Estimation of nitrogen supply for a dryland spring maize sustainable production in northwest China

Xiaorong Wu
Junjie Li
Zhimin Li
Xuanke Xue
Yingfei Zhao
Xuemei Zhang
Baoping Yang
Zhikuan Jia
Xudong Zhang
Qingfang Han (hanqf88@126.com)
Northwest A&F University: Northwest Agriculture and Forestry University

Research Article

Keywords: Total nitrogen supply, Critical nitrogen curve, Sustainable production, Nitrogen use efficiency, N loss

Posted Date: April 13th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1509381/v1

Abstract

Purpose There are environmental problems related to excessive fertilization the intensive spring maize production. The nitrate accumulation in the soil at 1m before sowing (N soil) should be considered for nitrogen (N) supply sources to implement sustainable N management. As such, the goal of this study was to identify the optimal total N supply (TNS) to satisfy crop requirements while lower environmental impacts.

Methods Five different fertilizer rates (0, 120, 175, 230, and 285 N kg ha^{-1}) were conducted in a 3-year on-farm experiment. Integrated N nutrition index (NNIi), and relative yield (RY), plant N use efficiency ($NutE_{BY}$), and N leaching in response to the total N supply (TNS, from 155 to 416 kg ha^{-1}) were measured.

Results The relationships between TNS and NNIi, RY, $NutE_{BY}$, and N leaching firmly fit quadratic, linear-plateau, linear-plateau, and linear models. A suitable TNS can satisfy crop requirements was 327 kg ha^{-1}, a suitable TNS can obtain higher $NutE_{BY}$ and lower N leaching 315 kg ha^{-1}. Therefore, the applicable TNS rate should be between 315 to 327 kg ha^{-1}. However, the suitable NNIi should be 1.0, corresponding to the appropriate N fertilizer rate of 230 kg ha^{-1}. Considering the high soil N residual, sustainable N management should consider the consumption of N soil and the minimum application of N fertilizer to obtain higher yield and lower environmental impacts. ***Conclusion*** The TNS was proposed as an indicator to implement sustainable N management suitable for spring maize with similar climatic patterns in northwest China.

Introduction

The global population will reach 9 billion by 2050 (Cui et al., 2018). Therefore, the demand for food will continue to grow steadily. In recent years, farmers have often applied excessive fertilizers to avoid any risk of yield reduction (Ravier et al., 2021). However, their risk avoidance strategies cause the waste of resources and lead to greenhouse gas emissions, eutrophication of water bodies, farmland soil pollution, and other adverse effects (Chen et al., 2014; Padilla et al., 2018; Ramanantenasoa et al., 2019). Therefore, fertilizer management decisions in crop systems must be changed to achieve more sustainable and effective agroecosystem management.

In rainfed agriculture, which accounts for approximately three-quarters of global arable land and the dominant agricultural system in drylands, soil nutrient deficiencies (mainly nitrogen (N) and phosphorus (P)) tend to be a significant factor in severely limiting plant growth and grain yields in dryland regions (Bradford et al., 2017). The Loess Plateau in northwest China is a typical dryland region. In this region, spring maize is one of the leading food crops, and the yield of spring maize plays an essential role in guaranteeing food security in China. Although the contribution of N fertilizer to the increase of maize yield in the Loess Plateau is between 30% and 50%, maize yield currently depends heavily on high fertilization or excessive fertilization inputs (Erisman et al., 2008). The excessive fertilization inputs have not been fully absorbed and utilized by crops, threatening the environment (Chen et al., 2014; Ramanantenasoa et al., 2019) and human health (Padilla et al., 2018). The Chinese government has invested heavily in research in comprehensive technology to reduce chemical fertilizer application and improve its efficiency in recent years. Therefore, implementing sustainable N management in dryland spring maize systems to reduce environmental pressure and maintain grain yield stability has become increasingly important.

N leaching is an environmental problem of widespread concern which could contribute to drinking water pollution and eutrophication of water bodies (Padilla et al., 2018). However, the N leaching caused by continuous large-scale N application in dry farmland has not received attention due to the common belief that the migration process of soil N to the subsoil is dominated by water. The level of nitrate-N accumulation in the 0-300 cm soil layer can exceed 714–798 kg ha^{-1} after 13 years of continuous N application in maize systems under different dry-farming cover measures (Dong et al., 2019). 105 groundwater samples were collected in the western Loess Plateau (78 from shallow aquifers and 27 from deep aquifers), and the results showed that 76.3% and 51.9% of samples from shallow aquifers and deep aquifers, respectively, had nitrate content in water exceeding the drinking nitrate limit (50 mg L^{-1}) (Su et al., 2021). Therefore, improving N fertilizer management strategies is necessary to reduce the risk of N leaching and control groundwater nitrate pollution (Meng et al., 2018).

The critical N curve (Nc) is a fundamental tool for improving N management, which can determine the N nutrition index (NNI) and diagnose crop N status (Ata-Ul-Karim et al., 2017; Bohman et al., 2021; Hu et al., 2014). Specific Nc has been identified for different crops, irrigation measures, and cropping systems, and these studies were based on reactions of N fertilizer to determine the best fertilization rate for maximum yield (Wang et al., 2016b; Yue et al., 2014; Zhou et al., 2021; Ziadi et al., 2008). However, these studies take little care of the total N supply (TNS). Therefore, it is still a need for a systematic understanding of the optimal N supply required to meet maize requirements while minimizing environmental impacts.

Mineral N accumulation can be regarded as one of the N sources to meet crop demand, and grain yield is strongly responsive to mineral N (Scharf and Alley, 1994; Cui et al., 2008a, 2008b). Thus soil mineral N pools should be consumed reasonably for crop production and prevent groundwater pollution (Bai et al., 2018; Yao et al., 2018). In addition, the amount of available N mainly depends on the mineralization and immobilization processes of different N sources entering the soil, and the amount of available N has a significant influence on N management (Burger and Venterea, 2008). Therefore, the balance of residual soil N and fertilizer N is crucial to improving N management and sustainable agricultural development. TNS, the sum of residual soil N and fertilizer N, should be considered for the most efficient reflection of N supply. To adequately acquaintance the response of crops to increased TNS, a series of indicators should be considered, like maize plant dry matter accumulation, plant N uptake, grain yield, various N use efficiency, and soil N leaching.

The objectives of this research were to:

(i). Determine the critical N curve in spring maize and maize response to NNIi.

(ii). Clarify the maximum grain yield with minimum TNS values in spring maize.

(iii). Clarify the response of plant N uptake, NUE, N leaching to TNS values.

(iv). Determine a suitable TNS rate to satisfy maize requirements and obtain a higher NUE and lower N leaching.

Materials And Methods

Experimental site

The field experiment was conducted at the Pengyang Experimental station (35°51¢N, 106°48¢E) on the Loess Plateau in Pengyang country of Ningxia Hui Autonomous Region, China. The climate is a typical semi-arid with an average yearly air temperature of 8.1 ^{o}C and average annual sunshine of 2518.2 h. The soil had a total N of 0.74 g kg^{-1}, 100.0 mg kg^{-1} available potassium, 7.39 g kg^{-1} organic carbon content, 12.62 g kg^{-1} soil organic matter, 4.3 mg kg^{-1} adequate phosphorus, and pH 8.8 in the 0-40 cm soil layer, respectively. In the maize growing seasons, the precipitation in 2018, 2019, and 2020 was 567.6, 650.9, and 491.0 mm, respectively, and the average temperature was 17.9, 17.3, and 17.3 ^{o}C, respectively Fig. 1.

Experimental design and crop management

The experiment started in 2018, and it was a design that used a randomized block design with fives treatments and three replications. Each plot area is 6 m ´ 7 m (42 m^2) and with a 1.2 wide isolation belt away from the others. The five fertilization rates (N_0, N_1, N_2, N_3, N_4) were 0, 120, 175, 230, and 285 kg N ha^{-1}, respectively.

The high-yield spring maize variety (Dafeng 30) was planted at 82500 ha^{-1} (wide (60 cm) and narrow (20.2 cm) row spacing) using a hand-planted at a depth of 3-5cm. Maize was sowed on April 25, 24, and 30, 2018-2020, respectively, and harvested on September 29, 29, and October 8. Urea (46% N) was applied to provide N, and diammonium phosphate (46% P and 18% N) provided phosphorus. The specific steps and details of these field management were described in Zhang et al. (2021a) and Zhang et al. (2021b).

Sampling and analysis

Soil NO_3^--N concentration and N balance

Soil samples were collected to analyze soil NO_3^--N content (AA3, SEAL Company, Germany) from 0-100 cm soil depths at 20 cm increments at about 0 and 160 days after sowing (DAS) during maize growing season. Soil samples were taken from the ridge, the furrow, and the section connecting ridges and furrows using a hand-held iron soil drill (54 mm diameter) and mixed thoroughly at the same soil depth. After removing impurities such as maize roots and straw, the soil samples were sieved and transported to the laboratory, and placed in a 4℃ refrigerator. Soil NO_3^--N was extracted using KCl (1 mol L^{-1}) solution. And, the samples were analyzed by the microflow AutoAnalyzer3 to determine NO_3^--N concentration.

Calculated the N residue (kg ha^{-1}) in each soil layer as follows (Yang et al., 2015):

NR=Cn BD d 0.1 (1)

Cn is the soil N concentration (mg kg^{-1}), BD is the soil bulk density (g cm^{-3}), d is the depth of the soil layer (cm), and 0.1 is a conversion factor.

The soil N balance was calculated as follows (Huang et al., 2020):

N soil +N fertilizer – N uptake –N residue =N loss (kg N ha^{-1}) (2)

N soil is the residual NO_3-N in 0-100 cm soil profile before sowing, N fertilizer is the amount of N fertilizer applied, N uptake is the plant N uptake, and N residue is the residual NO_3-N in 0-100 cm soil profile at harvest. In this study, N loss was quantitatively comparable to N leaching.

Total available N was calculated as follows (Ding et al., 2020; Huang et al., 2020):

TNS= N soil +N fertilizer (3)

TNS is the total N supply.

Dry matter accumulation and N concentration

Five maize plants were randomly selected from each plot at 35(V_1), 50(V_3), 60(V_6), 80(V_{12}), 100(R_1), 130(R_3), and 160(R_6) days after sowing by hand for determining the dry matter accumulation. Maize plants were first dried at 105°C for 0.5 h and continued to be dried at 75°C for 24 h. The N content of dry matter accumulation was analyzed using a Kjeldahl Autoanalyzer (Kjeltec 8400, FOSS, Denmark).

Maize yield

At the physiological maturity of maize, continuous and unbroken four-row plants (area 7.2 m^2) with a length of 3.0 m in the middle row were hand-harvested from each plot to determine the grain yield. The harvest index (HI) was calculated as the ratio of grain yield to biomass yield. The N harvest index (NHI) was determined by the ratio of grain N uptake to biomass N uptake.

Establishment and evaluation of N_C

The critical N dilution curve and N dilution boundary curves were determined and developed by Justes et al. (1994) and Plénet et al. (2000):

$Nc=aDM^{-b}$ (4)

Where Nc(%) is the N concentration in plant expressed in g 100 g^{-1} of aboveground biomass weight, DM is the weight of aboveground biomass (Mg ha^{-1}), a is the plant N concentration when the aboveground biomass is 1 Mg ha^{-1}, and b is the characteristic of decreasing nitrogen concentration during maize growth.

