Extreme Climate Increased Crop Nitrogen Surplus in the United States

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Abstract Increasing extreme climate conditions present significant threats to crop nitrogen (N) management and environmental conservation in the United States. Previous studies have examined the impacts of extreme climate on crop production but often overlooked its impacts on N loss from agricultural areas to the environments. Here we examine the relationship between county-level N surplus (the part of N that is not recovered by crops) and extreme climate conditions for corn in the U.S. from 1981-2016. We adopt multi-source long-term survey datasets of corn N budget and growing season (defined from May to August) maximum temperature and precipitation for each corn-planting county. Compared with the long-term N surplus trend, we find a 51% and 47% increase in corn N surplus associated with extremely high temperature and extremely low precipitations, respectively. A moderate N surplus increase (20%) is associated with extremely high precipitations, while a 14% N surplus decrease s shown to be related to extremely low temperatures. Across the U.S., the Midwest and the Northern Great Plains are identified as N surplus hotspots when extreme climate conditions occur. As the major corn-planting region, the Midwest on average yields 0.103 Tg yr^{-1} N surplus during extreme climate conditions. This amount is comparable to the annual total N surplus (0.1 Tg yr^{-1}) yielded in the Northeast region. Our results highlight the urgency of understanding the impacts of extreme climate conditions on crop nutrient losses and identifying the effective intervention practices to adapt to more frequent climate extremes in the future.

Key Words crop nutrient management, extreme climate, crop nitrogen surplus, county level, the United States

1 Introduction

Extreme climate has nonadditive effects on agricultural nitrogen (N) losses (Iqbal et al., 2018). Over the recent decades, extreme weather-induced agricultural N losses have been reported in many regions across the globe (El-Khoury et al., 2015; Gao et al., 2014; Wagner-Riddle et al., 2017). As the home of more than 30% of global corn production, the United States has experienced significant increases in extreme weather events, including but not limited to extremely hot, dry, and wet conditions, since the 1980s (Groisman et al., 2005; Janssen et al., 2014; Kunkel et al., 1999; Mazdiyasni and AghaKouchak, 2015). These extreme climate events have already caused substantial crop yield loss in the U.S. (Lobell et al., 2014, 2013; Schlenker and Roberts, 2009; Troy et al., 2015; Zipper et al., 2016). Corn's yield closely relates to its annual N surplus (N that is not utilized by crops and potentially reflects N losses to air and water systems) (Lu et al., 2019). Therefore, crop failures in extreme climate years can potentially cause a large amount of N surplus in the soils due to the declined crop N uptake. A large amount of residual N in the soil will likely be lost into the environments (e.g., air and water systems) and consequently cause environment quality degradation.

Many studies have already demonstrated that N loss (e.g., through nitrate leaching and N_2O emissions, etc.) often increases with changes in precipitation (Schwenke and Haigh, 2016; Zhao et al., 2016) and temperature (Jabloun et al., 2015; Marhan et al., 2015). On the other hand, N is comparatively more soluble and movable than other nutrients and so can more easily disperse to the environment following extreme weather events. By altering global hydrological cycling, warmer climates will likely intensify precipitation extremes with less frequent rainfall (Kirtman et al., 2013). Consequently, declined summer rainfall accompanied by higher air temperatures could form droughts more rapidly and severely (Trenberth et al., 2014). In particular, extreme rainfall following severe drought events can accelerate agricultural N loss. For example, heavy precipitation after a multi-year drought could potentially increase the likelihood of N leaching by 40% to 65% due to the accumulated soil N during the prior drought period (Lee et al., 2016). Additionally, heatwave and drought together will rapidly harm crop growth and yield, compared with each event alone (Jin et al., 2017), leading to a greater risk of N losses (Bowles et al., 2018).

Despite its environmental importance, few studies have examined the historical response of crop N surplus to various extreme climate types across regions because of the inconsistency of spatiotemporal scales between the agricultural N use data and the extreme climate records. For example, the crop N fertilizer (e.g., synthetic and manure fertilizer) data are often available at the national and state levels (Lassaletta et al., 2014; Lu et al., 2019; Zhang et al., 2015), which covers a large spatial extent. However, extreme weather can occur across various spatial scales (e.g., from local to regional scales). Current crop N input data with coarse spatial resolutions cannot be easily downscaled to match with the fine resolution of extreme climate events. Furthermore, the crop N fertilizer data are often temporally discontinuous, whereas the climate data that are used to detect extreme weathers are usually continuous across space. Such discontinuity in crop N fertilizer data also largely varies with political units, adding an additional level of complexity to the crop N budget estimates. Therefore, the inconsistency in data's spatial and temporal resolutions remains challenging to explore the relationship between crop N surplus and extreme climate conditions. It remains unclear how the dynamic of crop N surplus is affected by extreme climate conditions.

In this study, by using county-level long-term datasets of extreme climate and corn N inputs and outputs, we address this knowledge gap and evaluate corn (*Zea mays L.*) N surplus associated with four types of extreme climate in the U.S. from 1981 to 2016. The extreme climate types include extremely low and high precipitations as well as extremely low and high maximum temperatures. We also investigate the regional patterns of corn N surplus associated with these four extreme climate conditions. Finally, we discuss the possible mechanisms of climate conditions in determining corn N surplus. The following questions have guided this study: (*i*) to what extent have extreme climate affected corn N surplus? (*ii*) how have corn N surplus responses to extreme climate conditions varied spatially and temporally across the U.S.? and (*iii*) what are the dominant drivers responsible for corn N surplus changes when extreme climate conditions occur?

2 Data and Methods

2.1 Data

2.1.1 Crop yield data and N harvesting coefficients

We obtained county-level corn grain yield and planting area data from 1981 to 2016 from the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) database (https://quickstats.nass.usda.gov/). The NASS crop yield dataset has been widely used in many agriculture and environmental studies (Grassini et al., 2013; Kucharik and Ramankutty, 2005; Lu et al., 2019; Schlenker and Roberts, 2009; Troy et al., 2015; Zipper et al., 2016). By using the N harvesting coefficient provided by the Nutrient Use Geographic Information System (NuGIS, http://nugis.ipni.net/), we first used corn yield data to estimate recovered N in corn grain. Then we calculated the difference between total N input, to be explained below, and the recovered N to represent corn N surplus for each county. The detailed calculation is introduced in section 2.2.

2.1.2 Nitrogen input sources

We considered four major N input sources for corn in our study, including synthetic N fertilizer input, atmospheric N deposition, manure N input, and residual N from previous-year soybean fixation. These N input rates were first summed and then multiplied by the corn planting area to represent the annual total N input amount at a county level.

N fertilizer data: Corn N fertilizer consumption data from 1981-2016 were developed based on a recently published dataset (Cao et al., 2018). The county-level corn N fertilizer use rate was reconstructed by harmonizing the data sets of state-level corn N fertilizer use rate, county-level total N fertilizer consumption, and time-series gridded crop distribution maps. The total N fertilizer consumption was estimated based on the county-level N fertilizer sale data provided by the NuGIS. Details on the development of county-level crop N fertilizer use rate can be found in Cao, Lu, & Yu, (2018), Lu et al., (2019), and Zhang, Cao, & Lu (2021).

