and stover retention increased soil N_2O emission by up to 18 % relative to stover removal. Rye cover crop decreased soil N_2O emissions by 4 % compared to no cover crop, but this relationship was not significant ($p > 0.05$). Measured soil VWC was positively affected by irrigation and stover retention ($p < 0.05$). Full irrigation increased soil VWC by 3 % compared to deficit irrigation, and stover retention increased VWC by 4 % compared to stover removal. Measured soil temperature was not affected by treatments ($p > 0.05$).

3.4. Structural equation modeling of RZWQM2-simulated data (SEM_{sim})

To examine if RZWQM2 simulations could capture the observed management effects on N_2O, simulated results were evaluated using

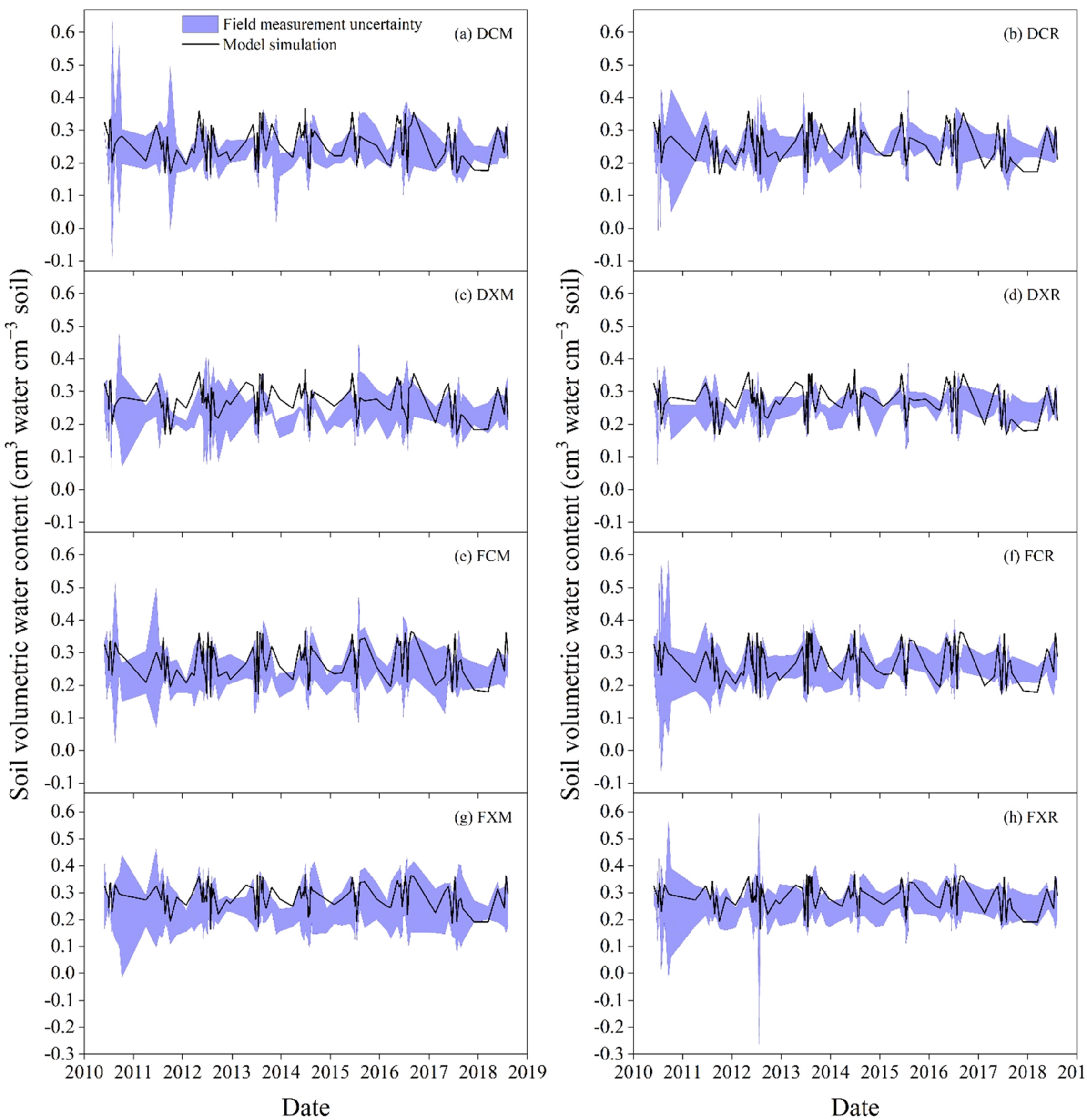

Fig. 5. Daily Soil volumetric water content with field measurement uncertainty. The field measurement range was calculated by means ± 3.9 × standard deviations. (a) DCM, deficit irrigation-cover crop-stover removal; (b) DCR, deficit irrigation-cover crop-stover retention; (c) DXM, deficit irrigation-no cover crop-stover removal; (d) DXR, deficit irrigation-no cover crop-stover retention; (e) FCM, full irrigation-cover crop-stover removal; (f) FCR, full irrigation-cover crop-stover retention; (g) FXM, full irrigation-no cover crop-stover removal; (8) FXR, full irrigation-no cover crop-stover retention.

SEM_{sim} (CMIN/DF = 0.618, GFI = 0.998, CFI = 1.000, RMSEA = 0.000, Fig. 8b). The R^2 of 0.262 indicates that SEM_{sim} explained 26.2 % of the variance in simulated soil N_2O. In SEM_{sim}, stover retention directly affected N_2O instead of being mediated by soil water content as shown in the SEM_{obs}. Simulated results also showed no relationship between cover crop and N_2O. Overall, simulated N_2O responded to irrigation, cover crop, and soil water and temperature in the same pattern but with slightly smaller effect sizes compared to field measurement (Table 3).