Curve validation was performed using the root mean square error (RMSE) and standardized root mean square error (NRMSE) to evaluate the curve fit. The curve stability was measured with reference to the criteria proposed by Jamieson et al. (1991): NRMSE < 10%, excellent curve stability; 10% < NRMSE < 20%, good curve stability; 20% < NRMSE < 30%, fair curve stability; NRMSE > 30%, poor curve stability.

Critical N uptake and nitrogen nutrition index

Nuptc (kg ha^{-1}), the plant N uptake corresponding to the maximum accumulated aboveground biomass of the crop at the critical N concentration state, was the critical N uptake.

$$Nuptc=10NcDM \quad (5)$$

Where Nuptc is the critical N uptake (g kg^{-1}).

Substitution of (4) into (5)：

$$Nuptc=10aDM^{1-b} \quad (6)$$

According to the N nutrient index (NNI) curve described by Lemaire et al. (2008),

$$NNI=Na/Nc \quad (7)$$

Where Na is the N concentration value (g kg^{-1}), and Nc is the critical N concentration value. If NNI < 1 indicated an N deficiency, NNI = 1 indicated just the right amount of N, and NNI > 1 indicated an excess of N.

In addition, the integrated NNI value (NNIi) was calculated to describe the crop N status of treatment throughout the whole growth period. An integrated NNI value was calculated as (Lemaire et al., 2008):

$$NNIi=1/D\ NNIs\ ds \quad (8)$$

Where D is the total number of days in the whole growth stages, NNIs is the NNI value under each sampling day, and ds is the interval between two sampling dates.

Nitrogen use efficiency

Calculated N use efficiency indexes as follows (Caviglia et al., 2014):

$$NuptE = (N\ uptake)/\ TNS \quad (9)$$

$$NutE_{GY} = GY/\ (N\ uptake) \quad (10)$$

$$NutE_{BY} = BY/\ (N\ uptake) \quad (11)$$

$$NUE_{GY} = GY/\ TNS \quad (12)$$

$$NUE_{BY} = BY/\ TNS \quad (13)$$

NuptE (kg kg^{-1}) is N uptake efficiency, NutE (kg kg^{-1}) is N use efficiency, N uptake is plant N uptake, GY is grain yield, BY is biomass yield, and TNS is total N supply.

Statistical analyses

Results were calculated using Microsoft Excel 2013, plotted with Origin 2021 software, and statistically analyzed using SPSS 26.0 software. Mean comparisons were made at $P < 0.05$ using Fisher's LSD (Least Significant Difference) test. Used 2018-2019 data to build the curve and used 2020 data for verification. This study evaluated linear, quadratic, and linear-plateau models and reported best-fitting curves (Cerrato and Blackmer, 1990).

Results

Determination and evaluation of a critical nitrogen curve for maize

Critical nitrogen curve for maize

N concentration decreased with increasing dry matter (Fig. 2). The maximum (Nmax, %) and minimum (Nmin, %) N concentration dilution curves for maize, i.e., the N dilution boundary curve, were obtained by simulating the maximum and minimum measured values of N concentrations for each sampling day, respectively, and were also consistent with an angle (4). The parameters are shown in Table 1. The NRMSE of the critical N dilution curve was calculated to be less than 10, indicating that the simulation performance of the constructed curve was excellent.

Nitrogen nutrition index

There were significant differences in the NNIi values among the N treatments during the 3-year experimental period (Table 2). The NNIi increased with fertilizer application increase from N_0 to N_3 treatments, which remained relatively stable. Differences were highly significant between N_0, N_1, N_2, and N_3 treatments and not significant between N_3 and N_4 treatments.

Critical nitrogen uptake

The relationships between estimated critical N uptake and measured plant N uptake under different fertilizer treatments (Fig. 3). The NRMSEs for critical N uptake were 674.3%, 86.7%, 44.9%, 13.1%, and 12.5%, respectively, and those for critical P uptake were 290.1%, 24.3%, 11.1%, 8.9%, and 6.8%, respectively. These results indicate that reasonable fertilization management practices were in N_3 treatment. The difference in NRMSEs between N_3 and N_4 treatments indicates a small luxury N uptake with a high N supply.

Agronomic response and nitrogen loss

Effect of fertilizer on yield and N uptake

The same trend was observed for grain yield, biomass, plant N uptake, and grain N uptake. For example, fertilizer application significantly affected spring maize grain yield in 2018, 2019, and 2020 maize growing seasons (Table 3). With increasing fertilizer, spring maize grain yield tended to increase. Statistically, the grain yield of maize showed no significant level of difference between N_3 and N_4 treatments in 2018, 2019, and 2020 maize growing seasons. Moreover, the N_3 treatment had the highest grain yield with a lower fertilizer supply than the N_4 treatment, which indicated that excessive fertilizer application could not significantly improve maize grain yield. Both HI and NHI tended to increase with increasing fertilizer. However, there was did not reach a significant level of difference between N_3 and N_4 treatments for HI and NHI.

Grain yield response to TNS and NNIi

Both maize grain yield and relative grain yield increased with increasing the TNS (Fig. 4b, d). A linear-plateau model can describe the relationship between maize grain yield and TNS in 2018, 2019, and 2020 maize growing seasons. In these three years, the maximum maize grain yield was estimated to be 10.95, 6.42, and 6.31 t ha^{-1}, respectively, with an R^2 value higher than 0.95. The minimum TNS values corresponding to the maximum maize grain yield were 316, 341, and 306 kg N ha^{-1} in the 2018, 2019, and 2020 maize growing seasons. A linear-plateau regression model can also be used for the relationship between maize relative grain yield and TNS, and the R^2 value is 0.95 (Fig. 4d). The minimum TNS value corresponding to the maximum maize relative grain yield was 327 kg N ha^{-1} (TNS_{RY-MAX}). The same trend was observed for NNIi.

A quadratic model can describe the relationship between the total N supply and the integrated NNI value with an R^2 value of 0.92 in the three-year experience (Fig. 5). The minimum NNIi value corresponding to the maximum relative grain yield was 1.00 ($NNIi_{RY-MAX}$). The $NNIi_{RY-MAX}$ value relevant TNS value was 326 kg N ha^{-1}.

Nitrogen use efficiency

Table 3 lists the values of each N use efficiency (NUE) at different fertilizer supply levels for spring maize in 2018, 2019, and 2020 maize growing seasons. The $NutE_{BY}$ decreased significantly with increasing TNS during the three-year experience. The $NutE_{BY}$ values decreased from 188.6 to 114.1, 184.2 to 88.3, and 141.4 to 89.2 kg kg^{-1} in 2018, 2019, and 2020 maize growing seasons, respectively.

A linear-plateau model can describe the relationship between $NutE_{BY}$ and plant N uptake (Fig. 6a), and the corresponded minimum plant N uptake at which the $NutE_{BY}$ tends to be stable value first appeared was 111 kg N ha^{-1}. The nitrogen use efficiency ($NutE_{BY}$) of plants decreased first and then tended to be stable with the increase of TNS or NNIi, which could also be specified by a linear-plateau model (Fig. 6c, d). The TNS_{RY-MAX} (327 kg N ha^{-1}) value corresponded to a $NutE_{BY}$ value was 96.6 kg kg^{-1}, and the $NNIi_{RY-MAX}$ (1.00) value corresponded to a $NutE_{BY}$ value was 96.1 kg kg^{-1}.

Effect of fertilizer on nitrogen loss

With the increase of TNS, the N residual amount increased (Table 4), and the soil nitrate-N residual amount in 2018, 2019, and 2020 maize growing seasons reached the maximum value of 70.2, 84.1, and 83.4 kg ha^{-1}, respectively. The TNS_{RY-MAX} (327 kg N ha^{-1}) value corresponded to a soil nitrate-N residual value was 66.0 kg ha^{-1} (Fig. 7).

N leaching increased with increasing TNS, and a linear model could describe the relationship with R^2 of 0.70 (Fig. 8a). The N leaching value corresponding to TNS_{RY-MAX} (327 kg N ha^{-1}) was 94.2 kg ha^{-1}. A quadratic model could describe the relationship between N leaching and NNIi with an R^2 of 0.38 (Fig. 8b). The N leaching value corresponding to $NNIi_{RY-MAX}$ (1.00) was 93.6 kg ha^{-1}.

Discussion

Critical N curve

Critical N curve in spring maize

In this study, a critical N curve ($Nc = 2.64DM^{-0.25}$) was established for a dryland spring maize sustainable production in northwest China, and the relationship between NNIi and relative yield, plant N use efficiency, and N leaching was studied. According to the critical N curve of spring maize, the relationship between the critical N content of spring maize and the aboveground biomass was a power function. The equation's determination coefficient was 0.8221, and the fitting degree reached a very significant level. Compared with the results of previous studies (Table 5), the plant critical N curve results were close to the range of other existing model parameters a and b, which ranged from 2.33-4.17 and 0.22-0.41. Therefore, we believe that the critical N curve is suitable for diagnosing the N nutrition of spring maize in the semi-arid area of northwest China. However, a recent review (Ciampitti et al., 2021) suggests minor variations in key N-curve parameters may occur in different cropping varieties and field management practices, including planting densities. However, since the experiment did not involve planting density and variety experiments, the model's universality may be insufficient. In the future maize production practice in the semi-arid area of northwest China, the variety and density experiments of dryland N application should be added to verify further and enhance the universality of the model.

NNIi and luxury N uptake

The minimum NNIi value corresponding to the maximum relative grain yield was 1.00. If the measured NNIi value is below 1, the relative grain yield decreases, and above 1, there is no increase in the relative grain yield. This NNIi identifies N nutrient deficiencies and non-deficiencies, and it can be used to assess the N status of maize in rainfed spring maize systems. However, the critical NNIi value corresponding to the maximum relative grain yield in this study was 1, which may be due to the one-time application of solid granular urea before sowing. It has been shown that two-stage N application can improve both grain yield and apparent N recovery efficiency while reducing N losses in semi-arid mulching maize planting systems compared to one-time fertilization before sowing (Wang et al., 2016a). However, with the advancement of simplified fertilizer management in dryland, one-time fertilization before sowing has increased interest. Then, whether a new critical N curve can be developed by replacing one-time fertilization before sowing with slow-release fertilizer is the direction that needs attention in the future.

When the soil N supply was higher than the plant N requirement, the NNI value of rice and pepper was significantly greater than 1.0 (Ata-Ul-Karim et al., 2017; Rodríguez et al., 2020; Wang et al., 2016b). However, in this study, the NNIi value of excess N supply was close to 1. The relationship between measured crop N accumulation and critical crop N accumulation under N_3 and N_4 treatments (Fig. 3) indicates that N accumulation under N_3 and N_4 treatments were similar to critical NRMSE. These results suggested little luxury N uptake by maize under high N supply. Similar results were reported for maize by Yue et al. (2014) and Zhou et al. (2021). Therefore, our study demonstrated that excessive N supply would not significantly increase the plant N uptake.