Manure N application data: We obtained the county-level total manure data from the NuGIS database and gap-filled the missing years based on national-level manure N use as calculated from FAO data (http://www.fao.org/faostat/en/#data/EMN). The FAO data maintain the inter-annual variations of manure N use. Then we obtained the state-level crop-specific manure use rate from USDA-ERS (https://www.ers.usda.gov/) and county-level planting area data from USDA-NASS. Missing gaps in the planting area data were filled respectively by a cubic spline approach and a distance-weighted interpolation method when missing years were less than and equal to and greater than three consecutive years (Cao et al., 2018). Then a factor was used to adjust the county-level crop-specific manure application rates. This factor was calculated as:

$$f_i = T_{i,NuGIS} / \sum (M_{i,j} \times A_{c,i,j}) \qquad (1)$$

where $T_{i,NuGIS}$ is the total manure amount for county i as obtained from the NuGIS database, $M_{i,j}$ is the state-level crop-specific manure application rate per acre for crop type j in county i as obtained from the USDA-ERS dataset, and $A_{c,i,j}$ is the planting area of crop j in county i as obtained from the USDA-NASS database. The final county-level corn manure application rate was calculated as:

$$M'_{i,corn} = M_{i,corn} \times f_i \qquad (2)$$

where $M_{i,corn}$ is the state-level corn-specific manure application rate and f_i is the adjustment factor calculated by equation (1). Details on the development of county-level manure fertilizer rate can be found in Cao, Lu, & Yu, (2018), Lu et al., (2019), and Zhang, Cao, & Lu (2021).

Atmospheric N deposition data: Total N deposition data at a 4-km × 4-km resolution for the period 2000 to 2015 were obtained from the National Atmospheric Deposition Program (NADP, http://nadp.slh.wisc.edu/committees/tdep/tdepmaps/). In this study, we assumed that the 2016 N deposition remained at the same level as 2015. We resampled the NADP N deposition to 5-arc-min × 5-arc-min maps in ArcMap 10.7 (ESRI, 2019). The spatial N deposition for the period 1981-1999 was based upon the N deposition trend developed by EDGAR (Dentener, 2006; Wei et al., 2014) by taking the NADP N deposition in 2000 as the endpoint. The corn-specific N deposition for each county was extracted based on 5-arc-min time-series crop distribution maps that were aggregated from 1-km land-use maps (Yu and Lu, 2018). During the development of the land-use maps, the county-level harvested area of each crop type in each year was kept consistent with the county-level survey records provided by NASS, USDA (http://www.nass.usda.gov/index.asp).

N residues from previous-year soybean fixation: Soybean-corn rotation systems predominate in many U.S. corn-growing states. We considered the residual benefit of N fixation from the previous year's soybean cultivation when calculating county-level corn N surplus. By using the Crop Data Layer (CDL, https://www.nass.usda.gov/Research_and_Science/Cropland/Release/index.php) land use and land cover data, we first estimated the percentages of national soybean area used for rotation with corn from 2008 to 2017. The corn-soybean rotation was identified in pixels where crop sequences follow “soybean-corn-soybean”, “soybean-corn-corn”, or “soybean-soybean-corn” in three consecutive years. A 93% and 91% of U.S. soybean acreage was reported to rotate with corn in 1993 (https://www.ers.usda.gov/webdocs/publications/41882/30078_arei4-2.pdf?v=0) and 1997 (Padgitt et al., 2000), respectively. Soybean farming in the U.S. started in ~1940 (https://ncsoy.org/mediaresources/history-of-soybeans/). Therefore, we assumed that soybean was 100% used to rotate with corn in 1940. We then interpolated the national area percentages of soybean rotating with corn in the gap-years, including 1940-1992, 1994-1996, and 1998-2007, by assuming a linear changing trend during the periods of 1940–1993, 1993–1997, and 1997–2008. We then estimated the residue of soybean-fixed N for corn in each county using the interpolated corn-soybean rotation area percentage. Details on the calculation of residual N from previous-year soybean fixation can be found in Lu et al., (2019) and Zhang, Cao, & Lu (2021).

2.2 Calculation of county-level corn N surplus

N surplus has been extensively used to assess excessive N input beyond crop N demands, and the potentials for agricultural N loss (De Notaris et al., 2018; Nett et al., 2011; Wachendorf et al., 2006). In this study, the N surplus (in units of kg N ha^{-1} yr^{-1}) was estimated as total N input minus corn recovered N in a given year. We first calculated the corn-recovered N by multiplying grain yield by a corn N recovery coefficient that indicates how much N is retained in the grain per unit yield. The N recovery coefficient, 0.012 kg N kg^{-1} grain that was obtained from the NuGIS, was used as a constant that does not vary with corn growing conditions or extreme climate conditions due to the lack of such information. N recovery from previous years’ N surplus was not considered in this study. Therefore, the N surplus defined in this study solely refers to the potential maximum N loss from agricultural systems to the environments.

2.3 Climate data and definitions of extreme climate

Extreme climate conditions in our study were defined as the county-level standardized anomaly of growing season (defined from May to August for corn) total precipitation and mean maximum temperature from 1981-2016 as developed by Li et al. (2019). The data of these two climate variables were originally obtained from the PRISM climate dataset (Daly et al., 2008). The standardized anomaly (known as the z-score) for these two variables was calculated as the departures from their multi-year average in a given year. To ensure the consistency of the county-year sample size during extreme climates, we defined extremely low and high precipitations as standardized anomalies lower than -2.0σ and larger than $+2.5\sigma$, respectively (Figure S1). These two extreme precipitation conditions accounted for roughly 1% of all country-year samples (0.97% and 1.12% for extremely low and high precipitations, respectively, Figure S1). For the same reason, extremely low and high maximum temperatures (hereafter referred to respectively as extremely low temperature and extremely high temperature) were also defined as standardized anomalies less than -2.0σ and larger than $+2.5\sigma$, respectively (Figure S1). These two extreme temperature conditions accounted for slightly over 1% of all country-year samples (1.27% and 1.31% for extremely low and high temperatures, respectively, Figure S1). Moderately low and high precipitations, as well as moderately low and high temperatures, were defined as standardized anomalies ranging from -2.0σ to -1.0σ and from $+1.0\sigma$ to $+2.5\sigma$, respectively (Figure S1). The standardized anomalies of these two climate variables ranging from -1.0σ to $+1.0\sigma$ were defined as non-extreme conditions (Figure S1).

To explore the non-additive impacts of precipitation and temperature on N surplus, we also identified county-year samples with the simultaneous occurrence of two extreme conditions. These conditions include extremely low temperature plus extremely high precipitation (0.09% of all county-year samples) and extremely high temperature plus extremely low precipitation (0.38%). We simply ignored extremely low temperature plus extremely low precipitation and extremely high temperature plus extremely high precipitation conditions since none of the county-year samples was detected as these two types. The identified county-year samples were used to calculate the state-level N surplus change weighted by the planting area to indicate the overall contributions of these extreme climate conditions on corn N surplus in the U.S.