4. Discussion

4.1. Effects of irrigation on daily soil N_2O emissions

Irrigation is commonly used as a means of increasing crop yield in arid or semiarid regions (Schmer et al., 2020; Sun et al., 2021). However, irrigation can also increase soil N_2O emissions (Chen et al., 2019; Hui et al., 2018). Our field measurement and RZWQM2 simulation both showed that increased irrigation amount can increase daily soil volumetric water content and then increase daily soil N_2O emissions (Fig. 8). Therefore, deficit irrigation can reduce daily soil N_2O emissions compared to full irrigation. Soil water content is considered one of the most important factors controlling soil N_2O emissions for its impacts on oxygen availability and substrate mobility (Barrat et al., 2020; Langarica-Fuentes et al., 2018; Schimel, 2018). Soil water filled pore space (WFPS) can regulate nitrification, nitrifier denitrification, denitrification, and nitrate ammonification, which are the four major biological processes that generate N_2O (Baggs, 2008). Soil WFPS determines the dominant contribution of nitrification *vs.* denitrification to N_2O emissions (Thilakarathna and Hernandez-Ramirez, 2021). Nitrification usually occurs at 10–80 % WFPS when soil is aerobic or partially aerobic, and denitrification at 60–100 % WFPS when soil is mostly anaerobic (Bateman and Baggs, 2005; Linn and Doran, 1984; Mekala and Nambi, 2017). Soil N_2O emissions increase with WFPS and have the highest value at 70 % WFPS and above (Barrat et al., 2020; Ding et al., 2019). Upon irrigation, increased WFPS will alter the

