

Nitrogen fertilization mitigates global food insecurity by increasing cereal yield and its stability

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ABSTRACT

It is well known that nitrogen (N) fertilization can significantly enhance cereal yield. However, unknowns remain regarding the effects of long-term N fertilization on cereal yield stability, which is as important as cereal yield in addressing the global food crisis. To address this knowledge gap, I synthesized 467 N application studies with duration ≥ 5 years in croplands across the world. Overall, long-term N fertilization increased both cereal yield ($3099 \pm 210 \text{ kg ha}^{-1} \text{ yr}^{-1}$ [95% CI] under control vs. $5163 \pm 303 \text{ kg ha}^{-1} \text{ yr}^{-1}$ under N fertilization) and its stability (interannual coefficient of variation: $34 \pm 3\%$ under control vs. $28 \pm 2\%$ under N fertilization). Soil properties mostly explained the variations of the responses of cereal yield (62%) and its stability (50%) to N fertilization. From fertilizer management perspective, the highest and most stable cereal yield were produced when N was applied with phosphorus and potassium fertilizers. Overall, this study suggests that long-term N fertilization can contribute to relieving the global food crisis by not only enhancing cereal yield but also promoting its stability.

1. Introduction

The global population has increased from 2.50 billion to 7.96 billion people in the past 70 years, which has led to a rapid increase of global food demand. Since nitrogen (N) fertilizers are responsible for feeding approximately half of the world's population (Erisman et al., 2008; Smil, 2002), the world will not be able to meet its food production goals without N fertilization. In addition, only 41% of grains are used for human consumption, and up to 35% are used for animal feed (Poutanen et al., 2022). Approximately 40% of the maize production in the United States is used for biofuel (Ranum et al., 2014). Moreover, as an important source of carbohydrate, cereal yield plays a great role in global dietary pattern (Seal et al., 2021). Overall, from the aspects of food, feed, and dietary choice, N fertilization plays a great role in global food security by influencing cereal yield. The food insecurity in Sri Lanka caused by the ban on chemical fertilizer imports from 2021 further proves the importance of chemical fertilization. Because of this, many relevant studies have been done in past decades. However, most studies only focused on how N fertilization affects cereal yield (Adams et al., 2020; Cardinael et al., 2022; Chen et al., 2021; Mi et al., 2019; Zhang et al., 2018) but overlooked its effect on cereal yield stability (Chen et al., 2018; Han et al., 2020; Macholdt et al., 2019), although both of

them are important for global food security (Garibaldi et al., 2011; Knapp and van der Heijden, 2018).

Cereal yield can fluctuate greatly from year to year (Chen et al., 2018; Han et al., 2020). Cereal yield stability, which can be represented by the interannual coefficient of variation of cereal yield (CV), plays a great role in global food security (Müller et al., 2018; Xu et al., 2019). For example, if N fertilization generally enhances cereal yield in the long term but decreases cereal yield stability, world crop production may not meet global food demand in some years. Nevertheless, N fertilization effects on cereal yield stability have been less studied (Chen et al., 2018; Macholdt and Honermeier, 2019), partly because the number of relevant long-term studies (e.g. ≥ 5 years) is small. Even among the limited number of studies reporting N effects on cereal yield stability, opposite results were found. For example, Han et al. (2020) conducted a 34-year field experiment and found that N increased yield stability of rice no matter whether N was applied with phosphorus (P) and potassium (K) fertilizers. When compared to control, however, yield stability of wheat decreased when N was applied along or with phosphorus fertilizer but increased when N was applied with both P and K fertilizers. These results indicate that N effects on yield stability vary greatly across crop type and fertilizer combination even at the field site scale. However, little is known regarding whether the same results exist at the global scale. In

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order to calculate a relatively accurate yield stability, a long-term measurement of cereal yield under N fertilization is required. At present, many more results of cereal yield have been reported by N fertilization experiments at multi-decadal timescales (e.g. Adams et al., 2020; Cardinael et al., 2022; Chen et al., 2021), which provides a great opportunity to determine N effects on cereal yield stability.