2.4 N surplus associated with extreme climates

The county-level N surplus rate (in the unit of g N m^{-2} yr^{-1}) associated with each extreme climate type was calculated as a multiple-year average when the extreme climate was identified. We also calculated the N surplus percentage change for each county as a standardized indicator to compare across regions. The historical corn yield in the U.S. has a long-term increasing trend owing to improvements in technology, seeds, and management (Li et al., 2019). A recent study demonstrates that corn yield in 381 counties (20% of corn-growing counties) in the U.S. experienced a non-linear trend during the period 1970-2016, and these counties disperse all over the U.S. (Kucharik et al., 2020). Since crop N recovery is closely related to yield, we assumed that crop N surplus would maintain a dichotomously non-linear trend if the yield changes non-linearly over time. We used a general additive model (GAM) to estimate the non-linear trend of corn N surplus for each county separately (Figure S2). This nonlinear trend was used to calculate N surplus percentage change for each county as equation (3) (Figure S2):

$$\Delta Nsurplus_{i,j}\ \% = \frac{(Nsurplus_{i,j} - Nsurplus_{GAM,i,j})}{Nsurplus_{GAM,i,j}} \times 100\% \quad (3)$$

where $\Delta Nsurplus_{i,j}\ \%$ is the N surplus percentage change in county i in year j, $Nsurplus_{i,j}$ is the N surplus rate in county i in year j, and $Nsurplus_{GAM,i,j}$ is the GAM-estimated N surplus in county i in year j. The percentage change represents the N surplus departure from the long-term trend determined by the combined environmental changes, including but not limited to climate variability, crop technology improvement, and farmers' management practices (e.g., fertilizer input, manure application, and corn-soybean rotations), etc. Here we examined the relationship between the extreme climate conditions and corn N surplus deviation away from the trend.

For an individual county, the annual average N surplus and N surplus percent change associated with each extreme climate type were estimated as the average over the identified extreme years, representing an average condition over the studied 36 years. The state- and national-level N surplus percent change were calculated by averaging all county-year samples based on an area-weighted approach (i.e. county's harvest area). The N surplus percentage change was then grouped to the corresponding temperature and precipitation anomaly bins at an interval of 0.5σ (Figure 1a), spanning from extremely low to extremely high precipitations as well as from extremely low to extremely high temperatures, respectively.

We also calculated the regional annual average total N surplus (unit in Tg N yr^{-1}) associated with each extreme climate type as equation (4):

$$N_{surplus}^{R} = \frac{\sum_{\substack{0 \le j \le 36 \\ 0 < i < n}} (Nsurplus_{i,j}^{R} \times A_{i,j}^{R})}{36} \quad (4)$$

where $N_{surplus}^{R}$ is the total N surplus amount in agricultural region R, $Nsurplus_{i,j}^{R}$ is N surplus rate in county i in year j within agricultural region R, and $A_{i,j}^{R}$ is the corn harvesting area in county *i* in year *j*, identified as an extreme climate year, within agricultural region *R* ranging from 1 to 7 (representing the Northeast, Southeast, Northwest, Southwest, Northern Great Plains, Southern Great Plains, and Midwest). The regional total N surplus was used to represent an average N surplus amount associated with each extreme climate type in each agricultural region. We present the regional total and climate extreme-specific N surplus in section 3.2 (Figure 3).

3 Results

3.1 The impacts of extreme climate on corn N surplus

We aggregated the N surplus change from county-year samples to the national scale to represent precipitation impacts on corn N surplus (Figure 1a). We found that non-extreme precipitations (precipitation anomaly ranging from -1.0σ to $+1.0\sigma$) were associated with negligible to small negative N surplus changes (up to 7% below long-term average). However, the below-average N surplus shifted to an above-average regime when precipitation deviated from normal toward drier and wetter conditions. Corn N surplus associated with extremely low (precipitation standardized anomaly $<-2.0\sigma$) and extremely high ($>+2.5\sigma$) precipitations substantially increased on average by 47.5% and 20.4%, respectively (Figure 1a). In particular, the precipitation with standardized anomaly $>+3.5\sigma$ could increase N surplus by 32.3%, and the precipitation with standardized anomaly $<-2.5\sigma$ was potentially associated with a 56% increase in corn N surplus with a large variation over years and space.

The corn N surplus percentage change associated with temperatures summarized from county-year samples showed a skewed pattern (Figure 1b). Specifically, the non-extreme temperature conditions (standardized anomaly ranging from -1.0σ to $+1.0\sigma$) reduced the corn N surplus by 1.4%. When temperature deviated from normal toward moderately low levels ($>-2.0\sigma$), corn N surplus demonstrated a small decrease (9% at most). The declines in corn N surplus reached up to 14% when the temperature was 2.5σ below average (i.e., extreme cold), indicating that lower temperature might decrease corn N surplus. However, when growing-season temperature deviated toward moderately high (+1.0σ to +2.5σ) and extremely high levels (>+2.5σ), corn N surplus was shown to be approximately 20% and 51% higher than the long-term trend, respectively. In particular, our analysis displays that temperatures with standardized anomaly >+3.5σ were associated with an N surplus increase of up to 55%.

Interactions between extreme temperature and precipitation showed that the extremely high temperature plus low precipitations had a stronger association with the increase in corn N surplus (Figure 1c). A median corn N surplus increase of 49% (interquartile range-IQR from 34% to 56%) was found under this extreme condition, with most county-year samples experienced increases in N surplus (Figure 1c). In contrast, the median corn N surplus was around 10% (IQR from -33% to 5%) below the long-term average under the extremely low temperature plus high precipitations, with a slight number of counties showing N surplus increases. Additionally, more than half of the county-year samples showed decreases in corn N surplus under this extreme climate condition (Figure 1c), indicating that cooler and wetter climate conditions likely help reduce crop N surplus.