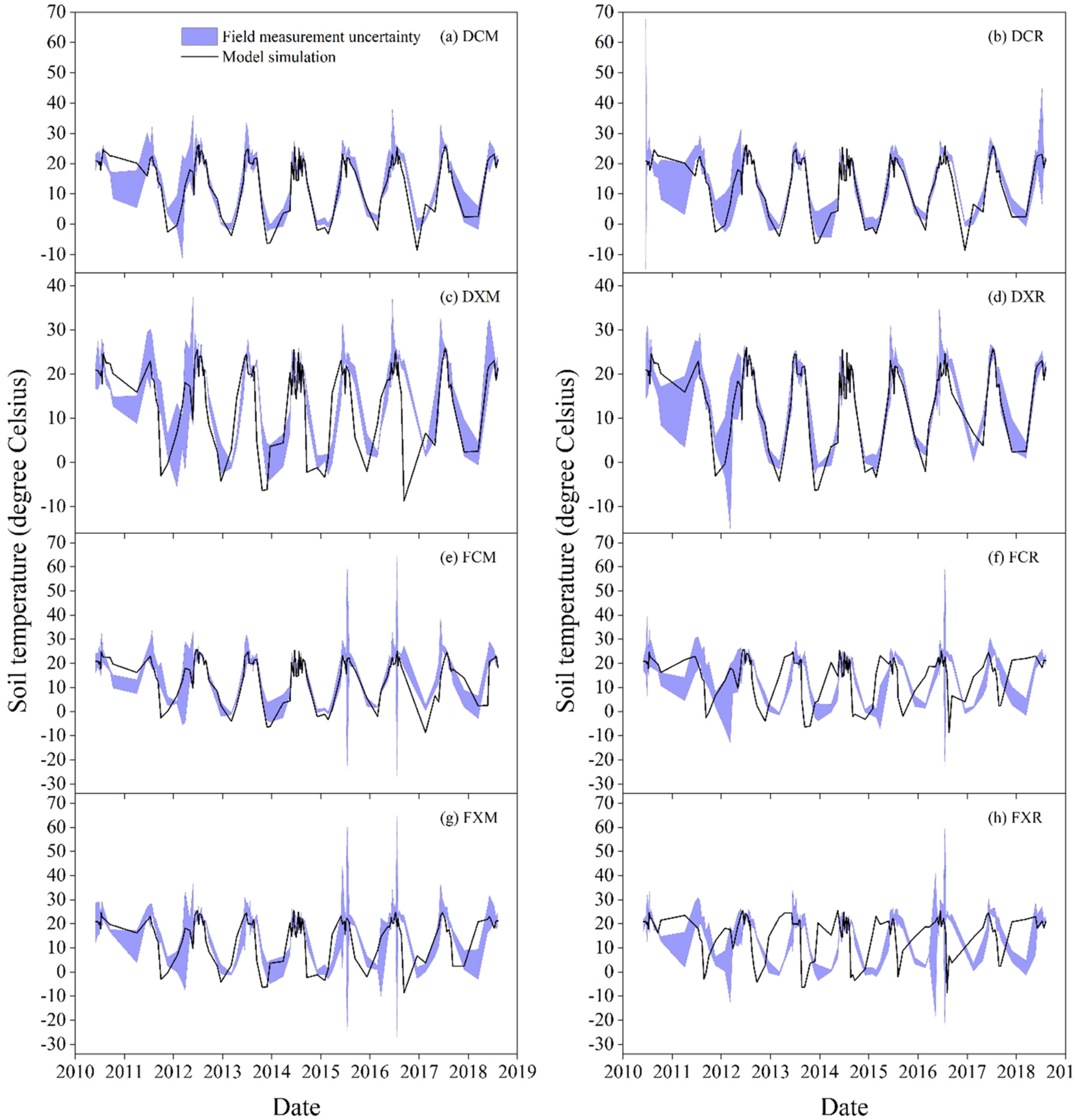

Fig. 6. Daily Soil temperature with field measurement uncertainty. The field measurement range was calculated by means ± 3.9 × standard deviations. (a) DCM, deficit irrigation-cover crop-stover removal; (b) DCR, deficit irrigation-cover crop-stover retention; (c) DXM, deficit irrigation-no cover crop-stover removal; (d) DXR, deficit irrigation-no cover crop-stover retention; (e) FCM, full irrigation-cover crop-stover removal; (f) FCR, full irrigation-cover crop-stover retention; (g) FXM, full irrigation-no cover crop-stover removal; (8) FXR, full irrigation-no cover crop-stover retention.

intensity and dominance of nitrification *vs.* denitrification as sources of N_2O emissions. Microbial community structure may shift with soil transitioning from aerobic to anaerobic conditions, and denitrifier population size can increase up to five fold (Langarica-Fuentes et al., 2018). This may lead to increase in denitrification-derived N_2O emissions (Clagnan et al., 2020). Also, soil water can control microbial activity as a solvent and transport medium for substrates (Schimel, 2018). Irrigation reconnects the hydrologically isolated substrates with soil microbes. The substrates can rapidly be utilized by the microbes and improve microbial activity. This may further consume oxygen and induce anaerobic conditions for denitrification (Barrat et al., 2020). The RZWQM2 also showed increased N_2O emissions *via* denitrification and decreased N_2O emissions *via* nitrification under full irrigation compared to deficit irrigation (Table S3). However, this needs to be further validated with field measurements since we did not partition measured N_2O into denitrification or nitrification as the source.