Overall, there are two main knowledge gaps regarding effects of N fertilization on cereal yield stability. First, there are very few studies reporting cereal yield under both control and constant N fertilization in the long-term (>15 years), which can be used to calculate cereal yield stability (Chen et al., 2018; Han et al., 2020; Macholdt and Honermeier, 2019). As a result, the information about the responses of cereal yield stability to N is limited at the global scale, although some relevant long-term studies have been conducted. Second, almost all long-term N studies were conducted at the local scale. In other words, it is difficult to comprehensively quantify controls on effects of N fertilization on cereal yield stability because each field site does not have large variations in climate, soil, and management. To address these two knowledge gaps, I synthesize 467 long-term (≥ 5 years) studies in croplands across the world. I hypothesized that 1) given the great role of N fertilization in improving soil fertility (Cai et al., 2019; Liang et al., 2015, 2019), not only cereal yield but also its stability could be enhanced by N; and 2) because of the ubiquitous N limitation in croplands (Ringeval et al., 2021), N application rate would be the most influential factor that affects the responses of cereal yield and its stability to N fertilization. It should be noted that, although food insecurity is a multidimensional issue, the present study mainly focused on cereal yield, which is only one of the dimensions. Overall, the results of this meta-analysis can provide information to help landowners and policymakers make decisions that address the global food crisis.

2. Methods

2.1. Data sources

I searched the Web of Science for papers that reported cereal yield under N application in croplands. The keywords consisted of “nitrogen addition” OR “nitrogen fertilizer” AND “crop yield” OR “grain yield”. To standardize the dataset, four criteria were used: (a) only yield of cereal was included in the present study, although tubers and oil crops also contribute to global food production; (b) annual cereal yield under both control (no chemical fertilization) and N fertilization treatments were reported at least 5 years from the beginning of the experiment; and (c) I regarded cereal yield from different crop types, tillage systems, irrigation treatments, or N application rates in the same study as independent observations. Following this preliminary screening, my meta-analysis included 467 N fertilizer case studies from 95 field sites (Figs. S1 and S2).

In addition to cereal yield under both control and N fertilization treatments, I also obtained site location (e.g. latitude and longitude), climate variables (e.g. mean annual temperature [MAT], mean annual precipitation [MAP], annual air temperature and precipitation), initial soil variables (e.g. organic carbon [SOC], total and available N, P, and K [TN, AN, TP, AP, TK, and AK], pH, clay content, and bulk density), fertilizer variables (fertilizer combination [e.g. N, NK, NP, and NPK], N form [e.g. mixed, NH_4 , NH_4NO_3 , urea, and CAN], and application rate), and crop related variables (crop type [e.g. barley, maize, millet, wheat, soybean, sorghum, and rice] and cropping system [e.g. monoculture and rotation]). If soil organic matter (SOM) was reported, SOC was calculated via dividing SOM by 1.724 (the Van Bemmelen factor). For N form, mixed represents that N type changed over time during the experiment; NH_4 includes ammonium sulphate, ammonium chloride, and ammonium phosphate; and CAN represents calcium NH_4NO_3 . The number of study reporting MAT, MAP, annual air temperature, annual precipitation, SOC, TN, AN, TP, AP, TK, AK, pH, clay content, and bulk density was 296, 300, 59, 154, 336, 251, 135, 125, 253, 104, 216, 335, 163, and

104, respectively. More information about the summary of the dataset that was used in this meta-analysis study can be found from Table S1. Engauge Digitizer software 12.1 was used to extract the data if the results were presented in figures.

2.2. Data analysis

2.2.1. Cereal yield and its stability

The interannual coefficient of variation of cereal yield (CV) under control or N fertilization treatment for each study was calculated to represent cereal yield instability as follows:

$$\text{CV} = \sigma/\mu \times 100 \quad (1)$$

where σ is the standard deviation of cereal yield during the experiment; and μ is average cereal yield ($\text{kg ha}^{-1} \text{ yr}^{-1}$). The higher CV of cereal yield, the lower cereal yield stability.

The response ratios of cereal yield (RR_{yield}) and its stability (RR_{CV}) were calculated as follows:

$$\text{RR} = \ln (X_t / X_c) \quad (3)$$

where X_t is the average of cereal yield in all experimental years or CV under N fertilization treatment; and X_c is the average of cereal yield in all experimental years or CV under control.