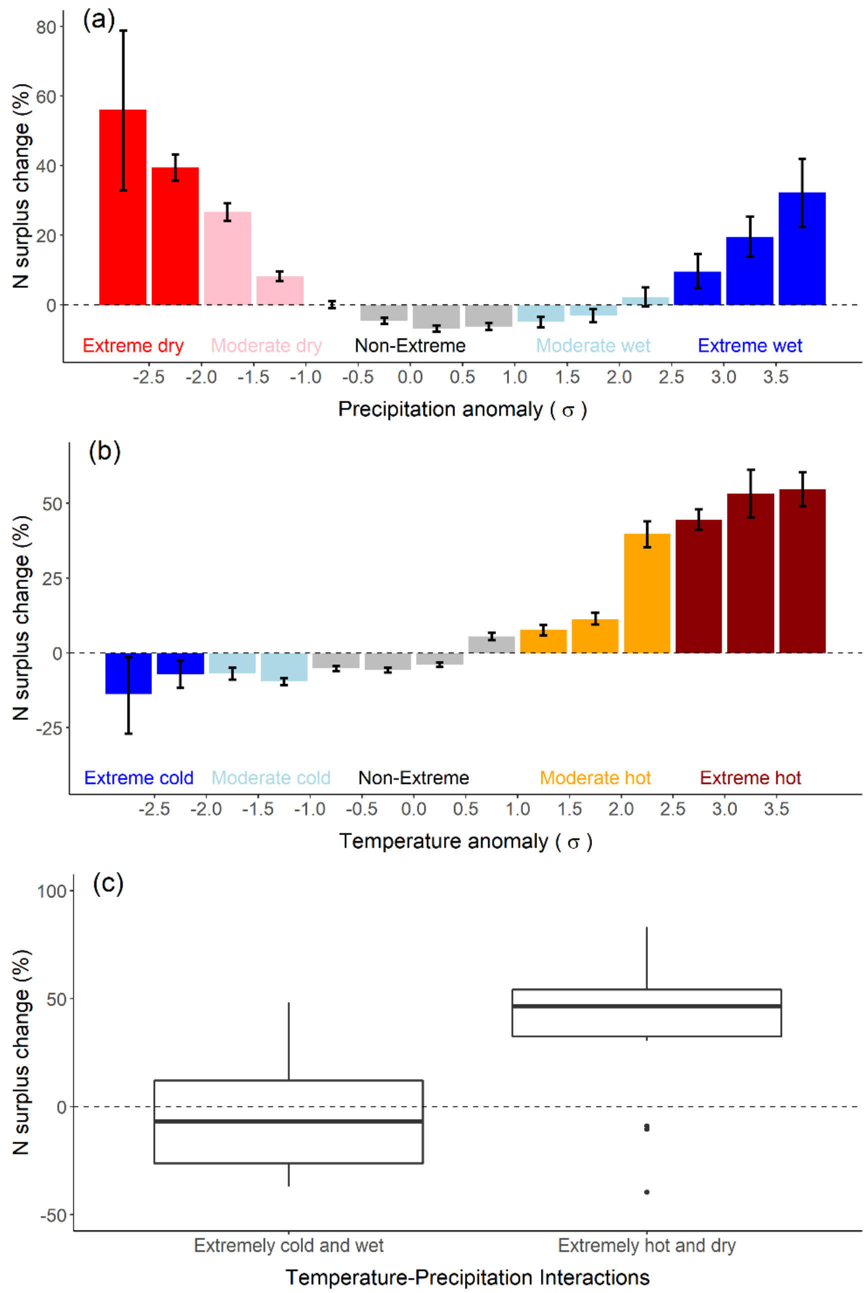

Figure 1. Corn N surplus percentage change associated with extreme climate conditions (single and combined climate variables). Corn N surplus percentage change associated with growing season precipitation anomaly (a) and growing season temperature anomaly (b) from 1981 to 2016. (c) Corn N surplus percentage associated with extremely low temperature and extremely high precipitation as well as extremely high temperature and extremely low precipitations from 1981-

2016. Each bar in (a) and (b) represents the N surplus change weighted by planting area from county samples in the corresponding precipitation and temperature anomaly range from 1981-2016, respectively. Error bars in panels a and b denote the 95% confidence interval estimated from 1,000 bootstrap draws. The boxplot in panel c denotes the interquartile range (IQR), the minimum and the maximum (the 25th percentile – 1.5×IQR and the 75th percentile + 1.5×IQR), and the outliers.

3.2 The spatial patterns of corn N surplus associated with extreme climate

The corn N surplus associated with extremely low and high precipitations varied across space (Figure 2a,c). Generally, N surplus ranged from 5 g N m^{-2} yr^{-1} (North Dakota) to 15 g N m^{-2} yr^{-1} (Kansas) under extremely high precipitations, and it ranged from 2 g N m^{-2} yr^{-1} (South Dakota) to 20 g N m^{-2} yr^{-1} (Illinois) under extremely low precipitations. The corn N surplus change under extremely high precipitations was spatially variable, with increases mainly found in Iowa, Minnesota, Nebraska, North Dakota, and Kansas (Figure 2b). On the other hand, a consistent N surplus percentage increase was found in most regions when extremely low precipitations occurred (Figure 2d). N surplus in some major corn-producing states in the U.S. (e.g., Illinois, Indiana, Ohio, and Michigan) were severely affected by extremely low precipitations. For example, it ranged from 5 g N m^{-2} yr^{-1} in Michigan to >20 g N m^{-2} yr^{-1} in Ohio (Figure 2c), which were respectively about 30% and 133% of the national long-term average corn N fertilizer use rate (15 g N m^{-2} yr^{-1}, averaged from 1980-2015) (Cao et al., 2018).

The corn N surplus associated with extremely low and high temperatures also showed a large spatial variation (Figure 2e,g). Specifically, corn N surplus was more spatially variable when extremely low temperatures occurred throughout the U.S. (Figure 2e). For example, increased N surplus percentage was found in northern states, including Minnesota, North Dakota, and

Wisconsin, and decreased N surplus in southern states, including Kansas, Tennessee, Kentucky, and Virginia (Figure 2f). However, a consistent N surplus percentage increase was found in most regions when extremely high temperatures occurred (Figure 2h). Under this extreme condition, the major corn-producing states (e.g., Illinois, Iowa, Minnesota, Missouri, Dakotas, Nebraska, and Wisconsin) experienced a large N surplus rate, ranging from 2 g N m^{-2} yr^{-1} in Dakotas to >20 g N m^{-2} yr^{-1} in Missouri (Figure 2g), which respectively accounts for 13% and >133% of the national long-term average N fertilizer use rate (Figure 2h).