Response of spring maize to total nitrogen supply and NNIi

Grain yield

The highest yields were achieved in the 2018 crops, with a maximum grain yield of 11.54 t ha^{-1}. Under the same N supply condition, the grain yields in 2019 and 2020 were lower, with the maximum yield of 6.27 and 5.96 t ha^{-1}-the uneven distribution of precipitation presumably an influential contributing factor. In 2018, there was more precipitation in the silking stage and lower precipitation in the grain filling stage, while 2019 and 2020 were opposite to 2018. The water sensitivity in rainfed spring maize of China at different growth stages was in the order of silking stage > nutrient stage > filling stage, and drought during the maize silking stage will shorten the grain filling time, thereby reducing the ear length and the number of grains per ear, ultimately reducing maize yield (Jia et al., 2018; Liu et al., 2013).

Nitrogen use efficiency

This study indicated that N uptake rates decreased with increasing TNS. Similar results were reported in potatoes and peppers and in other horticultural crops (Bohman et al., 2021; Hagai et al., 2013; Rodríguez et al., 2020). Therefore, N uptake was negatively correlated with TNS in field crops (Table 5). With the increase of N uptake by plants, plants' N use efficiency ($NutE_{BY}$) decreased first and then stabilized. The minimum plant N uptake when $NutE_{BY}$ first appeared stable was 111 kg N ha^{-1}.

This data proved to reduce initially influence reductions with NUE_{BY} increasing N supply in NuptE and $NutE_{BY}$. When the plant N uptake values were higher than about 111 kg N ha^{-1}, the reductions in NUE_{BY} were due to a reduction in relatively large NuptE. Caviglia et al. (2014) and Rodríguez et al. (2020) reported similar results on potatoes and peppers. Therefore, our study demonstrated that the N uptake efficiency (NuptE) is crucial for maize NUE rather than is N use efficiency in field crops when the plant N uptake values were higher than the critical threshold.

Most studies show that NutE, NUE_{BY}, and NUE_{GY} are only related to the N application rate, not TNS (Bohman et al., 2021; Caviglia et al., 2014). Milroy et al. (2019) and Rodríguez et al. (2020) in horticultural crops considered nitrate-N residues affected NutE, NUE_{BY}, and NUE_{GY} change, similar to the results of this study. Thus, TNS may significantly affect NutE, NUE_{BY}, and NUE_{GY} changes in horticultural and field crops.

NO_3^- leaching into the environment

The amount of soil N leaching increased with the increase of TNS, and this was consistent with the effect of fertilization on soil N leaching in farmland (Dai et al., 2015; Ju et al., 2006). These results suggest that reducing the total N supply to crops can help reduce environmental N loss in this system. Compared with N_4 treatment, N_3 treatment reduced soil N leaching by 11.4%-41.5% without reducing grain yield, which agrees with Quan et al. (2020) and Milroy et al. (2019). Therefore, reducing N input can reduce the amount of soil N leaching to a certain extent in field crops systems. In other words, the surest way to reduce soil N leaching is to ensure that as little nitrate-N remains in the soil at all times. It was found that there was no significant difference in plant N accumulation between N_3 and N_4 treatments (Table 4), which indicated that the total N supplied to crops by N_3 treatment had already met the N demand of plants. Therefore, maintaining a balance between crop N demand and total N supply to crops effectively reduces N leaching, reducing soil environmental pollution (Ju et al., 2009). Therefore, the total N supply reflects the N supply capacity of the cropping system.

Table 4 shows that the level of residual nitrate-N is related to the amount of N application. Huang et al. (2020) reported similar results. Residual nitrate-N mainly comes from excessive N application (Ju et al., 2006; Huang et al., 2020), which is closely related to nitrate leaching (Cui et al., 2010; Chen et al., 2014). In addition, the amount of water flowing through the soil affects N leaching (Cameron et al., 2013). A large amount of concentrated precipitation in July and August will produce a large amount of N leaching (Dong et al., 2019; Lu et al., 2021), which can explain why the N leaching amount of each treatment in 2019 was higher than that in 2018 and 2020. Therefore, accumulated nitrate-N must be exhausted to reduce leaching risk.

Suitable total N supply and N application guidance

The relationships between the TNS, relative grain yield (RY), N leaching, and N use efficiency were summarized in Fig. 9. TNS was the sum of residual soil N and fertilizer N. When the TNS was more significant than 327 kg ha^{-1} (Fig. 4d), maize achieved its maximum relative grain yield (determined by linear-plateau modal between TNS and RY). However, when the TNS was not exceeded 315 kg ha^{-1}, maize first achieved its minimum $NutE_{BY}$ (96.6 kg kg^{-1}). Furthermore, the relationships between TNS and N leaching firmly fit the linear model. Therefore, the appropriate TNS rates should be between 315 to 327 kg ha^{-1}, at the same time to ensure high grain yields and minimize environmental impacts.

The integrated N nutrition index (NNIi), RY, N leaching, and N use efficiency were summarized in Fig. 9. This study found that suitable NNIi should be 1.0, corresponding to the appropriate N fertilizer rate of 230 kg ha^{-1}. Spring maize planting system of residual NO_3^-- N accumulation should not be more than 100 kg ha^{-1}. The more you exceed this value, the higher the environmental cost (Cui et al., 2010; Chen et al., 2014). As a result, the value is defined as a safety threshold for the nitrate accumulation of residues in soil N management. If the residual amount of nitrate-N in the soil before sowing exceeds 100 kg ha^{-1}, the sum of soil mineral N and suitable fertilizer will be higher than the reasonable total N supply rate, resulting in high environmental impacts. Therefore, to balance the relationship between soil N supply and crop N demand, we propose to use total N supply as an indicator to implement sustainable N management in dryland spring maize systems. Hence, this can reduce fertilizer N input and N leaching and achieve a high grain yield. However, how to make the most of these recommendations could be challenging. We show a flowchart (Fig. 10) classified according to N supply rate to illustrate the recommended N fertilizer application at reasonable TNS rates by measuring soil nitrate-N residues before sowing.

Conclusions

In conclusion, integrated N nutrition index (NNIi), RY, plant N use efficiency ($NutE_{BY}$), and N leaching in response to the TNS (total N supply, sum of the soil N supply (N soil)and fertilizer N supply (N fertilizer)) fit quadratic, linear-plateau, linear-plateau, and linear models, respectively. The applicable TNS rates should be between 315 to 327 kg ha^{-1}, at the same time to ensure high grain yields and minimize environmental impacts. However, the suitable NNIi should be 1.0, corresponding to the appropriate N fertilizer rate of 230 kg ha^{-1}. When considering the Nsoil (>100 kg ha^{-1}), the Nsoil plus Nfertilizer (230 kg ha^{-1}) may be higher than the suitable TNS. Therefore, TNS may be a sustainable N supply that can reduce the input of N fertilizers. In terms of reflecting N supply in spring maize systems, the TNS was proposed as an indicator to implement sustainable N management.

Declarations

The authors declare that we have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Funding

This work was supported by the National High-Tech Research and Development Program of China ("863 Program"), the 12th 5-Year Plan (2013AA102902), and the Program of Introducing Talents of Discipline to Universities (B12007), and the China Postdoctoral Science Foundation (2020M683582).

Competing interests

We declare no conflict of interests and all authors approved the manuscript.

Availability of data and material

Not applicable

Code availability

Not applicable

Author contributions

Xiaorong Wu, Xudong Zhang and Qingfang Han designed the study, Xiaorong Wu, Junjie Li, and Xuanke Xue interpreted data and wrote the manuscript, Xuemei Zhang, Yingfei Zhao and Zhimin Li contributed to sample and data collection, Baoping Yang and Zhikuan Jia provided technical advice and support for the study.

Ethics approval

Not applicable

Consent to participate

Not applicable

Consent for publication

Not applicable

References

1. Ata-Ul-Karim S, Liu X, Lu Z, Zheng H, Cao W, Zhu Y (2017) Estimation of nitrogen fertilizer requirement for rice crop using critical nitrogen dilution curve. Field Crops Research 201:32–40
2. Bai Z, Lu J, Zhao H, Velthof G, Oenema O, Chadwick D, Williams J, Jin S, Liu H, Wang M, Strokal M, Kroeze C, Hu C, Ma L (2018) Designing vulnerable zones of nitrogen and phosphorus transfers to control water pollution in China. Environ Sci Technol 52:8987–8988
3. Bohman BJ, Rosen C, Mulla D (2021) Relating nitrogen use efficiency to nitrogen nutrition index for evaluation of agronomic and environmental outcomes in potato. Field Crops Research 262:108041
4. Bradford J, Schlaepfer D, Lauenroth W, Yackulic C, Duniway M, Hall S, Jia G, Jamiyansharav K, Munson S, Wilson S, Tietjen B (2017) Future soil moisture and temperature extremes imply expanding suitability for rainfed agriculture in temperate drylands. Sci Rep 7(1):12923
5. Burger M, Venterea R (2008) Nitrogen immobilization and mineralization kinetics of cattle, hog, and Turkey manure applied to soil. Soil Sci Soc Am J 72:1570–1579
6. Cameron K, Di H, Moir J (2013) Nitrogen losses from the soil/plant system: a review. Ann Appl Biol 162(2):145–173