4.2. Effects of corn stover retention on daily soil N_2O emissions

With the effects of corn stover retention being intensively studied, various effects were observed. Stover retention was observed to increase, decrease, or have no effect on soil N_2O emissions (Drury et al., 2020; Jin et al., 2014; Johnson and Barbour, 2019). Our observations show that stover retention increased the measured daily soil N_2O emissions relative to stover removal through increasing soil volumetric water content (Fig. 8a). In contrast, RZWQM2 simulations showed that stover retention directly increased daily N_2O emissions instead of indirectly through changes in daily soil volumetric water content (Fig. 8b). This indicates that the complex responses of soil water, substrate availability, aggregation, oxygen availability, and temperature to stover management may affect soil N_2O emissions altogether. Stover retention reduces evapotranspiration and increases soil sorptivity and water retention (Blanco-Canqui and Lal, 2008; Schneekloth et al., 2020; Shaver et al., 2013). Pairing higher soil water content with increased C

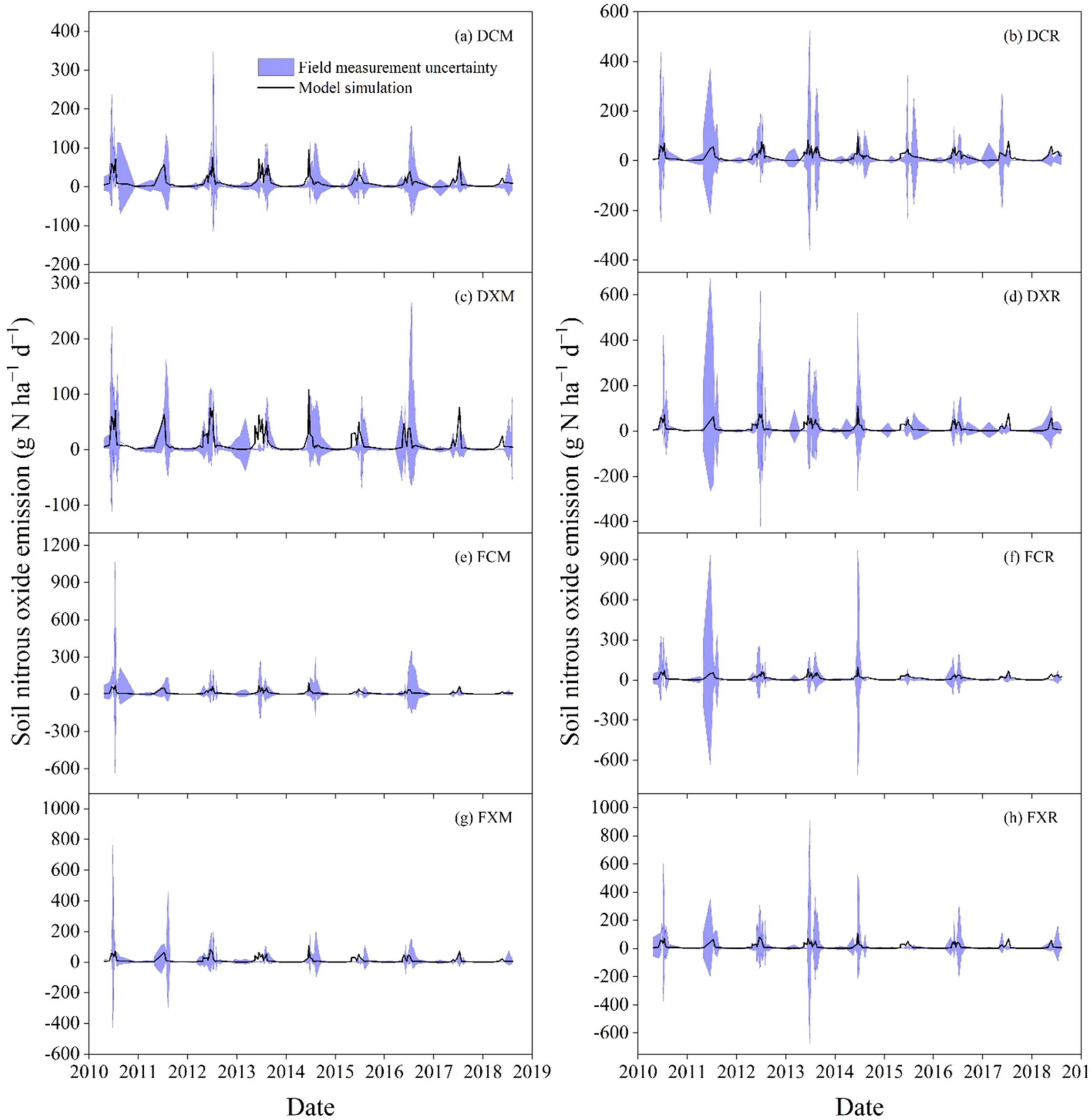

Fig. 7. Daily soil N_2O emissions with field measurement uncertainty. The field measurement range was calculated by means ± 3.9 × standard deviations. (a) DCM, deficit irrigation-cover crop-stover removal; (b) DCR, deficit irrigation-cover crop-stover retention; (c) DXM, deficit irrigation-no cover crop-stover removal; (d) DXR, deficit irrigation-no cover crop-stover retention; (e) FCM, full irrigation-cover crop-stover removal; (f) FCR, full irrigation-cover crop-stover retention; (g) FXM, full irrigation-no cover crop-stover removal; (8) FXR, full irrigation-no cover crop-stover retention.