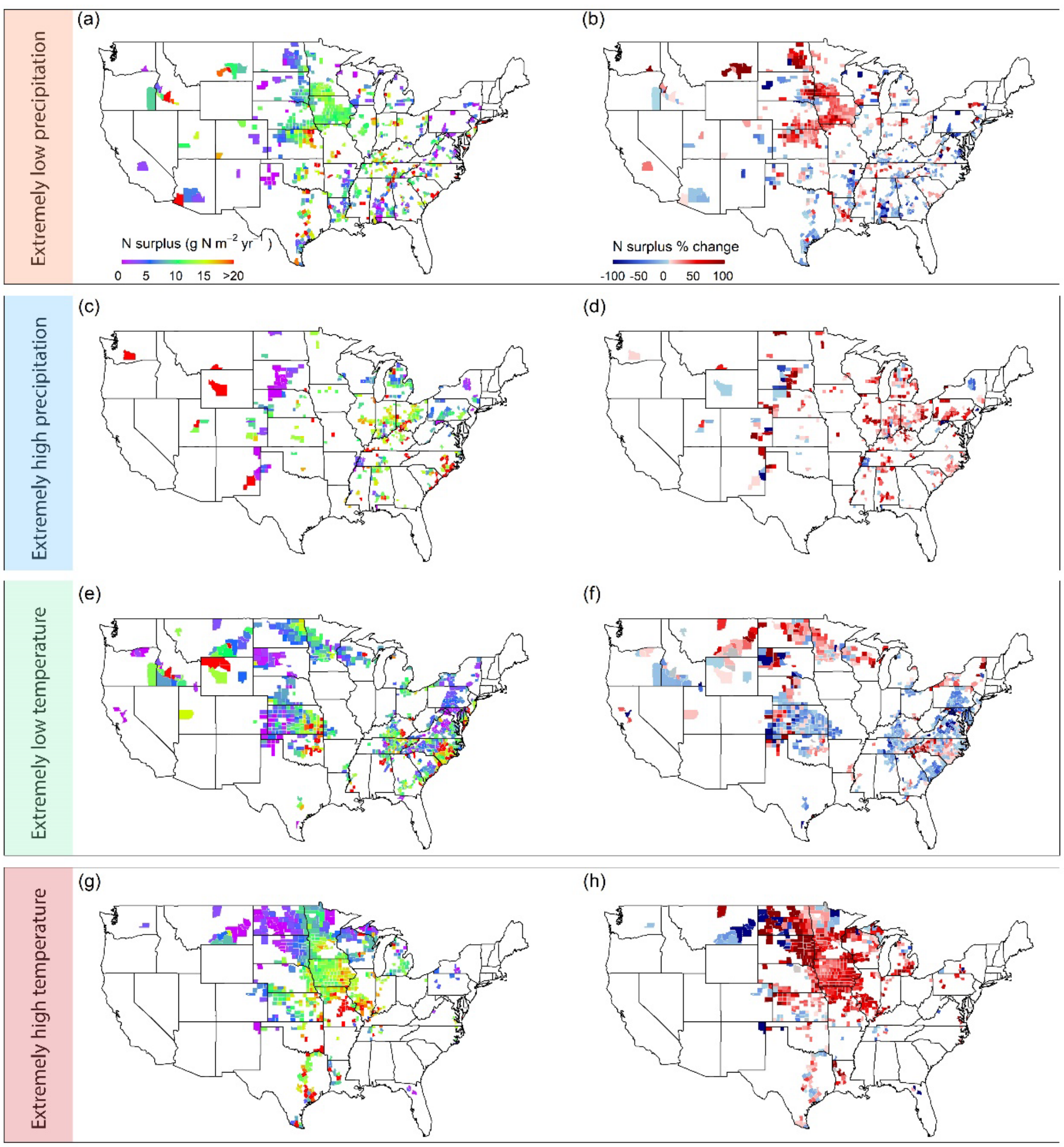

Figure 2. Corn N surplus amount (a, c, e, g) and its percentage change (b, d, f, h) averaged over extreme years from 1981 to 2016. Panels indicate climate conditions, including extremely low precipitation years (a-b), extremely high precipitation years (c-d), extremely low temperature years (e-f), and extremely high temperature years (g-h). The amount of N surplus is calculated as planting area-weighted average N surplus from all extreme years during the study period in each county. The N surplus percentage change is calculated as the ratio of extreme-year average N surplus amount to the long-term average. White areas indicate no data because of either lacking planting activities or no extreme climate detected.

We aggregated corn N surplus in the years with extreme climate from county-level to regional-scale and calculated the yearly average for the seven regions (e.g., Northwest, Southwest, Northern Great Plains, Southern Great Plains, Midwest, Northeast, and Southeast) in the lower U.S. Despite small areas experiencing extreme climate conditions, they together contributed 3% to 6% of the regional total N surplus, with a large variation among regions (Figure S3). Not surprisingly, producing 49% of national corn, the Midwest yielded an annual average of 0.103 Tg N yr^{-1} N surplus during extreme years only, ranking the first place among the seven regions (Figure 3). Among extreme climate conditions, extremely high temperatures accounted for 36% of the regional total N surplus during extreme years; extremely high precipitations and extremely low precipitations plus extremely high temperatures respectively accounted for 24% and 22%, followed by extremely low precipitations (13%) and extremely low temperatures (5%). The Northern Great Plains (NGP) yielded ~0.025 Tg N yr^{-1} N surplus during extreme years only (Figure S3). Specifically, extremely high temperatures contributed the most (36%) of the regional total N surplus during extreme years, followed by extremely high precipitations (27.8%). Extremely high temperatures plus extremely low precipitations, extremely low temperatures, and extremely low precipitations respectively contributed to 17%, 11%, and 8% of the regional total N surplus aggregated from extreme county-year samples. Extremely high precipitation plus extremely low temperatures only yielded 0.2% of the regional total N surplus during extreme years (Figure 3). Extreme county-year samples in the other five regions sum up to less than 0.02 Tg N yr^{-1} N surplus (e.g., 0.009 Tg N yr^{-1} in the Southern Great Plains, 0.01 Tg N yr^{-1} in the Southeast, 0.001 Tg N yr^{-1} in the Southwest, 0.002 Tg N yr^{-1} in the Northeast, and 0.0004 Tg N yr^{-1} in the Northwest) (Figure S3), which makes their pie charts negligible compared with the Midwest and the NGP regions.

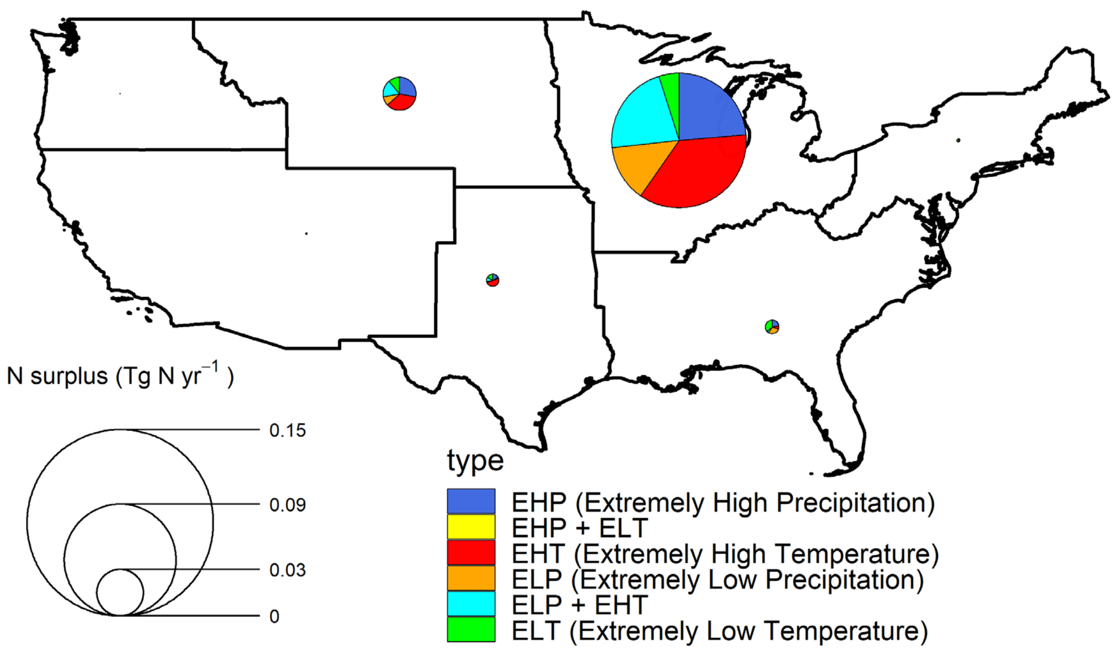

Figure 3. The annual average N surplus from 1981 to 2016 aggregated from counties with extreme climate conditions to the seven regions in the U.S. Because the N surplus in the Northwest, Northeast, and Southwest regions was very small, the pie chart details in the three regions cannot be shown as explicit as in the other regions.