RR_{yield} and RR_{CV} were weighted by sample size and experimental duration as follows (César et al., 2016):

$$w = (n_c \times n_t) / (n_c + n_t) + (\text{yr} \times \text{yr}) / (\text{yr} + \text{yr}) \quad (4)$$

where W is the weighting factor; n_c and n_t is sample size under control and N fertilization treatment, respectively; and yr is the length of the study in years. For the studies that did not provide sample sizes (46 of 467 studies), they were assigned as the median of sample sizes (3) of the other 421 studies. 95% CI was calculated for $\text{WRR}_{\text{yield}}$ and WRR_{CV} . If 95% CI did not overlap with zero, N fertilization effects on cereal yield and its stability were significant.

I detected possible publication bias in two ways: first, funnel plots were created by using the “funnel” function; second, I used mixed-effects meta-regression version of the Egger test to statistically test the possible publication bias (“regtest” function). Overall, no significant publication bias was found (Fig. S3). I conducted the meta-analyses using “metafor” package in the R studio (Viechtbauer, 2010).

2.2.2. Factors controlling N fertilization effects on cereal yield and its stability

The response ratio of cereal yield during each year was calculated for each study. Spearman rank-order correlation test was performed to test the relationship between the response ratio of cereal yield during each year and annual air temperature or precipitation. Among 59 studies reporting annual air temperature during the experiment, only 10 studies showed significant relationships ($|\text{coefficient}| \geq 0.6$) between the response ratio of cereal yield and annual air temperature (Fig. S4). Moreover, among 155 studies reporting annual precipitation during the experiment, only 22 studies showed significant relationships ($|\text{coefficient}| \geq 0.6$) between the response ratio of cereal yield and annual precipitation (Fig. S5). These results indicate that interannual variation of climate does not significantly explain N effects on cereal yield over time and its stability. Therefore, annual temperature and precipitation were not included in the latter statistical analyses.

It should be noted that cereal yield may increase over time because of agronomic and genetic technologies, leading to technological trend. Therefore, I performed Spearman rank-order correlation test to determine the relationship between experimental duration (year) and cereal yield under control treatment. I found that only 21 out of 467 studies showed significantly increased temporal trend of cereal yield under control treatment ($|\text{coefficient}| \geq 0.6$), indicating that technological

trend of cereal yield was not common. Moreover, almost no studies provided the relevant information (e.g. whether agronomic and genetic technologies were changed during the experiment), making it difficult to include this potential factor in the analysis. In addition, given that improved agronomic and genetic technologies should be applied under both control and N fertilization treatments, the effect of technological trend on my results in the present study should be relatively weak.

Simple linear regression was used to determine the relationships among RR_{yield} , RR_{CV} , climate variables (MAT and MAP), N application rate, and all soil variables. The boosted regression tree (BRT) analysis was performed in R with “gbm” package (Greenwell, 2019) to quantify the relative influences of predictor variables on RR_{yield} and RR_{CV} . Parameter values used for the BRT analysis such as shrinkage, interaction.depth, and ntree were set as 0.01, 2 and 12,000, respectively. Predictor variables consisted of MAT, MAP, N application rate, N form, fertilizer combination, crop type, cropping system, and initial soil variables. 84% of the variation in RR_{yield} and 83% in RR_{CV} were explained by the BRT analysis. All statistical analyses and graphs were conducted in R (R Core Team, 2020).

3. Results

3.1. Cereal yield

N enhanced cereal yield at the global scale (Fig. 1). More specifically, cereal yield under control and N treatment was $3099 \pm 210 \text{ kg ha}^{-1} \text{ yr}^{-1}$ and $5163 \pm 303 \text{ kg ha}^{-1} \text{ yr}^{-1}$, respectively (Table S2). After considering the contribution to world cereal yield of each continent, I roughly estimated that N fertilization increased global cereal yield by 62% (Table S3). The greatest effect of N on cereal yield was found when N was applied along with P (NP) or with both P and K fertilizers (NPK) (Fig. 1). N effects on cereal yield also varied with N type, and cropping system did not significantly alter N fertilization effects on cereal yield.