7. Caviglia O, Melchiori R, Sadras V (2014) Nitrogen utilization efficiency in maize as affected by hybrid and N rate in late-sown crops. Field Crops Research 168:27–37
8. Cerrato M, Blackmer A (1990) Comparison of models for describing corn yield response to nitrogen fertilizer. Agron J 82:138–143
9. Chen X, Cui Z, Fan M, Vitousek P, Zhao M, Ma W, Wang Z, Zhang W, Yan X, Yang J, Deng X, Gao Q, Zhang Q, Guo S, Ren J, Li S, Ye Y, Wang Z, Huang J, Tang Q, Sun Y, Peng X, Zhang J, He M, Zhu Y, Xue J, Wang G, Wu L, An N, Wu L, Ma L, Zhang W, Zhang F (2014) Producing more grain with lower environmental costs. Nature 514(7523):486–489
10. Ciampitti I, Fernandez F, Tamagno S, Zhao B, Lemaire G, Makowski D (2021) Does the critical N dilution curve for maize crop vary across genotype x environment x management scenarios? - a Bayesian analysis. Eur J Agron 123:126202
11. Cui Z, Chen X, Miao Y, Li F, Zhang F, Li J, Ye Y, Yang Z, Zhang Q, Liu C (2008a) On-farm evaluation of winter wheat yield response to residual soil nitrate-N in north China plain. Agron J 100:1527–1534
12. Cui Z, Zhang F, Miao Y, Sun Q, Li F, Chen X, Li J, Ye Y, Yang Z, Zhang Q, Liu C (2008b) Soil nitrate-N levels required for high yield maize production in the North China Plain. Nutr Cycl Agrosyst 82:187–196
13. Cui Z, Zhang F, Chen X, Dou Z, Li J (2010) In-season nitrogen management strategy for winter wheat: Maximizing yields, minimizing environmental impact in an over-fertilization context. Field Crops Research 116(1–2):140–146
14. Cui Z, Zhang H, Chen X, Zhang C, Ma W, Huang C, Zhang W, Mi G, Miao Y, Li X, Gao Q, Yang J, Wang Z, Ye Y, Guo S, Lu J, Huang J, Lv S, Sun Y, Liu Y, Peng X, Ren J, Li S, Deng X, Shi X, Zhang Q, Yang Z, Tang L, Wei C, Jia L, Zhang J, He M, Tong Y, Tang Q, Zhong X, Liu Z, Cao N, Kou C, Ying H, Yin Y, Jiao X, Zhang Q, Fan M, Jiang R, Zhang F, Dou Z (2018) Pursuing sustainable productivity with millions of smallholder farmers. Nature 555(7696):363–366
15. Dai J, Wang Z, Li F, He G, Wang S, Li Q, Cao C, Luo L, Zan Y, Meng X, Zhang W, Wang R, Malhi S (2015) Optimizing nitrogen input by balancing winter wheat yield and residual nitrate-N in soil in a long-term dryland field experiment in the Loess Plateau of China. Field Crops Research 181:32–41
16. Ding W, Xu X, He P, Zhang J, Cui Z, Zhou W (2020) Estimating regional N application rates for rice in China based on target yield, indigenous N supply, and N loss. Environmental Pollution 263(Pt B):114408
17. Dong Q, Dang T, Guo S, Hao M (2019) Effects of mulching measures on soil moisture and N leaching potential in a spring maize planting system in the southern Loess Plateau. Agric Water Manage 213:803–808
18. Erisman J, Sutton M, Galloway J, Klimont Z, Winiwarter W (2008) How a century of ammonia synthesis changed the world. Nat Geosci 1:636–639
19. Hagai Y, Ben-Gal A, Uri Y (2013) Nitrogen Management of Greenhouse Pepper Production: Agronomic, Nutritional, and Environmental Implications. HortScience 48(10):1241–1249
20. Hu D, Sun Z, Li T, Yan H, Zhang H (2014) Nitrogen Nutrition Index and Its Relationship with N Use Efficiency, Tuber Yield, Radiation Use Efficiency, and Leaf Parameters in Potatoes. J Integr Agric 13(5):1008–1016
21. Huang S, Ding W, Yang J, Zhang J, Ullah S, Xu X, Liu Y, Yang Y, Liu M, He P, Jia L (2020) Estimation of nitrogen supply for winter wheat production through a long-term field trial in China. J Environ Manage 270:110929
22. Jamieson P, Porter J, Wilson D (1991) A test of the computer simulation model ARCWHEAT1 on wheat crops grown in New Zealand. Field Crops Research 27:337–350
23. Jia Q, Sun L, Wang J, Li J, Ali S, Liu T, Zhang P, Lian Y, Ding R, Ren X, Jia Z (2018) Limited irrigation and planting densities for enhanced water productivity and economic returns under the ridge-furrow system in semi-arid regions of China. Field Crops Research 221:207–218
24. Ju X, Xing G, Chen X, Zhang S, Zhang L, Liu X, Cui Z, Yin B, Christie P, Zhu Z (2009) Reducing environmental risk by improving N management in intensive Chinese agricultural systems. Proceedings of the National Academy of Sciences 106(9): 3041–3046
25. Ju X, Kou C, Zhang F, Christie P (2006) Nitrogen balance and groundwater nitrate contamination: Comparison among three intensive cropping systems on the North China Plain. Environ Pollut 143(1):117–125
26. Justes E, Mary B, Meynard J, Machet J, Thelier-Huche L (1994) Determination of A critical nitrogen dilution curve for winter-wheat Crops. Ann Botany 74:397–407

27. Lemaire G, Jeuffroy M, Gastal F (2008) Diagnosis tool for plant and crop N status in vegetative stage. Eur J Agron 28(4):614–624
28. Liang X, Zhang J, Zhou L, Li X, Zhou S (2013) Critical Nitrogen Dilution Curve and Nitrogen Nutrition Index for Summer-Maize in North China Plain. Acta Agron Sinica 39(2):292–299
29. Liu P, Shi Z, Ning F, Wang R, Wang X, Li J (2020) Critical nitrogen dilution curves and nitrogen nutrition diagnosis of spring maize under different precipitation patterns in Weibei dryland. Acta Agron Sinica 46(8):1225–1237
30. Liu Z, Shao M, Wang Y (2013) Spatial patterns of soil total nitrogen and soil total phosphorus across the entire Loess Plateau region of China. Geoderma 197–198:67–78
31. Lu J, Hu T, Zhang B, Wang L, Yang S, Fan J, Yan S, Zhang F (2021) Nitrogen fertilizer management effects on soil nitrate leaching, grain yield and economic benefit of summer maize in Northwest China. Agric Water Manage 247:106739
32. Meng Q, Cui Z, Yang H, Zhang F, Chen X (2018) Establishing High-Yielding Maize System for Sustainable Intensification in China. Advances in Agronomy, pp 85–109
33. Milroy S, Wang P, Sadras V (2019) Defining upper limits of nitrogen uptake and nitrogen use efficiency of potato in response to crop N supply. Field Crops Research 239:38–46
34. Padilla F, Gallardo M, Manzano-Agugliaro F (2018) Global trends in nitrate leaching research in the 1960–2017 period. Sci Total Environ 643:400–413
35. Plénet D, Lemaire G (2000) Relationships between dynamics of nitrogen uptake and dry matter accumulation in maize crops. Determination of critical N concentration. Plant Soil 216:65–82
36. Quan Z, Li S, Zhang X, Zhu F, Li P, Sheng R, Chen X, Zhang L, He J, Wei W, Fang Y (2020) Fertilizer nitrogen use efficiency and fates in maize cropping systems across China: Field ^{15}N tracer studies. Soil Tillage Res 197:104498
37. Ramanantenasoa M, Genermont S, Gilliot J, Bedos C, Makowski D (2019) Meta-modeling methods for estimating ammonia volatilization from nitrogen fertilizer and manure applications. J Environ Manage 236:195–205
38. Ravier C, Jeuffroy M, Meynard J (2021) Mismatch between a science-based decision tool and its use: The case of the balance-sheet method for nitrogen fertilization in France. NJAS: Wageningen Journal of Life Sciences 79(1):31–40
39. Rodríguez A, Peña-Fleitas M, Gallardo M, Souza R, Padilla F, Thompson R (2020) Sweet pepper and nitrogen supply in greenhouse production: Critical nitrogen curve, agronomic responses and risk of nitrogen loss. Eur J Agron 117:126046
40. Scharf P, Alley M (1994) Residual soil nitrogen in humid region wheat production. J Prod Agric 7:81
41. Su H, Kang W, Li Y, Li Z (2021) Fluoride and nitrate contamination of groundwater in the Loess Plateau, China: Sources and related human health risks. Environ Pollution 286:117287
42. Su W, Xie J, Han J, Liu T, Han Q (2020) Construction of critical nitrogen dilution curve based on dry matter in diffe rent organs of summer maize and estimation of grain yield. Acta Agron Sinica 47(3):530–545
43. Wang S, Luo S, Yue S, Shen Y, Li S (2016a) Fate of ^{15}N fertilizer under different nitrogen split applications to plastic mulched maize in semiarid farmland. Nutr Cycl Agrosyst 105(2):129–140
44. Wang Y, Shi P, Zhang G, Ran J, Shi W, Wang D (2016b) A critical nitrogen dilution curve for japonica rice based on canopy images. Field Crops Research 198:93–100
45. Yao Z, Zhang D, Yao P, Zhao N, Li Y, Zhang S, Zhai B, Huang D, Ma A, Zuo Y, Cao W, Gao Y (2018) Optimizing the synthetic nitrogen rate to balance residual nitrate and crop yield in a leguminous green-manured wheat cropping system. Sci Total Environ 631–632:1234–1242
46. Yang X, Lu Y, Tong Y, Yin X (2015) A 5-year lysimeter monitoring of nitrate leaching from wheat-maize rotation system: Comparison between optimum N fertilization and conventional farmer N fertilization. Agric Ecosyst Environ 199:34–42
47. Yue S, Sun F, Meng Q, Zhao R, Li F, Chen X, Zhang F, Cui Z (2014) Validation of a Critical Nitrogen Curve for Summer Maize in the North China Plain. Pedosphere 24(1):76–83
48. Zhang X, Dong Z, Wu X, Gan Y, Chen X, Xia H, Kamran M, Jia Z, Han Q, Shayakhmetova A, Siddique K (2021a) Matching fertilization with water availability enhances maize productivity and water use efficiency in a semi-arid area: Mechanisms and solutions. Soil Tillage Res 214:105164

49. Zhang X, Wang R, Dong Z, Zhang P, Jia Z, Han Q (2021b) Nutritional quality degradation: A potential risk due to nutrient dilution effects in film-mulched maize. Agric Water Manage 257:107133

50. Zhao B, Ata-Ul-Karim S, Liu Z, Ning D, Xiao J, Liu Z, Qin A, Nan J, Duan A (2017) Development of a critical nitrogen dilution curve based on leaf dry matter for summer maize. Field Crops Research 208:60–68

51. Zhou L, Feng H, Zhao W (2021) Plastic film mulching affects the critical nitrogen dilution curve of drip-irrigated maize. Field Crops Research 263:108055

Tables

Table 1 Model parameters values and verification of critical N concentration dilution curve in maize growing seasons.

		Model parameters		Validation		
		a	b	R^2	RMSE	NRMSE
N	Nmin	2.15	0.24	0.84	0.18	8.33
	Nmax	2.78	0.26	0.83	0.25	11.8
	Nc	2.64	0.25	0.82	0.16	9.68

Table 2 The integrated N nutrition index (NNIi) values for each treatment in 2018, 2019, and 2020 maize growing seasons.

Treatment	Integrated NNI		
	2018	2019	2020
N_0	0.57±0.01d	0.54±0.01d	0.65±0.01d
N_1	0.79±0.01c	0.81±0.01c	0.83±0.01c
N_2	0.95±0.01b	0.95±0.01b	0.96±0.01b
N_3	1.04±0.00a	1.01±0.03a	1.02±0.02a
N_4	1.02±0.02a	1.02±0.00a	1.02±0.02a
Significance	**	**	**

Note: ** means extremely significant difference level, * means difference level, NS means no difference level. The values represent the mean ± standard error (n =3). Different letters indicate differences (P < 0.05) among treatments.

Table 3 Maize yield and N uptake and utilization for each treatment in 2018, 2019, and 2020 maize growing seasons.