3.3 Explanatory factors for the regionally varying impacts of extreme climate conditions

We compared the corn N surplus change associated with extreme climate conditions among climate groups indicated by growing season average temperature and total precipitation. Using the long-term average temperature and precipitation, we divided the county-year samples into five climate groups (i.e. dry: precipitation from 0-350 mm yr^{-1}, wet: precipitation 350-700 mm yr^{-1}, cold: temperature between 19-25°C, warm: 25-32°C, and hot: 32-39°C). In extremely low precipitation years, the increases in corn N surplus of the wet counties were significantly higher than that of the dry counties ($p< 0.05$, Figure 4a), while it showed no significant difference among temperature groups (Figure 4b). This finding indicates that corn N surplus in wet regions may be more sensitive to drought conditions.

In contrast, during extremely high precipitation years, corn N surplus only showed an insignificant difference among precipitation groups (Figure 4c), while it was significantly different among temperature groups ($p<0.01$), with a negative N surplus change found in the hot climate group (Figure 4d). This is likely due to the beneficial effects of extremely high precipitations to crop growth by fulfilling crop water demand and mitigating heat stress due to the high evaporation (Li et al., 2019).

Corn N surplus change along with the climate groups showed a contrasting pattern when extremely low temperatures occurred (Figure 4e,f). Specifically, the corn N surplus changes were below the average in the wet counties (Figure 4e) and the warm and hot counties (Figure 4f). under extremely low temperatures, corn N surplus in these counties was significantly lower than that in drier and colder counties. This finding implies that the reduced growing season temperature could benefit corn growth and its N uptake by decreasing the water deficiency in warmer and wetter regions (Goldblum, 2009).

In extremely high temperature years, wet corn-planting counties had significantly higher N surplus change (30%-40%) than the dry counties ($p<0.0001$, Figure 2g). However, hot counties had the smallest N surplus increase that was significantly lower than those in the cold and warm counties (Figure 2h). Our findings suggest that extremely high temperatures likely play a smaller role in enhancing N surplus in the southern states with hot and dry climates than in the rest of the regions, which might be due to climate adaptation practices such as irrigation and improved genetics (Carter et al., 2016).

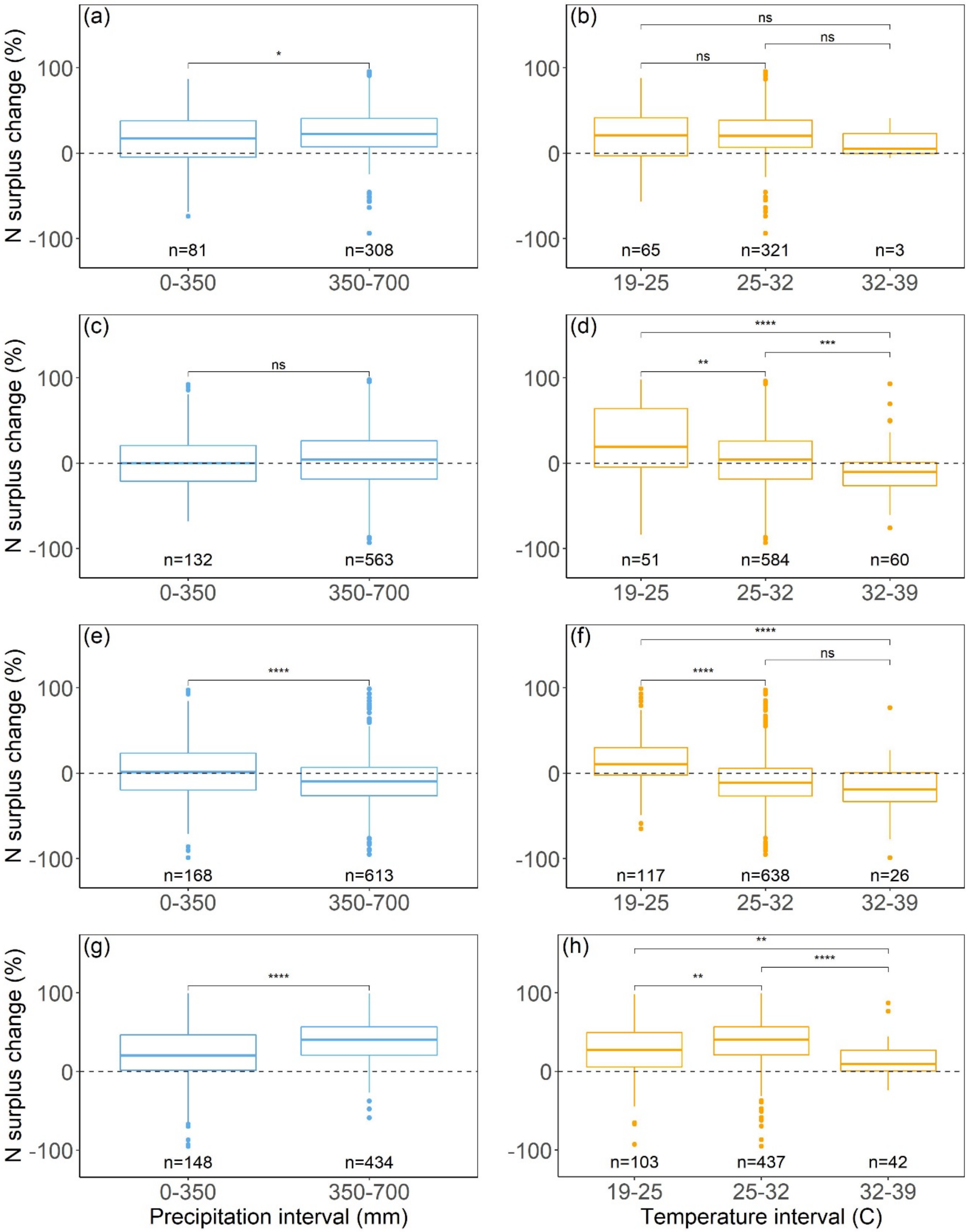

Figure 4. County-level corn N surplus percent change along with the groups of growing-season precipitation (a,c,e,g) and growing-season average temperature (b,d,f,h) under extremely low precipitations (a,b), extremely high precipitations (c,d), extremely low temperatures (e,f), and

extremely high temperatures (g,h). In all box plots, the bounds of the box represent the 25th percentile (Q1 quartile) and 75th percentile (Q3 quartile), and the lower whiskers extend from the 25th percentile to the minimum value, whereas the upper whisker extends from 75th percentile to the maximum value. The dots in the boxplots represent values that are greater than 1.5 times the box width. Each "n" below the boxplots represents the number of county-year samples falling in the temperature or precipitation bin. Growing season precipitation and temperature are calculated as the long-term average from 1981 to 2016 in each identified county. Asterisks denote that the difference between each pair of mean values is significant, with one asterisk meaning the significance level of 95%, two means 99%, three means 99.9%, and four means 99.99%. The "ns" means no significant difference between the two mean values.