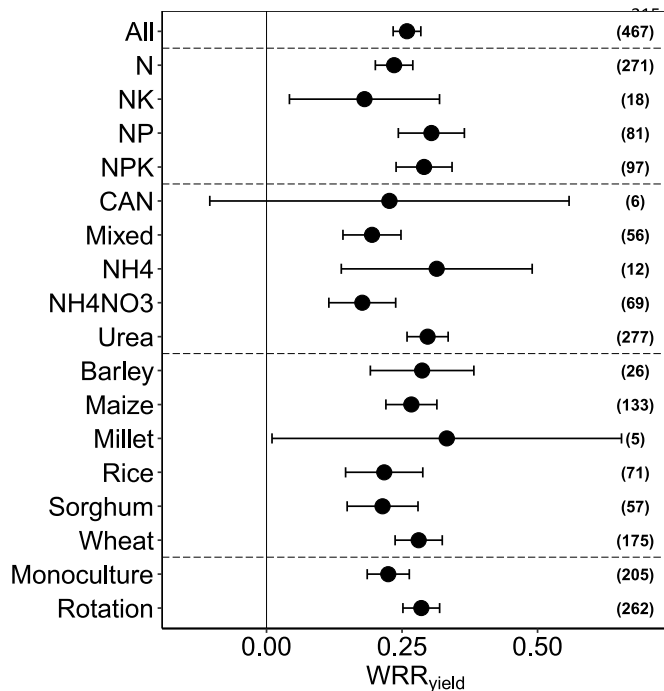


Fig. 1. Weighted response ratios of cereal yield (WRR_{yield}) under N fertilization in studies grouped by fertilizer combination, crop type, N form, and cropping system. The dots and bars represent the mean and 95% confidence intervals, respectively. The number next to the dots is the sample size of each variable. P values indicate the significance of the difference in WRR_{yield} among variables in each group.

According to the results of linear regression, RR_{yield} was positively correlated with MAT, MAP, pH, N application rate, and soil bulk density but was negatively related to SOC, TK, and AP (Table 1). According to BRT analysis, for individual predictor variables, SOC mostly contributed to the change in RR_{yield} (Fig. 3a). For grouped predictor variables, soil variables had the greatest influence on RR_{yield} , which accounted for 62.0% of its variation, followed by fertilizer (23.8%), climate (10.6%), and crop variables (3.6%).

3.2. Cereal yield stability

N significantly increased yield stability across the world (Fig. 2). Specifically, CV under control and N treatment was $34 \pm 3\%$ and $28 \pm 2\%$, respectively (Table S2). N effects on yield stability were insignificant when N was applied with K fertilizer (NK), but became positive when N was applied alone (N) or with P (NP) or both P and K (NPK). The greatest positive effect of N on yield stability was found when N was applied along with both P and K fertilizers (NPK). Greater positive effect of N fertilization on yield stability was found when N form was NH_4 than others except for CAN. The effect of N fertilization on yield stability was insignificant when crop type was millet and rice, but became significantly positive when crop type was barley, maize, sorghum, and wheat.

According to the results of linear regression, the response ratio of yield stability was positively correlated with soil pH, N application rate, and AP (Table 1). By contrast, negative correlations were found among the response ratio of yield stability, MAP, clay content, SOC, and AN. According to BRT analysis, for individual predictor variables, MAT and MAP mostly explained the change in the response ratio of yield stability (Fig. 3b). For grouped predictor variables, soil variables were the most influential variables affecting the response ratio of yield stability, which accounted for 50.0% of its variation, followed by climate (23.7%), fertilizer (17.6%), and crop variables (8.7%).

Table 1

Relationships between the response ratios of cereal yield (RR_{yield}) and its stability (RR_{CV}) and climate, fertilizer, and soil variables according to a simple linear regression.

	RR_{yield}		RR_{CV}	
	Relationship	P value	Relationship	P value
MAT	+	< 0.001	0	0.64
MAP	+	< 0.01	+	< 0.05
pH	+	< 0.01	–	< 0.05
Clay	0	0.28	+	< 0.05
Rate	+	< 0.001	–	< 0.001
SOC	–	< 0.05	+	< 0.05
TN	0	0.35	0	0.15
TP	0	0.82	0	0.70
TK	–	< 0.01	0	0.45
AN	0	0.06	+	< 0.05
AP	–	< 0.05	–	< 0.01
AK	0	0.76	0	0.88
BD	+	< 0.01	0	0.07

Notes: For the simple linear regression, RR_{yield} and RR_{CV} were dependent variables, and climate, fertilizer, and soil variables are independent variables. W (the weighting factor) was used as weight in the linear regression. + represents significantly positive relationship; – indicates significantly negative relationship; and 0 means insignificant relationship. Significant relationships ($P < 0.05$) are highlighted in bold. MAT: mean annual temperature; MAP: mean annual precipitation; pH: soil pH; Clay: soil clay content; Rate: N application rate; SOC: soil organic carbon; TN: soil total nitrogen; TP: soil total phosphorus; TK: soil total potassium; AN: soil available nitrogen; AP: soil available phosphorus; AK: soil available potassium; BD: soil bulk density.