availability can further induce N_2O production (Langarica-Fuentes et al., 2018). Moreover, stover retention enhances soil aggregate formation and stability (Ojekanmi and Johnson, 2021). Denitrification may simultaneously occur with nitrification at low soil water content due to soil heterogeneity since anoxic micropores can still be developed for denitrification within large aggregates even at 31 % WFPS (Thilakarathna and Hernandez-Ramirez, 2021). Indeed, simulated soil N_2O emissions *via* nitrification and denitrification were both promoted by stover retention (Table S3). Additionally, stover retention is expected to decrease soil temperature (Blanco-Canqui et al., 2006) and thus decrease N_2O emissions, but in our study stover retention decreased soil surface temperature only by 3 % compared to no retention and this decrease was not statistically significant.

4.3. Effects of winter cereal rye cover crop on daily soil N_2O emissions

Previous studies have shown that cereal rye cover crop increased (Mitchell et al., 2013) or decreased soil N_2O emissions (Parkin et al., 2016). The effect of cover crop on soil N_2O emissions has not reached consensus yet since the effect is determined by residue biomass quantity and quality. Neither our field measurement nor RZWQM2 simulation showed significant effects of rye cover crop on daily soil N_2O emissions (Fig. 8). The rye cover crop returned low amounts of biomass to the soil and significantly less than biomass returned through corn stover retention (Fig. S9). The low biomass of the rye cover crop resulted from a short growing period from planting after corn harvest to terminating prior to corn planting. The rye never reached grain-fill before termination, resulting in minimal aboveground biomass (0.8 Mg ha^{-1} yr^{-1}) (Sindelar et al., 2019b). The other reason could possibly be the gas sampling timing. Rye cover crop can reduce N_2O emissions by 66 % from rye planting to termination but did not affect soil N_2O emissions during corn growing season (Reicks et al., 2021). In this study, gas was more intensively sampled during corn growing season. Additionally, a legume cover crop would have more significant effect on soil N_2O emissions than a nonlegume due to more N supply (Muhammad et al., 2019). Soil N_2O emissions were higher with vetch than rye cover crops