We also investigated the corn N surplus change along with climate groups when extreme temperatures and precipitation simultaneously occurred (Figure S4). Under extreme dry and hot conditions, corn N surplus percent change was significantly higher in the wet counties than in the dry counties ($p<0.0001$, Figure S4a), while it did not show any significant difference among temperature groups (Figure S4b). Besides, we did not find any significant difference in corn N surplus change among precipitation groups or temperature groups under extreme wet and cold conditions (Figure S4c,d). However, the mean corn N surplus was below average across all county groups under extremely wet-cold climate conditions. Our results indicate that a cooler and wetter condition might provide benefits to reducing N surplus, especially in counties with hot and dry growing seasons.

4 Discussion

This study provides a comprehensive analysis of N surplus associated with extreme climate conditions in the corn-growing counties in the U.S. using long-term data. We found that extremely low precipitation, extremely high precipitation, and extremely high temperatures were more associated with increases in corn N surplus (Figure 1). The interactions between extremely low precipitation and high temperatures had a larger impact on corn N surplus, compared with the interactions between extremely high precipitation and low temperatures (Figure 1). We found that the Midwest region, including major corn-producing states (e.g., Iowa, Illinois, and Indiana), produced the largest N surplus, with leading contributions of extremely low precipitation and extremely high temperatures (Figure 2). Furthermore, we observed that counties in wetter states yielded a larger N surplus when extremely low precipitation occurred, whereas counties in colder states tended to yield higher N surplus when extremely high precipitations occurred (Figure 3 and 4). However, large variations in corn N surplus existed among counties (Figure 4), indicating that specific environmental conditions and crop variety differences should be considered when making N management recommendations at local scales. This study provides insights for understanding and investigating the long-term impacts of extreme climate conditions on crop N surplus from the county to national scales.

4.1 Corn N surplus response to extreme climate

Our results demonstrated that increases in corn N surplus were magnified under extremely low precipitation, extremely high precipitation, and extremely high temperatures, implying that current corn hybrids may not be able to successfully take up N under these extreme climate conditions. Uneven seedling emergence can cause grain yield losses (Carter and Nafziger, 1990; Nafziger et al., 1991). Corn emergence requires approximately 100 to 120 growing degree units (GDUs) and usually occurs four to five days after planting under favorable weather conditions (Abendroth et al., 2011). If the low temperature or low precipitations exist, emergence may be delayed by several weeks, and the development of the root system is restricted by exposure to high temperatures and dry soils (Nielsen, 2002). Since the majority of N fertilizer is applied to cornfields one to two weeks before its planting (Lu et al., 2020), corn with delayed development and impaired root systems would leave the majority of applied N in the soils. An existing study has shown the significant linear positive relationship between N surplus and soil N pool size in a corn planting system (Grignani et al., 2007). Hence, subsequent extreme precipitation could flush out and eventually deliver the mobile soil N into the river system (Lee et al., 2016; Lu et al., 2020). Such heavy precipitation events can also physically harm crops in association with adverse weather events (e.g., hail and wind) (Li et al., 2019), which leads to further N surplus.

Our results also demonstrated that the combined drought and heat stress related to increases in corn N surplus across the U.S. (Figure 1c). The occurrence of extreme temperatures is known to impact corn tolerance to drought (Otegui and Andrade, 2000). One previous study showed that corn's tolerance to either drought or heat alone did not confer its tolerance to the combined drought and heat stress, indicating potential crop failure during the combined stress (Cairns et al., 2013). High temperatures can hurt the seed set, thereby limiting the number of days for photosynthesis during the ear establishment period and leading to reduced subsequent kernel set and kernel growth (Cantarero et al., 1999). Another experimental study carried out in northern Indiana showed that increased temperatures and vapor pressure deficit (VPD) during combined extreme heat and drought conditions in 2012 significantly reduced corn leaf photosynthesis (Roth et al., 2013). Additionally, although not significant, higher N input could further harm corn yield during drought conditions (Roth et al., 2013). The reduced leaf growth and impaired yield could potentially create a large amount of N surplus. The legacy N in agricultural lands likely exacerbates water and air quality and contributes to greenhouse gas emissions (Robertson and Vitousek, 2009; Van Meter et al., 2018). Our finding indicates that with the confounding effects from extreme climate conditions and high soil N content, the crop N surplus would be easily induced, and local stakeholders should cautiously consider the weather conditions for more sustainable agricultural N management.

4.2 Reasons for the spatial variability of corn N surplus across the U.S.

Corn N surplus associated with extremely high temperatures was centered in the Midwestern U.S. (e.g., 2.35 Mha in Iowa (~22% of total cropland area), 1.51 Mha in Minnesota (14%), and 0.97 Mha in Illinois (9%)) and was more spatially connected than that under other extreme stresses (Figure 2). Also, our results demonstrated that corn N surplus was increased to a similar level across contiguous counties, with the largest percentage increase found in Illinois (Figure 3d), indicating the homogeneous impacts of extreme heat on corn growth and N surplus. By raising VPD, extreme heat in this region was shown to have a stronger influence on corn water stress than low precipitation (Lobell et al., 2013). Consequently, extreme heat stress can largely suppress corn yield (Schlenker and Roberts, 2009). Even though extreme heat would decrease soil moisture content and consequently reduce the likelihood of soil N leaching, soil residual N could be lost from cornfields to the atmosphere through N_2O emission that was shown to exponentially increase with temperature (Song and Zhang, 2009). Therefore, gaseous N loss is likely elevated by extremely high temperatures in corn-growing areas with high N fertilizer input.

Extreme droughts were robustly associated with the increases in N surplus across the U.S. corn-producing counties. For example, the major affected counties were mainly located in the rain-fed Midwest, including Illinois (0.2 Mha), Indiana (0.2 Mha), and Ohio (0.13 Mha), with a respective 50%, 24%, 18% increase in corn N surplus. While in Nebraska, where corn production heavily relies on irrigation, the drought-affected areas were relatively small (0.12 Mha) (Figure 3c,d). Other studies found that irrigation from groundwater pumping can significantly mitigate the impacts of drought on crop yield loss (Troy et al., 2015; Zipper et al., 2016). However, nitrate from irrigation return flow can lead to degraded water quality in streams and aquifer in the Great Plains regions (Dennehy et al., 2002). Our study did not consider the N sources from irrigation return flow in the irrigated corn-planting counties due to the lack of such information. Further research is required to investigate the impacts of irrigation on crop N surplus in intensive agricultural watersheds.