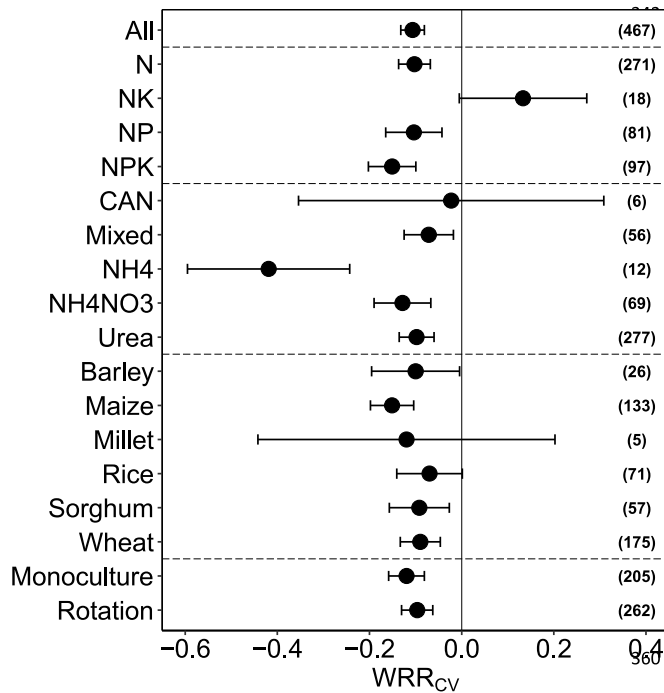


Fig. 2. Weighted response ratios of interannual coefficient of variation of cereal yield (WRR_{CV}) under N fertilization in studies grouped by fertilizer combination, crop type, N form, and cropping system. The dots and bars represent the mean and 95% confidence intervals, respectively. The number next to the dots is the sample size of each variable. P values indicate the significance of the difference in WRR_{CV} among variables in each group.

4. Discussion

4.1. N effects on cereal yield and the controls

My study found that long term N increased cereal yield by 62%, which indicates the great role of N in stimulating cereal yield. This value was higher than the results of previous studies (e.g. 44%–48% from [Erismann et al., 2008](#)). It is partly due to the higher N application rate ($126 \text{ kg N ha}^{-1} \text{ yr}^{-1}$) from the long-term studies that were included in this meta-analysis study than the average N application rate in the real world ($74 \text{ kg N ha}^{-1} \text{ yr}^{-1}$) ([Lu and Tian, 2017](#)). Due to the “Bucket effect”, it is not surprising that N effects on cereal yield were greater when

N was applied along with either P or both P and K fertilizers than when N was applied alone ([Fig. 1](#)). N fertilization can significantly improve soil nutrients, which are essential for cereal yield ([Cai et al., 2019](#); [Liang et al., 2015, 2019](#)). However, the positive effect of N fertilization on cereal yield may decrease in soils with good nutrient condition. Therefore, I found negative correlations between RR_{yield} , initial SOC, AP, and TK ([Table 1](#)). In addition to soil nutrient condition, high precipitation and air temperature usually stimulate crop yield ([Ray et al., 2015](#)). Therefore, positive correlations among RR_{yield} , MAT, and MAP were found in the present study. My results also showed that the magnitude of N effects on cereal yield increased with the increasing of N application rate. However, it should be noted that nitrogen agronomic efficiency decreases with the increasing of N application rate ([Anas et al., 2020](#); [Liang et al., 2022](#)). In other words, the increase in cereal yield caused by per unit of N fertilization ($1 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ here) would be higher in the extremely poor countries (e.g. Africa) than high income countries (e.g. Europe and North America) because of higher N application rate in the developed countries. Therefore, the great difference in N application rate across regions should be considered when scaling my results to the globe. Overall, this meta-analysis study suggests that optimal instead of excessive amount of N fertilizer should be applied into croplands.