Year/ Treatment	Grain yield (GY, t ha^{-1})	Biomass yield (BY, t ha^{-1})	Grain N uptake (GNU, kg ha^{-1})	Crop N uptake (CNU, kg ha^{-1})	HI (kg kg^{-1})	NHI (kg kg^{-1})	$NutE_{GY}$ (kg kg^{-1})	$NutE_{BY}$ (kg kg^{-1})	NUE_{GY} (kg kg^{-1})	NUE_{BY} (kg kg^{-1})	NuptE (kg kg^{-1})
2018											
N_0	1.1 d	4.8 d	7.1 d	25.5 d	0.24 c	0.28 c	44.4 b	188.6 a	60.0 a	255.0 a	1.35 a
N_1	5.7 c	15.2 c	39.4 c	89.4 c	0.36 b	0.44 b	63.4 a	170.1 b	36.5 b	98.0 b	0.58 b
N_2	7.2 b	18.4 b	79.8 b	147.4 b	0.39 b	0.54 a	48.8 b	124.6 c	31.3 b	80.1 c	0.64 b
N_3	11.1 a	24.1 a	122.6 a	203.1 a	0.46 a	0.53 a	54.6 a	118.9 c	35.0 b	76.2 c	0.64 b
N_4	11.5 a	24.9 a	120.9 a	218.0 a	0.46 a	0.55 a	53.0 b	114.1 c	32.0 b	69.1 c	0.51 bc
2019											
N_0	0.2 d	2.7 e	3.1 d	14.6 e	0.06 b	0.21 c	10.3 d	184.2 a	3.7 c	66.7 a	0.36 c
N_1	3.9 c	10.9 d	33.5 c	88.0 d	0.36 a	0.39 b	44.3 a	124.7 b	19.8 a	55.4 a	0.45 b
N_2	4.8 b	13.4 c	68.6 b	145.2 c	0.36 a	0.47 a	33.1 b	92.0 c	17.5 ab	48.4 b	0.53 a
N_3	6.6 a	16.1 b	93.5 a	178.4 b	0.41 a	0.52 a	36.8 b	90.4 c	18.5 ab	45.4 bc	0.50 a
N_4	6.3 a	17.5 a	97.7 a	197.8 a	0.36 a	0.49 a	31.7 c	88.3 c	15.1 b	42.0 c	0.48 a
2020											
N_0	0.1 d	2.7 d	5.9 d	19.3 d	0.02 c	0.31 d	3.0 c	141.4 a	1.4 c	68.2 a	0.48 a
N_1	3.6 c	10.1 c	41.2 c	88.0 c	0.35 b	0.47 c	40.4 a	114.4 b	20.1 a	56.7 a	0.50 a
N_2	4.2 b	11.4 b	60.4 b	116.6 b	0.37 b	0.52 b	35.7 b	97.6 c	17.6 b	47.9 b	0.49 a
N_3	5.9 a	13.8 a	93.9 a	158.7 a	0.43 a	0.59 a	37.3 a	86.9 d	18.5 ab	43.0 b	0.49 a
N_4	6.0 a	14.1 a	93.8 a	158.3 a	0.43 a	0.59 a	37.7 a	89.2 d	15.3 b	36.2 c	0.41 b
Tests of Treatment Effect											
T	**	**	**	**	**	**	**	**	**	**	**
Y	**	**	**	**	**	**	**	**	**	**	**
T*Y	**	**	**	**	**	**	**	**	**	**	**

Note: HI is harvest index, NHI is nitrogen harvest index, $NutE_{GY}$ is N utilization efficiency for grain yield, $NutE_{BY}$ is N utilization efficiency for biomass yield, NuptE is N uptake efficiency, NUE_{GY} is nitrogen use efficiency for grain yield, and NUE_{BY} is nitrogen use efficiency for biomass yield. ** means extremely difference level ($P < 0.01$), * means difference level ($P < 0.05$), NS means no difference level. The values represent the mean ± standard error (n = 3). Different letters indicate differences ($P < 0.05$) among treatments.

Table 4 Soil N balance in 0-100cm soil layer for each treatment in 2018, 2019, and 2020 maize growing seasons.

Year/ Treatment	N fertilizer (kg ha^{-1})	N initial (kg ha^{-1})	N residual (NR, kg ha^{-1})	N leached (NL, kg ha^{-1})	N uptake (kg ha^{-1})	TNS (kg ha^{-1})
2018						
N_1	120	35.1	26.0 d	39.7 d	89.4 c	155.1 d
N_2	175	54.1	36.0 c	45.8 c	147.4 b	229.1 c
N_3	230	86.7	52.6 b	60.9 b	203.1 a	316.7 b
N_4	285	75.3	70.2 a	72.1 a	218.0 a	360.3 a
2019						
N_1	120	75.9	40.2 d	67.7 d	88.0 d	195.6 d
N_2	175	100.9	48.4 c	82.3 c	145.2 c	275.9 c
N_3	230	125.4	58.3 b	118.6 b	178.4 b	355.4 b
N_4	285	130.8	84.1 a	133.8 a	197.8 a	415.8 a
2020						
N_1	120	46.0	62.6 d	26.7 d	88.0 c	177.3 d
N_2	175	62.2	69.1 c	51.6 c	116.6 b	237.2 c
N_3	230	90.7	75.4 b	86.7 b	158.7 a	320.7 b
N_4	285	104.9	83.4 a	148.3 a	158.3 a	389.9 a
Tests of Treatment Effect						
T	-	-	**	**	**	**
Y	-	-	**	**	**	**
T*Y	-	-	**	**	**	**

Note: ** means extremely difference level ($P < 0.01$), * means difference level ($P < 0.05$), NS means no difference level. The values represent the mean ± standard error (n = 3). Different letters indicate differences ($P < 0.05$) among treatments.

Table 5 Comparison of the critical N curve for maize and other model parameters.

Reference	Field cultivation	Growth period	DM	Model parameters			Associated indicators				
			(t ha^{-1})	a	b	R^2	NNI	NUE	Yield	NO_3^--N	N leaching
(Plénet et al., 2000)	N/A	V_1-R_3	DM<1	3.40		N/A	N/A	N/A	N/A	N/A	N/A
			22≥DM≥1	3.40	0.37						
(Liang et al., 2013)	N/A	V_{13}-R_6	DM≥1	3.49	0.41	0.82	Y	N/A	Y	N/A	N/A
(Yue et al., 2014)	N/A	V_6-R_3	11.17≥DM≥0.64	2.72	0.27	N/A	Y	N/A	Y	Y	N/A
(Zhao et al., 2017)	N/A	V_6-R_3	N/A	3.45	0.22	N/A	Y	Y	Y	N/A	N/A
(Liu et al., 2020)	Plastic film mulching of dry land	V_6-R_6	23.1≥DM≥1	3.60	0.35	0.99	Y	N/A	Y	N/A	N/A
			15.2≥DM≥1	3.50	0.23	0.96	Y	N/A	Y	N/A	N/A
(Zhou et al., 2021)	drip-irrigated	V_6-R_6	21.2≥DM≥1	3.58	0.36	0.98	Y	N/A	Y	Y	N/A
	Plastic film mulching of drip-irrigated		22.6≥DM≥1	4.17	0.35	0.94	Y	N/A	Y	Y	N/A
(Su et al., 2020)	irrigated	V_3-R_6	10≥DM≥1	2.47	0.24	0.92	Y	Y	Y	N/A	N/A
			10.5≥DM≥1	2.33	0.26	0.98	Y	Y	Y	N/A	N/A
Present study	Plastic film mulching of dry land	V_1-R_6	24.9> DM> 0.02	2.64	0.25	0.82	Y	Y	Y	Y	Y

Note: N/A indicate that there is no data in the reference papers.

Figures

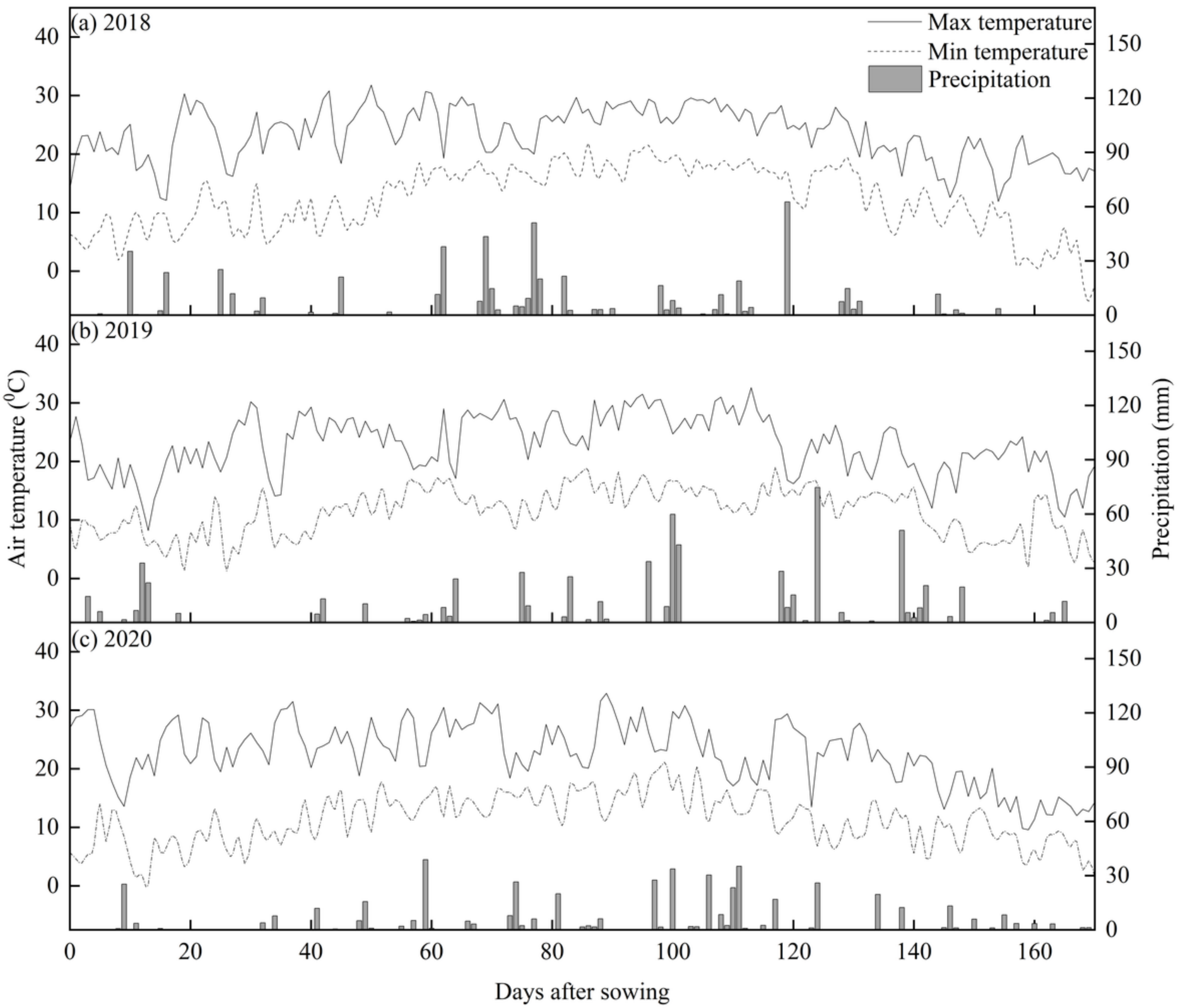

Figure 1

Dynamics of temperature and precipitation from 2018 to 2020 at the experimental site.

