Effects of nitrogen fertilizer application on saline-alkali land cotton in China quantified using meta-analysis and regression analysis

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Abstract: Nitrogen fertilizer application is an important means to promote cotton production in saline-alkali land. A meta-analysis and regression analysis of 49 peer-reviewed studies were conducted using yield data (373 data points), dry matter accumulation (114 data points), and water use efficiency (157 data points) to quantify the effect of nitrogen fertilizer on the yield, dry matter accumulation, and water use efficiency of cotton in saline-alkali land in China for different planting management practices and different growing environments. The results showed that the nitrogen application significantly improved the yield, dry matter accumulation, and water use efficiency by 34.11%, 36.27%, and 33.87%, respectively, compared with no nitrogen application. The largest improvements in the yield, dry matter accumulation, and water use efficiency occurred in areas where saline-alkali land had been improved for many years, in Eastern China, South Central China, and Northwest China (areas with annual average precipitation ≤200 mm or >800 mm, and annual average evaporation ≤800 mm or >2400 mm), in areas with trickle irrigation, and fields with a planting density of 100 000 to 250 000 plants/hm^2. Cotton exhibited the optimal response to nitrogen application at a rate of 300-375 kg/hm^2, a basal application ratio of 20%-40%, and top-dressing in the cotton bud, flowering boll, and full boll stages. The effect of nitrogen application increased as the salinity increased. A suitable nitrogen application rate, top-dressing ratio, and top-dressing period are crucial for increasing cotton production in saline-alkali land, although environmental differences and planting measures have to be considered. This study provided information on the correct application of nitrogen fertilizer to maximize its benefits and suggests controlling nitrogen fertilizer inputs in agriculture to protect the soil environment and ensure sustainable agricultural development.

Keywords: meta-analysis, regression analysis, nitrogen fertilizer application, saline-alkali land, cotton
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1 Introduction

Using limited crop production resources and continuously changing production conditions to meet the growing population demand is a major problem facing the current society[1]. Especially for cotton as an important textile raw material, and the second largest crop after grain. China's cotton production accounts for nearly one-third of the world's total cotton[2,3]. Cotton is suitable for growing in areas with high temperatures and sufficient sunlight[4]. However, while the main cotton growing areas in China have specific climatic conditions suitable for cotton growth, there is also a widespread distribution of saline land caused by scarce precipitation, strong evaporation, and lack of water resources[5,6]. Although cotton is a salt-tolerant crop, salt aggregation and lack of nutrients in the tillage layer of saline-alkaline land soils can also hinder seed germination, and root and plant growth, ultimately affecting cotton production[7].

Studies have shown that nitrogen fertilizer is an essential nutrient element required for cotton growth and development[8,9], and suitable amounts of water and fertilizer are essential for the agricultural production of cotton in salinized farmland[10]. Adequate amounts of water and fertilizer can increase cotton yield in salinized cotton fields under drought stress[11-13]. Du et al.[14] demonstrated that nitrogen fertilizer application (NFA) increased the photosynthetic rate and dry matter accumulation (DMA) of cotton under drought stress in a saline-alkaline area. A sufficient amount of dry matter is required for cotton to absorb nutrients. The number of bolls per plant, the total number of bolls, and the quality of single bolls of cotton can be significantly improved, increasing the cotton yield and achieving high and stable yields[15-17]. Some studies have found that NFA could improve soil fertility and the soil environment and increase the mineral nitrogen content in the soil[12,18], minimizing the adverse effects of a harsh environment on cotton growth and development[19-22]. The adequate distribution of nitrogen fertilizer provides the necessary nutrients for cotton growth during the critical growth period to ensure the development of roots, stems, leaves, and branches of cotton[18] and enable the plants to deal with salinity

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and drought stress and produce a high yield[13,23].

However, cotton is sensitive to the application amount and application period of nitrogen fertilizer. Nitrogen participates in all metabolic processes during cotton growth and affects the cotton yield, DMA, and water use efficiency (WUE)[9,24-26]. Improper NFA to cotton in saline-alkali land leads to a decline in cotton yield, DMA, WUE, and quality, pollutes the groundwater, destroys farmland ecosystems, and exacerbates soil salinization, soil compaction, soil acidification, and loss of soil organic matter and nitrogen[18,27,28].

Numerous domestic and foreign scholars researched NFA to cotton planted in saline-alkali land. However, no systematic study has been conducted on the required application of nitrogen fertilizer at different growth stages, different saline-alkali gradients, planting conditions, and management patterns. This information is required to guide NFA to cotton in saline-alkali land and control agricultural nitrogen fertilizer inputs. Meta-analysis allows for a comprehensive analysis of multiple studies on the same topic by quantifying effect indicators and integrating multiple studies to provide a systematic analysis of the combined effects and influencing factors under specific conditions[29]. Therefore, a meta-analysis of relevant research data was conducted by the authors in the past 20 years and quantitatively analyzed the effect of NFA under different conditions on the yield, DMA, and WUE of cotton. The sources of heterogeneity and the main influencing factors were identified by meta-analysis and regression analysis. The purpose of this study was to provide guidance for NFA to cotton for different salinity levels and different regions in China to improve the field management of cotton in saline-alkali land. The results of this study provided a basis for the strict control of agricultural nitrogen fertilizer pollution and quantitative theoretical support for the protection of farmland ecosystems to change the misconception of farmers that more fertilizer results in higher yields.