4.2. N effects on cereal yield stability and the controls

To the best of my knowledge, this is the first study that found N fertilization increased yield stability at the global scale ([Fig. 2](#)). Generally speaking, N fertilization may improve yield stability in multiple ways. From the aspect of plants, N fertilization can stimulate leaf photosynthesis ([Fang et al., 2018](#)) and root growth ([Sarker et al., 2017](#)) in croplands, and thus enhancing crops' capacity to uptake water and nutrients ([Yan et al., 2021](#); [Yu et al., 2013](#)). Therefore, crops are better developed under N fertilization, and then are more resistant against environmental (e.g. drought) and pest stresses. From the aspect of soils, N fertilization can significantly improve soil physical (e.g. soil aggregation ([Wang et al., 2018](#))), chemical (e.g. soil C and N content ([Liang et al., 2021](#))), and biological properties (e.g. soil enzyme activities ([Miao et al., 2019](#))). All these effects can lead to sustained soil fertility, which in turns enhances soils' resilience to stresses across years. From the aspect of plant-soil-microbe interactions, N fertilization usually increases root biomass ([Zhang et al., 2020](#)) and exudates ([Zhu et al., 2016](#)) in croplands. On one hand, roots are usually left in soils after the harvest in croplands, which can provide a large amount C for soil microbial growth. On the other hand, root exudates are considered as high quality of C input, which can increase soil microbial C use efficiency ([Sokol and](#)

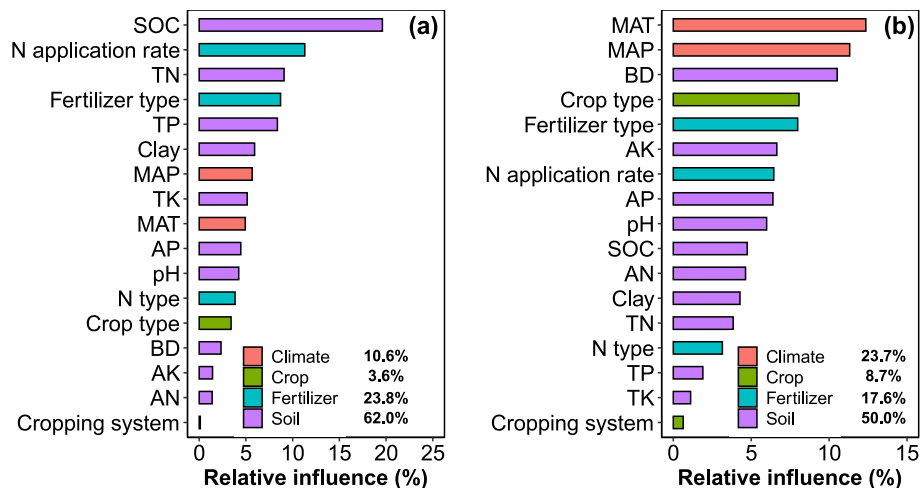


Fig. 3. The relative contributions (%) of predictor variables for the boosted regression tree model of response ratios of cereal yield (a) and its stability (b) and sustainability (c). See [Fig. 1](#) for the abbreviations of variables and the scenarios that fertilizer combination, crop type, N form, and cropping system include.

Bradford, 2019). Higher root biomass and exudates under N fertilization finally result in a more favorable growing conditions for soil microbes, which play a great role in nutrient cycling.