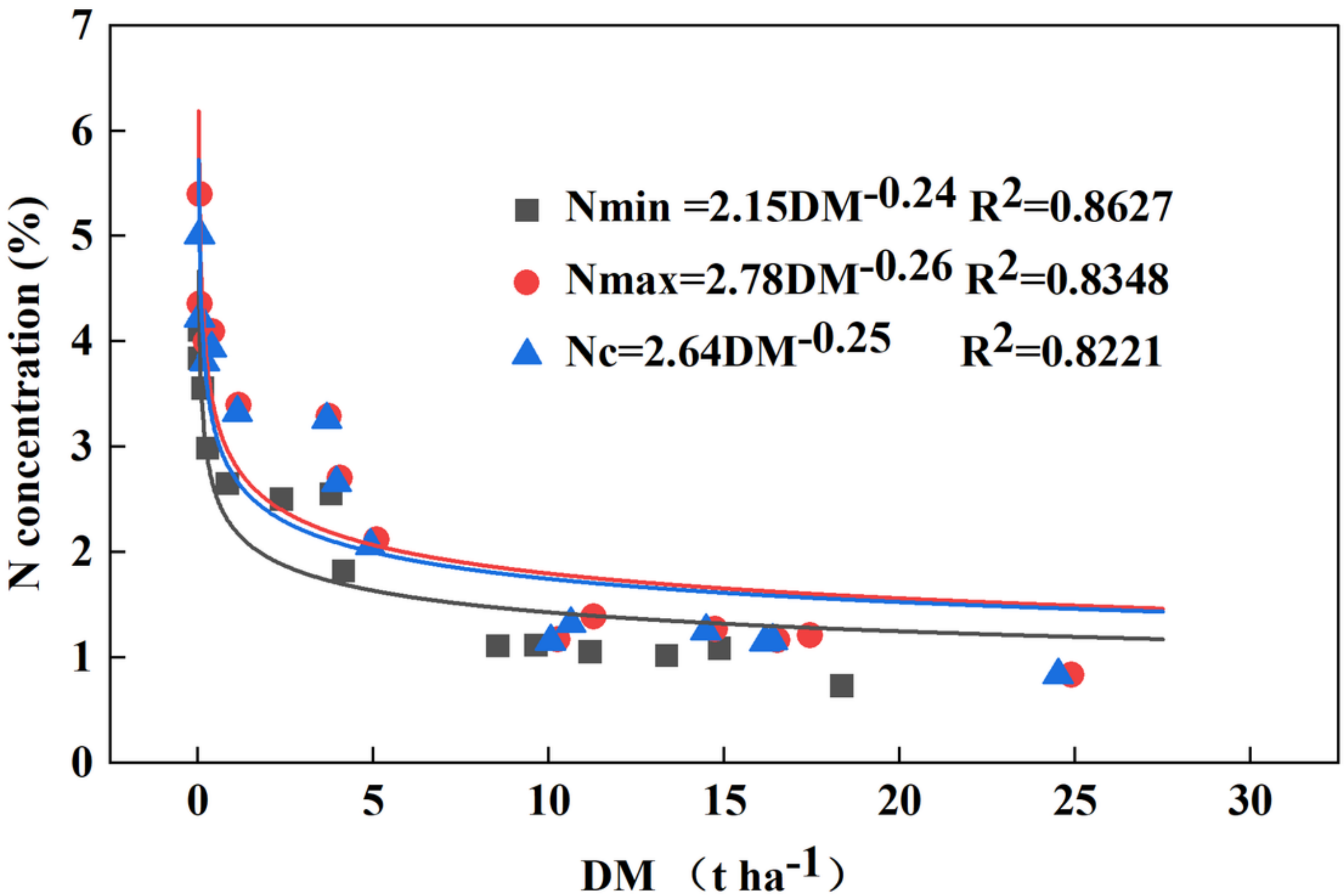

Figure 2

(a) Critical N curve for maize using plant N content and dry matter accumulation (DM), and (b) Critical P curve for maize using plant P content and dry matter accumulation (DM).

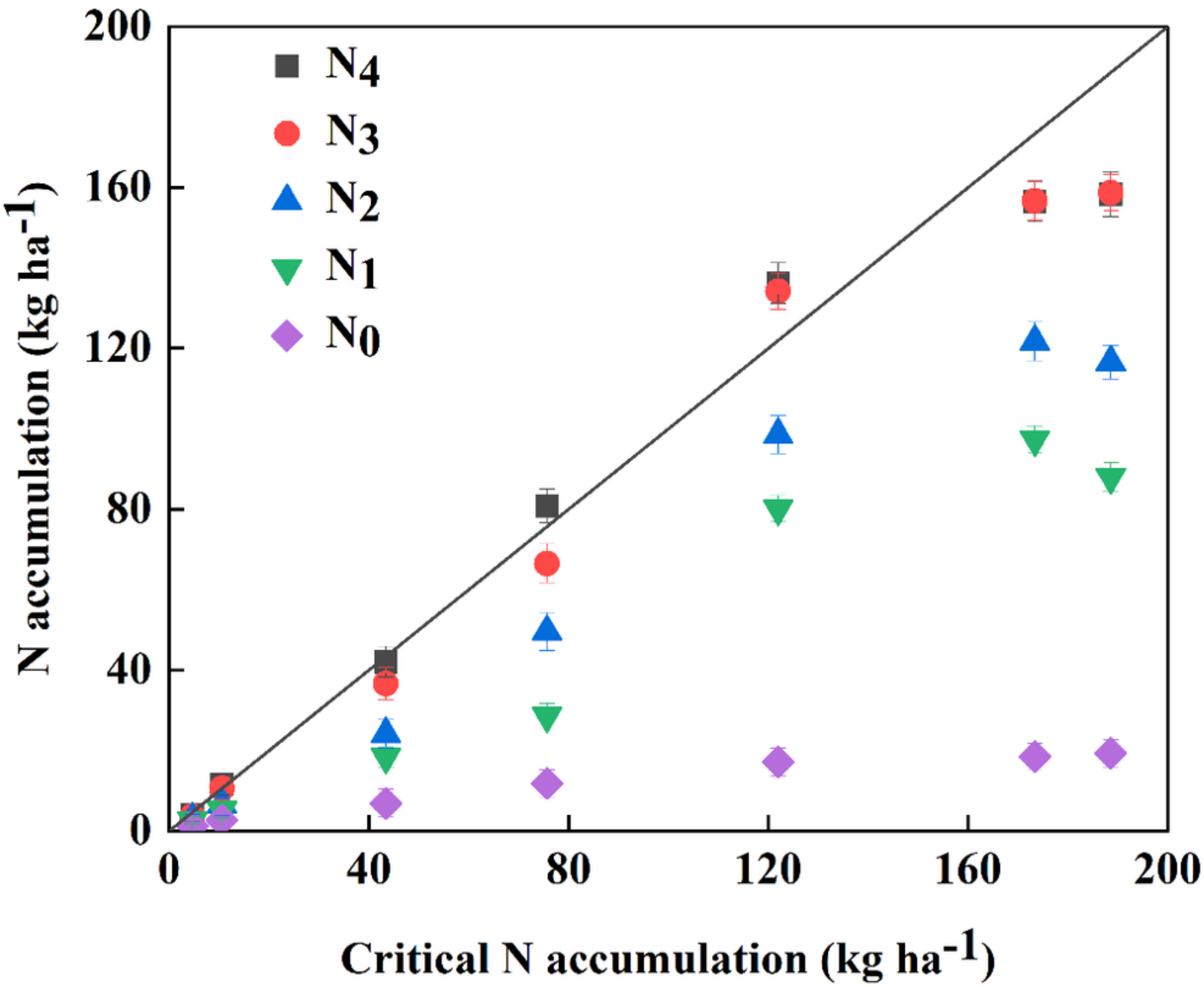

Figure 3

(a) 1:1 comparison of critical N accumulation and measured plant N accumulation for each treatment, and (b) 1:1 comparison of critical P accumulation and measured plant P accumulation for each treatment.

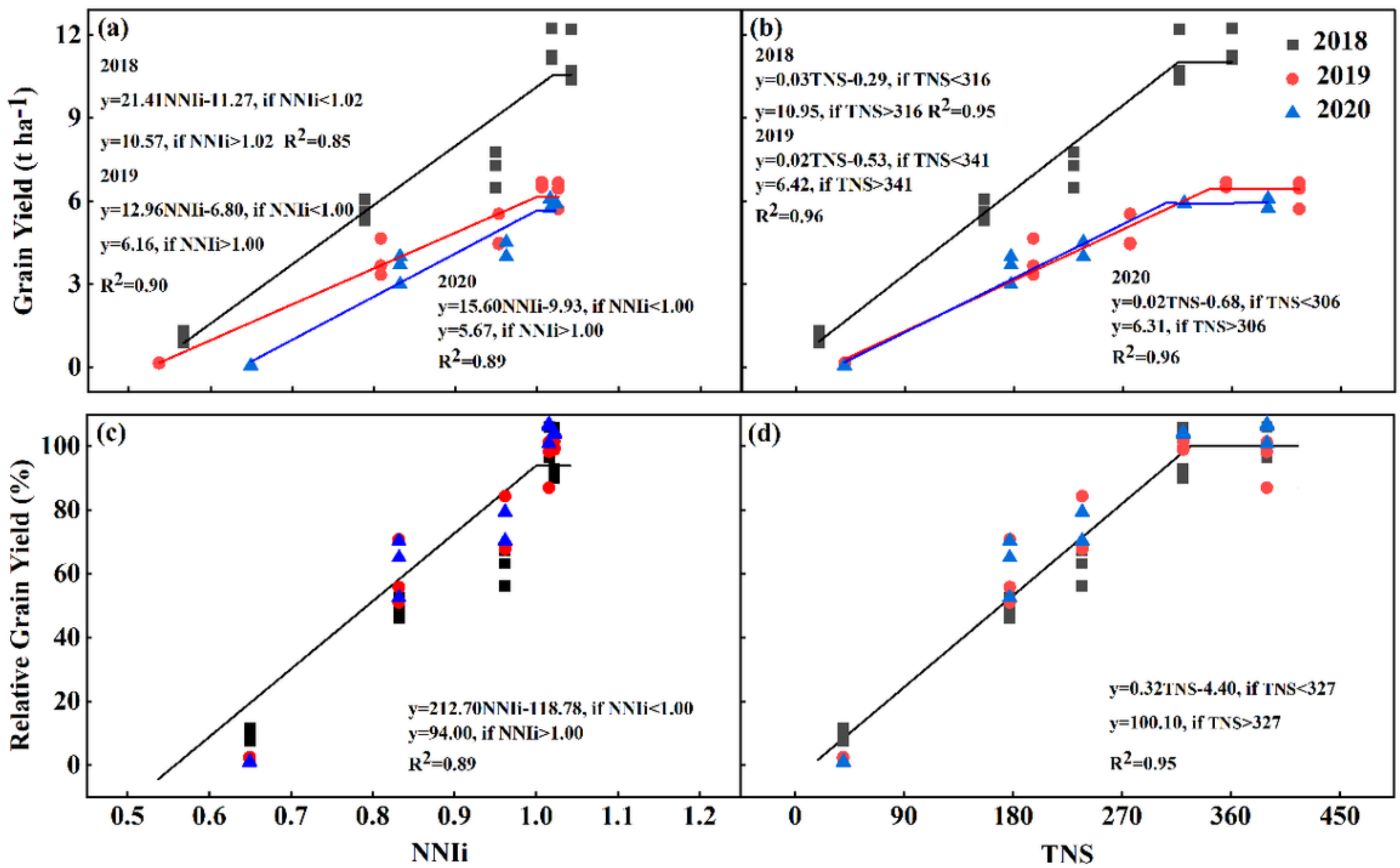

Figure 4

Grain yield in response to the integrated N nutrition index (NNIi) and total N supply (TNS) in 2018, 2019, and 2020 maize growing seasons were applying a linear-plateau model with (a, b) grain yield and (c, d) relative grain yield values.