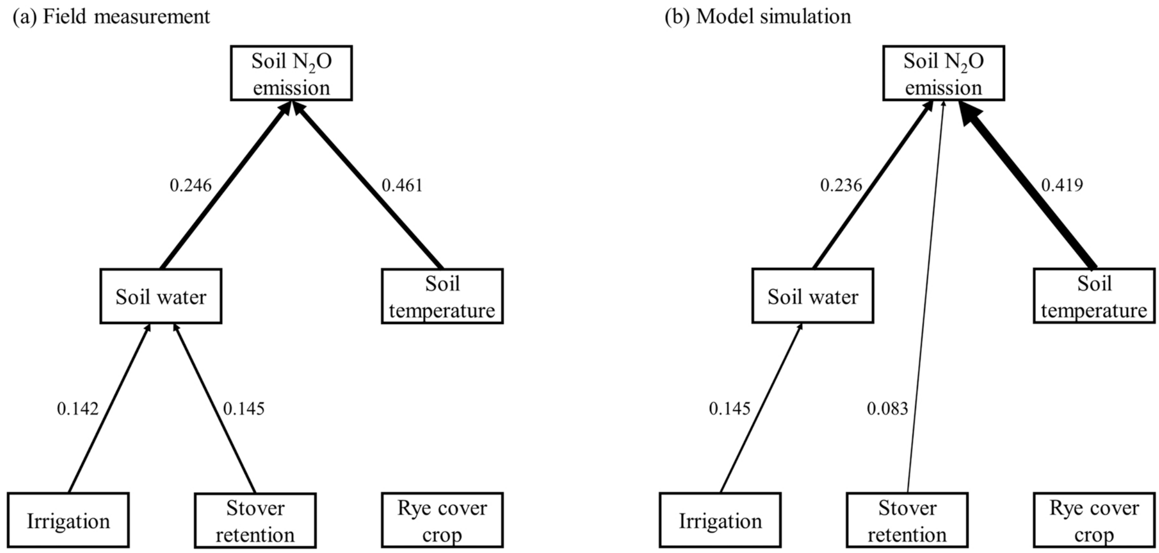

Fig. 8. Structural equation modeling for effects of management on daily soil N_2O emissions with field measurement (a) and RZWQM2 simulation (b). Boxes represent variables, and arrows causal relationships. Numbers beside arrows are standardized path coefficients (*i.e.*, effect size). All the pathways were significant at $p < 0.01$. See Table 2 for total effects.

Table 3
Standardized total effects of management on daily soil N_2O emissions.

		Irrigation	Stover retention	Cover crop	Soil VWC	Soil temperature
Soil N_2O	Measured	0.035	0.036	0.000	0.246	0.461
Soil VWC		0.142	0.145	0.000	-	0.000
Soil N_2O	Simulated	0.034	0.083	0.000	0.236	0.419
Soil VWC		0.145	0.000	0.000	-	0.000

See Fig. 8 for individual pathways.

attributed to the lower C/N ratio of vetch residues (Fiorini et al., 2020). Rye cover crop may have not significantly reduced N_2O emissions but is effective for erosion control, reducing nitrate loss, increasing earthworm population, *etc*. (Korucu et al., 2018; Otte et al., 2019; Sainju et al., 1998; Waring et al., 2020).

5. Conclusions

We measured soil N_2O emissions for nine years in a continuous corn system under the effects of irrigation, stover retention, and winter rye cover crop. Our results show that lower irrigation amount decreased daily soil N_2O emissions by decreasing soil water content compared to higher irrigation amount. Soil water content controls oxygen availability and substrate mobility and thus affects nitrification and denitrification. Compared to stover retention, stover removal decreased daily soil N_2O emissions. Although the low biomass return from winter rye cover crop used here did not significantly reduce daily soil N_2O emissions, winter rye cover crop combined with deficit irrigation decreased annual soil N_2O emissions. The RZWQM2 captured these management effects on daily soil N_2O emissions as evaluated by structural equation modeling. The use of structural equation modeling provides a novel approach to evaluate whether model simulations are capturing relationships rather than just individual variable response. This is a unique contribution to better understanding model performance, in addition to the more traditional measures of performance. Overall, our study revealed the mechanisms of how field management affects N_2O emissions from agricultural soils and can help inform mitigation strategies and better constrain the global N_2O budget from agricultural production.

CRediT authorship contribution statement

Lidong Li: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Liwang Ma:** Software, Validation, Writing – review & editing. **Zhiming Qi:** Software, Validation, Writing – review & editing. **Quanxiao Fang:** Software, Validation, Writing – review & editing. **R. Daren Harmel:** Methodology, Validation, Writing – review & editing. **Marty R. Schmer:** Project administration, Resources, Supervision, Validation, Writing – review & editing. **Virginia L. Jin:** Conceptualization, Data curation, Funding acquisition, Project administration, Resources, Supervision, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2023.126807.

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