Our results also show that extremely high precipitation could cause variations (increases or decreases) in corn N surplus, depending on the region (Figure 2; Figure S5 and S6). Specifically, this extreme climatic condition largely increased N surplus in the Midwestern counties but decreased N surplus outside the Midwest (Figure 3a). Soil property was found to be a key factor in determining the impacts of excessive precipitations and low temperatures on corn yield (Li et al., 2019). Therefore, soil property could indirectly affect crop N surplus. Our results show that states with extensive application of tile drainage (e.g., Iowa and Minnesota) likely experienced higher N surplus during excessive precipitation. This suggests that artificially accelerated soil drainage in these areas may increase corn N surplus by bypassing N quickly through the soil column (i.e. soil N leaching). Another possibility in these states is that, when excessive precipitation occurs, crop roots are waterlogged in the soils without tile drainage. Consequently, crops would not grow normally to consume the applied N, leading to increases in N surplus. However, the annual data used in our analysis could not reveal further evidence due to the lack of seasonality of N surplus patterns. Within-season dynamics of crop N surplus and its relationship with extreme climate deserve further research.

Our analyses demonstrated that extremely low temperatures were associated with declines in corn N surplus, except in colder states like North Dakota and Minnesota (Figure 2c and Figure 4e,f). A significantly positive correlation between corn yield and growing season temperature was reported in Jilin, China (Chen et al., 2011), where the climate is generally colder (e.g., the annual mean temperature is 3-5°C). This finding indicates that temperature decreases may lead to declines in corn yield and consequently lead to increases in crop N surplus. This is likely the reason for the corn N surplus increases in colder states (e.g., North Dakota where annual mean temperatures range from 3-6 °C) under extremely low temperature conditions. On the other hand, maximum temperatures are usually associated with low atmospheric humidity and strong winds, which could cause depleted soil moisture through enhanced evapotranspiration, the main reason for summer drought (Dong et al., 2011). Therefore, reduced growing season maximum temperature could be beneficial to crop growth and N uptake in states with warmer growing seasons—like Kansas—by decreasing its water deficiency (Goldblum, 2009), leading to less crop N surplus.

4.3 Future agricultural management challenges during extreme climate

Over-used fertilizer leads to the enrichment of reactive N in the environment with consequent impairment of the recipient ecosystems (Byrnes, 1990; Harrison and Webb, 2001; Robertson and Vitousek, 2009; Smith et al., 1999). Agricultural management practices are often adopted to avoid using extra N while maintaining crop yield (Ju et al., 2009). For example, improving N management−like the “4R” principle (applying the right rate and right type of N fertilizer at the right timing and right place) and using previous legume crops−help increase crop nitrogen use efficiency (NUE) and reduce N losses (Randall and Mulla, 2001). A recent study has shown that corn NUE on average begins to decline when N fertilizer application rate exceeds 150 kg N ha^{-1} yr^{-1} (Lu et al., 2019). Another study has shown that commercial genetically engineered corn has higher NUE than traditional corn (Gallais and Coque, 2005). Therefore, when managing N fertilizer use at local fields, farmers should comprehensively consider the differences in NUE and tolerance to extreme climatic events among corn varieties.

Extreme precipitation events, which frequently occurred during early springs, have been shown to bring additional challenges to N loading reduction (Lu et al., 2020). Besides, fall-applied N for corn could contribute greatly to leaching N losses (Randall and Vetsch, 2005). By using computer modeling, Lu et al., (2020) showed that delayed N fertilizer application from spring to early summer, multi-time applications, and reduced fall application amount could greatly reduce the N loading to the Gulf of Mexico. This study highlights the benefit of fertilizer management and the importance of extreme rainfall events in reducing N loss. Corn grain yield in a corn-soybean rotation system with cover crops was much higher than in the conventional cropping system during an extreme drought year (Lotter et al., 2003), which is likely due to the higher soil water-holding capacity in the rotation-based system. On the other hand, higher than normal leachable nitrates and poor corn growth was found in the conventional system, suggesting that cover crops and crop rotations can largely reduce leachable nitrates (Lotter et al., 2003).

We also found a higher corn N surplus in major corn-producing states (e.g., Illinois and Iowa) during the extreme climate years than in the minor states (Figure 2; Figure S5 and S6). Existing studies pointed out that higher seeding density in the bigger corn-producing states likely led to greater yield sensitivity to drought (Li et al., 2019; Lobell et al., 2014). Higher N input rates and the large planting areas in these regions with intensive applications of tile drainage also lead to the hotspots of corn N surplus over decades (Zhang et al., 2021). Therefore, the stakeholders in the artificially drained agricultural watersheds (e.g., the Midwest) must consider the spatiotemporal patterns of extreme climatic events to better manage leachable N and maintain crop production

(Randall and Mulla, 2001). As extreme climate conditions will likely become more frequent and severe in the future (Cayan et al., 2010; Munoz and Dee, 2017; Wuebbles et al., 2014), optimal and sustainable crop nutrient management must be well understood as developing environmental guidelines to better mitigate agricultural N loss and environmental pollution.

4.4 Uncertainty

The data and methods adopted in our analysis have several limitations. First, the N recovery coefficient was assumed to not vary with climate conditions. Also, the N recovery coefficient would differ across corn-growing counties within the U.S. However, there is no systematic method that accounts for such variations with climate conditions and across space. Considering that the N recovery coefficient is provided by the latest survey, the estimated corn N surplus for the periods that were older than the survey time would be underestimated because old crop varieties had a lower unit production and weaker N recovery ability than the modern varieties. Therefore, the spatiotemporal patterns of county-level N surplus associated with extreme climate detected in our analysis serve as an effective starting point for future studies. Second, our study did not account for the previous year's soil residual N surplus (not from soybean fixation) that is available for corn to recover in the following year due to the lack of data. Existing studies have argued that plant N recovery from previous-year soil residual N is closely tied to the geophysical features and the weather conditions before the growing season (Powlson et al., 2009). Finally, our study only focused on corn grain N recovery and ignored recovered N by other compartments due to the lack of data. Abendroth et al., (2011) has shown that corn biomass as the leaf, tassel, stalk, etc. could account for about 70% of total recovered N during its vegetative stage. Therefore, corn N surplus induced by extreme climate conditions can be related to the recovered N in non-grain compartments. However, the productivity of corn compartments remains un-surveyed at the county level across the U.S., which is the challenge for such analysis. Future research may provide more insights in understanding the effects of previous-year N surplus legacy, and of the harvested N by other corn compartments on N surplus dynamics.

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Author contributions

C.L. and J.Z. conceived and designed the study. J.Z. performed the data analysis; J.Z. and C.L. led the data analysis and manuscript writing with contributions from H.F., D.H, Y.G., and M.M.W.

Data availability

The underlying corn nitrogen surplus data supporting the conclusions of this study can be found from our public data repository at https://doi.org/10.6084/m9.figshare.13030436.

Conflict of interest

The authors declare no conflicts of interest.

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