According to “Bucket effect”, the limited nutrients can shift from N to P and K after long-term N application. In other words, no inputs of exogenous P and K may create an un-balanced nutrient supply, resulting in unsustainable condition. Therefore, it is not surprising that cereal yield was more stable when N was applied with both P and K fertilizers. As another fertilizer related variable, N form also significantly changed N impacts on yield stability. For example, more stable cereal yield was found when N was applied as NH_4 . This might be explained by two reasons. First, when compared to NO_3 , NH_4 is more energetically efficient since NH_4 can be directly incorporated into glutamate via an NH_4 assimilation pathway. Therefore, crops can uptake N for their growth with very low energy input even under extreme conditions (e.g. drought or pest pressure) when N form is NH_4 . Second, long-term N application can lead to severe soil acidification, which can significantly inhibit crop growth (Guo et al., 2010). For example, soil pH decreased from 5.7 to 4.0 in a wheat-maize rotation system after 25-year N fertilization (Cai et al., 2019). As a result, cereal yield under N fertilization continuously decreased over time. After 10-year continuous N application, crop failure started and continued to the end of the experiment, which indicates that N fertilization led to unstable cereal yield by causing soil acidification. By conducting a meta-analysis study, Tian and Niu (2015) found that soil pH decreased when N form was urea or NH_4NO_3 but did not significantly change when N was applied as NH_4 . In other words, soil acidification can be avoided by using NH_4 . Consequently, cereal yield was more stable when N fertilizer was applied as NH_4 , although this might be an artefact of the relatively small number of studies applying NH_4 as N fertilizer. It should be noted that N loss via ammonia volatilization is usually higher when N type is urea or NH_4 than NH_4NO_3 (He et al., 1999). Therefore, more studies should be done in the future to better explain why more stable yield was found when N type was NH_4 . Theoretically speaking, high N application rate may reduce yield stability by inducing pest damage and lodging (Iskra et al., 2018). According to the findings from this study, however, the positive effect of N on yield stability increased with the increasing of N application rate. This might be because, in order to relieve the potential issues (e.g. plant diseases and insect pests) caused by high N application rate, some relevant measures (e.g. crop breeding and pesticide) have been taken in the experiments. It should be noted that, although high N application resulted in high cereal yield and more stable yield, optimum instead of excessive N fertilizer should be applied in croplands. This is because overuse of N fertilizer not only causes low fertilizer use efficiency but also leads to soil degradation and environmental problems (e.g. soil acidification, nutrient run-off, and increased greenhouse emissions) (Guo et al., 2010; Miao et al., 2011; Zhang et al., 2013).

In addition to fertilizer-related variables, climate variation was another important factor affecting cereal yield worldwide (Ray et al., 2015). I found that positive effect of N on yield stability tended to decrease with the increasing of MAP, and MAT and MAP were the most important variables explaining N effects on yield stability. These results might be explained by the following reasons. First, P limitation is more severe under high MAP (Hou et al., 2020), which can be further aggravated by applying N. As a result, unbalanced soil nutrient condition is not beneficial for stable yield. Second, soil pH decreases with the increasing of MAP (Slessarev et al., 2016). Therefore, soil acidification caused by N fertilization can be more serious under high MAP, resulting in high variation in cereal yield between years (e.g. continuously decreased cereal yield). Third, high precipitation amount can lead to serious nutrient loss (e.g. N, P, K, and other microelements) (Yao et al., 2021). In other words, more frequent precipitation pulses in regions with high MAP can cause greater variation in soil nutrient condition between years, which in turn decreases N effects on yield stability.

Both linear regression and BRT analysis showed that soil pH significantly mediated N impacts on yield stability. Specifically, cereal yield

under N fertilization was more stable in soils with high initial pH, which reflects the significant role of soil pH in yield stability. High initial soil pH has greater capacity to buffer soil acidification caused by long-term N fertilization than low initial soil pH. Consequently, relatively high soil pH can result in more favorable condition for both plants and microbes, and thus increasing yield stability. This result indicates that, in order to achieve maximum effects of N fertilization on cereal yield stability, some measures (e.g. applying lime or organic fertilizers) should be taken to solve soil acidification caused by long term fertilization.

5. Conclusions

Both cereal yield and its stability play a great role in addressing global food crisis. Compared to N fertilization effects on cereal yield, how cereal yield stability responds to long-term N fertilization at the global scale is less understood. By overlooking this, we may estimate future global food security inaccurately. To determine long term N fertilization effects on cereal yield and its stability, I collected data from 467 long-term N application studies (≥ 5 years) in croplands across the world. I found that long term N fertilization not only enhanced cereal yield but also promoted its stability. Overall, soil variables mostly explained the variations in N effects on cereal yield and its stability. From the perspective of fertilizer management, in order to achieve the highest values of cereal yield and its stability, N should be applied along with P and K fertilizers. This meta-analysis study indicates that long-term N fertilization can contribute to relieving the global food crisis by not only enhancing cereal yield but also promoting its stability.

Authors contribution

G.L. designed the study, analyzed the data, and wrote the manuscript.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.gfs.2022.100652>.

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