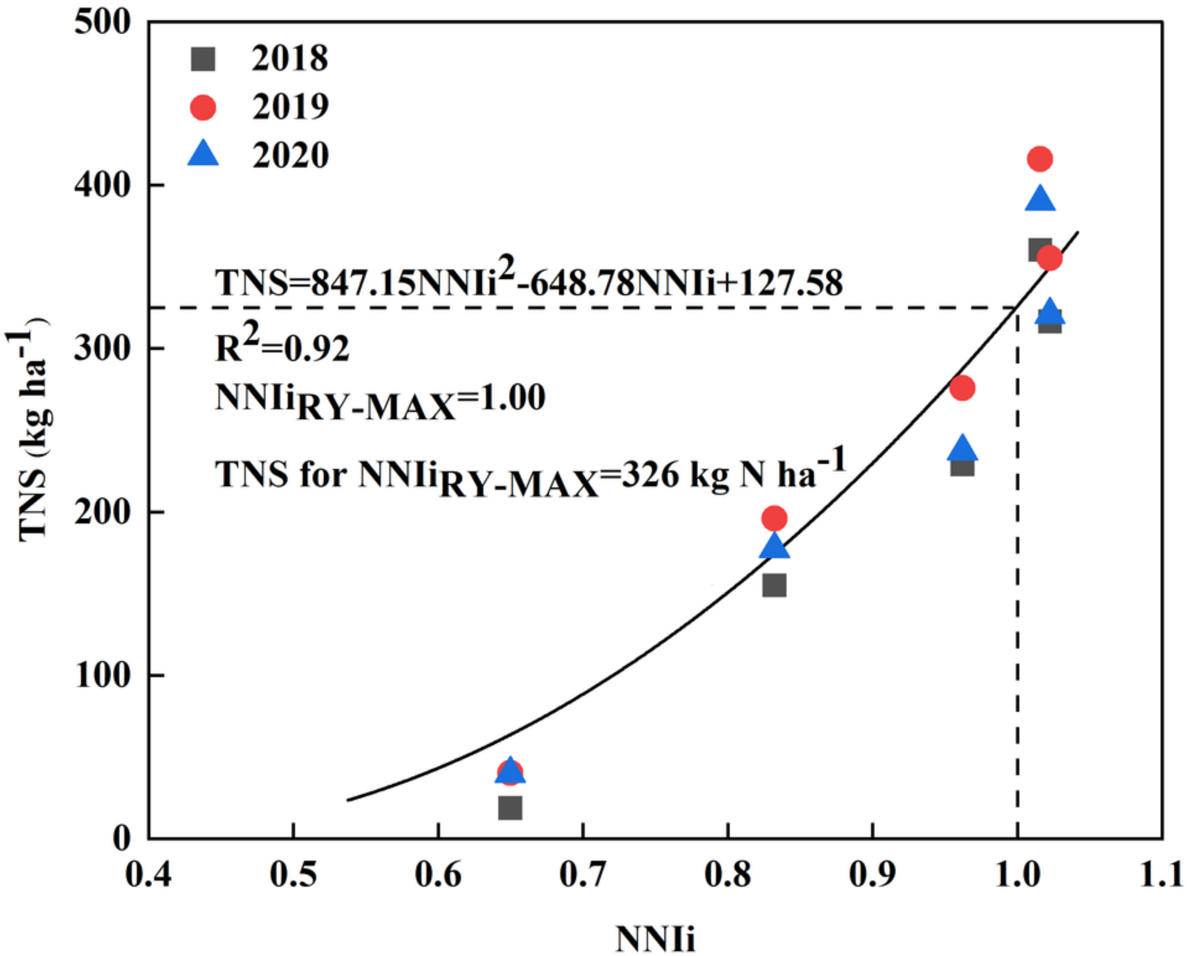

Figure 5

Relationship between the integrated N nutrition index (NNIi) and total N supply (TNS) in 2018, 2019, and 2020 maize growing seasons. $NNIi_{RY\text{-}Max}$ is the minimum value of NNIi associated with the minimum relative yield from Fig. 4c.

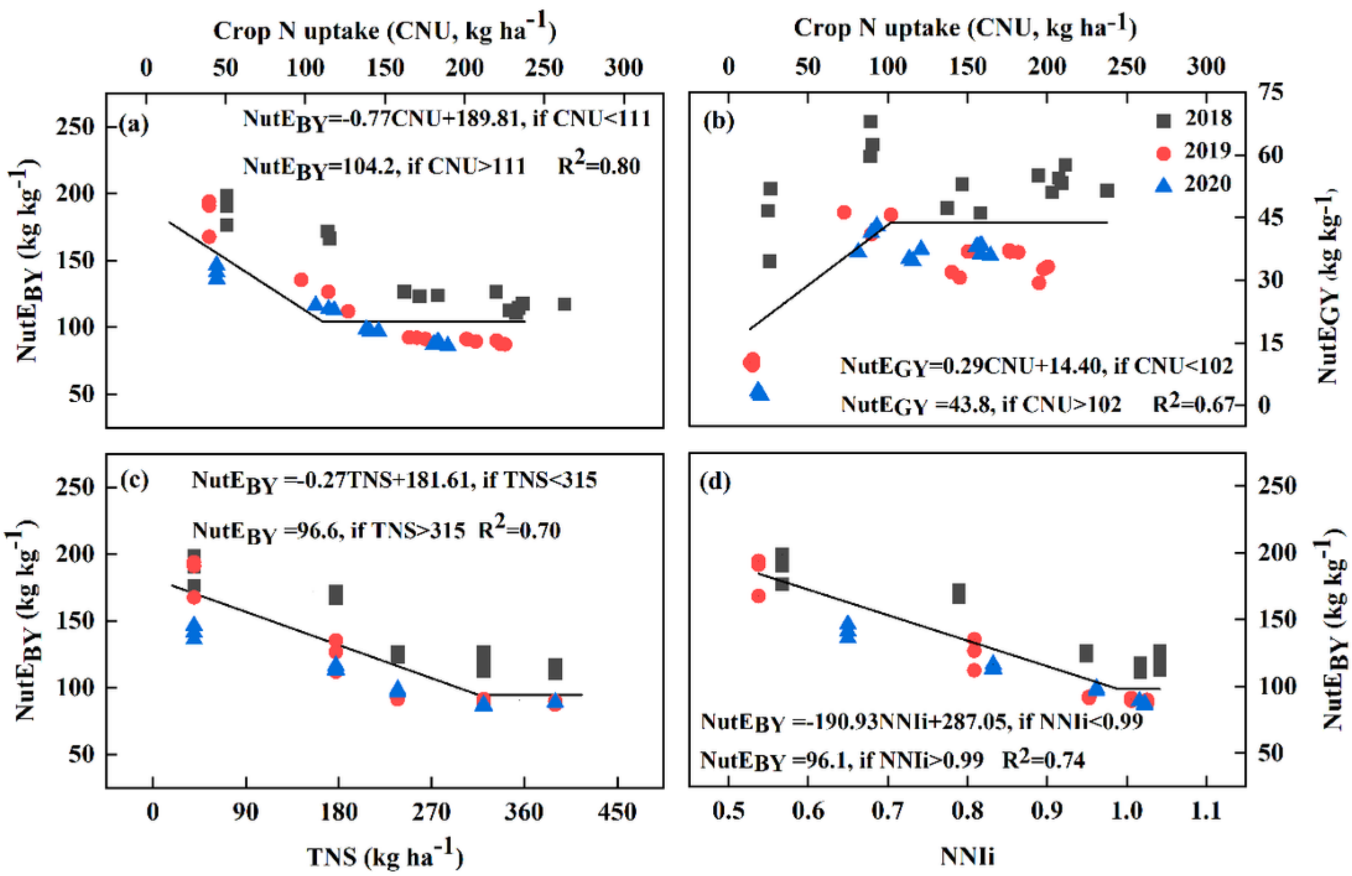

Figure 6

Nitrogen utilization efficiency for (a) dry matter biomass per unit of N uptake ($NutE_{BY}$), and (b) grain yield per unit of N uptake ($NutE_{GY}$), to crop N uptake in 2018, 2019, and 2020 maize growing seasons, (c) the relationship between biomass yield N utilization efficiency ($NutE_{BY}$) and total N supply (TNS) in 2018, 2019, and 2020 maize growing seasons, (d) the relationship between biomass yield N utilization efficiency ($NutE_{BY}$) and the integrated N nutrition index (NNIi) in 2018, 2019, and 2020 maize growing seasons.

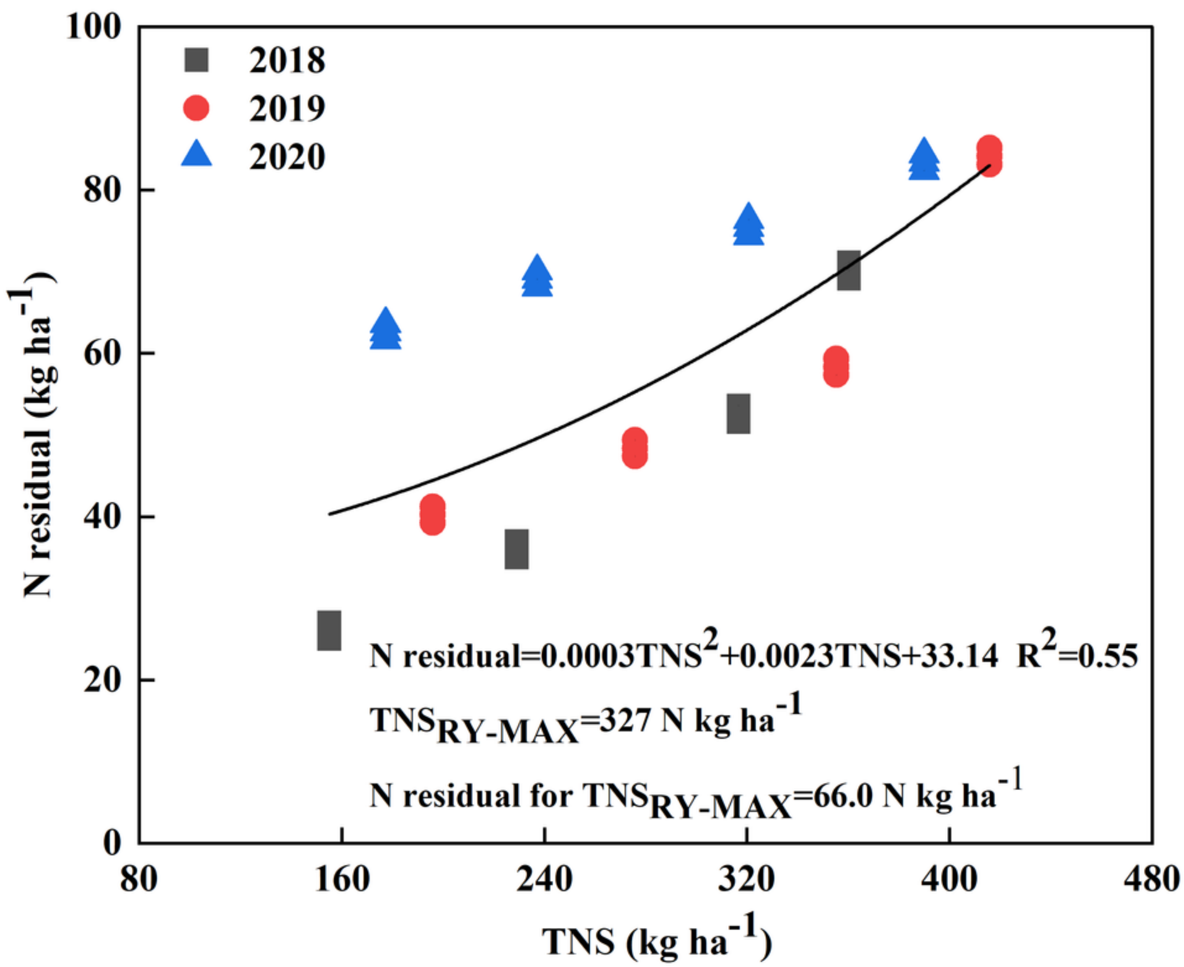

Figure 7

The relationship between residual mineral N in the soil at the end of 2018, 2019, and 2020 maize growing seasons and total N supply (TNS). A quadratic model represents the best-fit model. $TNS_{RY\text{-}Max}$ is the minimum amount of TNS associated with maximum relative yield from Fig. 4d.

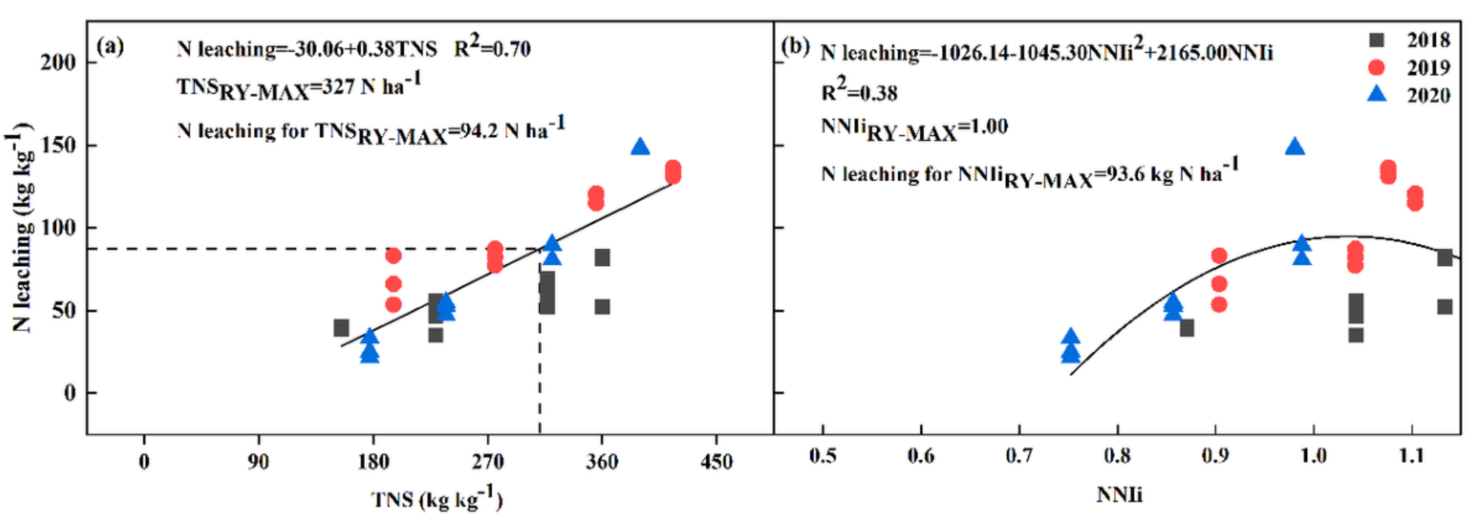

Figure 8

Relationship between N leaching in the soil at the end of 2018, 2019, and 2020 maize growing seasons, and (a) total N supply (TNS) and (b) the integrated N nutrition index (NNIi).

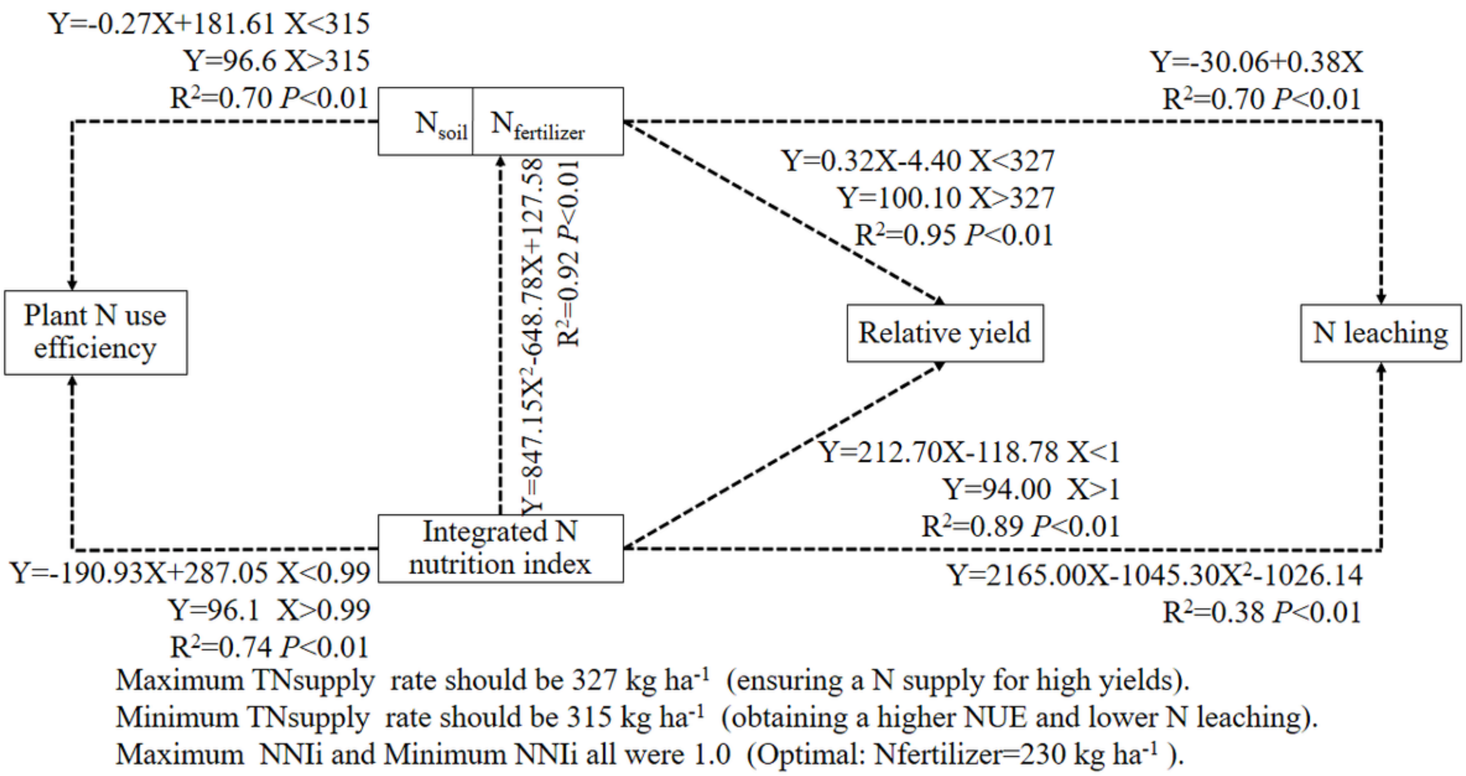

Figure 9

Summary of the relationships between total nitrogen supply (TNS), integrated N nutrition index (NNIi), relative grain yield (RY), N leaching, and NUE. Note: The dependent variable Y in the figure represents the variable in front of the arrow, while the independent variable X represents the variable at the end of the arrow.

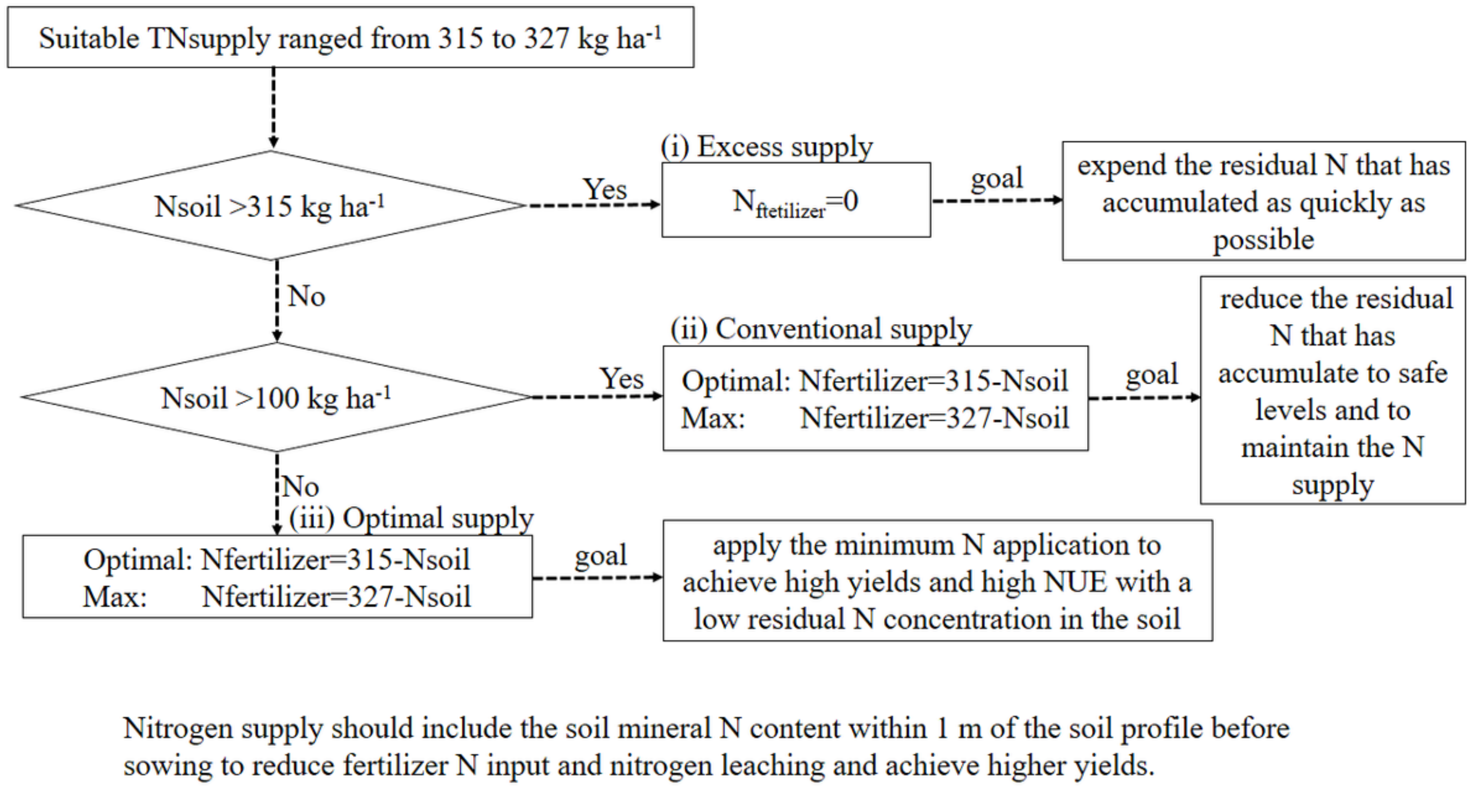

Figure 10

Flowchart of the suitable total nitrogen supply (TNS) rate. Note: The units are kilograms per hectare.