2 Materials and methods

2.1 Data sources

The publications were retrieved from multiple Chinese and English databases, including the Web of Science (http://accesss.webofknowledge.com/) and the China National Knowledge Infrastructure (CNKI) (https://www.cnki.net/). Chinese and international articles were obtained and published before 2020 on the effects of nitrogen fertilizer on the yield, DMA, and WUE of cotton grown in saline-alkali land in China. The search keywords included "nitrogen application rate" OR "nitrogen fertilizer application" AND "cotton" AND "yield" OR "production" AND "dry matter accumulation" AND "water use efficiency". We retrieved 1162 publications. The following screening criteria were used to meet the data requirements of the meta-analysis: 1) The study area is located in China, and the study site and start and end years of the experiment are described in the text; 2) The experiment is a field experiment, and the treatment must include NFA and a control (no NFA). The proportions of the basal fertilizer and top-dressing fertilizer are listed; 3) The paper describes the yield (lint yield), DMA (total DMA), and WUE of each treatment and the standard deviation or multi-year experimental data; 4) The planting management measures are described, such as the row spacing and plant spacing (planting density). After filtering the data using the four screening criteria, a total of 49 valid publications were obtained, containing 373 sets of yield-related data, 114 sets of DMA-related data, and 157 sets of WUE-related data. The studies were conducted in 13 provinces.

To find more detailed information on heterogeneity. In addition to the four screening criteria, it was ensured that other factors affecting the growth of cotton were included in the publication, such as precipitation, evaporation, air temperature, altitude, soil type, cotton variety, irrigation methods, irrigation amounts, mulching materials, nitrogen fertilizer types, and planting patterns.

2.2 Data classification

The screened data were organized and grouped. All nitrogen fertilizers were urea. The phosphorus and potassium fertilizers and the irrigation water amounts in the publications were based on conventional local management. All fertilizers were applied with water. Precipitation, evaporation, temperature, and other factors were categorized according to climate types, such as humid, arid, and semi-arid areas, and temperature zones, such as cold, intermediate, and warm temperate zones. The other subgroups were classified according to gradients (some subgroups were categorized based on the influence of the sample size on the analysis results) (see Appendix Table A1). According to meteorological conditions, administrative divisions, and farming systems, we divided the 13 provinces into North China (Hebei, Shanxi), Northeast China (Liaoning), Eastern China (Jiangxi, Anhui, Jiangxi, Shandong), South Central China (Henan, Hubei, Hunan), Southwest China (Sichuan) and Northwest China (Gansu, Xinjiang).

2.3 Data analysis

2.3.1 Meta-analysis

The effect size y_i and the within-study variance V_i were calculated using the average yield (average DMA, average WUE) and its standard deviation and the number of replicates in each study with NFA (treatment group) and no NFA (control group)[30].

$$y_i = \ln R = \ln\left(\frac{Y_e}{Y_c}\right) \tag{1}$$

$$V_i = \frac{S_e^2}{N_e Y_e^2} + \frac{S_c^2}{N_c Y_c^2} \tag{2}$$

where, y_i is the effect size; R is the response ratio; Y_e is the average yield (average DMA, average WUE) of each experimental group; Y_c is the average yield (average DMA, average WUE) of each control group; V_i is the variance within the study; S_e is the standard deviation of each experimental group; S_c is the standard deviation of each control group; N_e is the number of replicates in each experimental group; N_c is the number of replicates in each control group.

R software was used to calculate the combined effect size y_i and within-study variance v_i of NFA on cotton yield, DMA, and WUE, and a heterogeneity test to obtain the Q statistic. A random effects model was selected based on the results[31,32].

$$w = \frac{1}{v} \tag{3}$$

$$\ln R^* = \frac{\sum_{i=1}^{N} W_i \ln R_i}{\sum_{i=1}^{N} W_i} \tag{4}$$

$$S(\ln R^*) = \sqrt{\frac{1}{\sum_{i=1}^{N} W_i}} \tag{5}$$

$$95\%\text{CI} = \ln R^* \pm 1.96 S(\ln R^*) \tag{6}$$

$$Q=\sum_{i=1}^{N}w_i(\ln R_i)^2-\frac{\sum_{i=1}^{N}w_i(\ln R_i)^2}{\sum_{i=1}^{N}W_i} \tag{7}$$

where, N represents the number of samples in the meta-analysis; w_i represents the weight of the i^{th} study; $\ln R_i$ represents the effect size of the i^{th} study.

The result of the effect size y_i was converted into the effect rate Z[30]:

$$Z=\left(\exp(\ln R)-1\right)\times 100\% \tag{8}$$

If the 95% confidence interval of the impact rate Z does not intersect (intersects) with zero, NFA has a significant (no significant) impact on the yield, DMA, and WUE of cotton in saline-alkali land. A value greater than zero indicates a positive effect and vice versa.

The presence of publication bias can significantly affect the results of a meta-analysis[33-35]. Funnel plots and rank correlation tests, which can be evaluated visually, were used in this study to test for publication bias[36].

$$t_i=\beta_1+\beta_0\left(\frac{1}{\ln R_i}\right)+v_i \tag{9}$$

$$v=\varepsilon_i/\ln R_i \tag{10}$$

where, t_i represents the t-test statistic for the i^{th} sample; β_0 and β_1 represent the intercept and coefficient, respectively; ε_i represents the residual for the i^{th} study; v represents the ratio of the residual and the effect size for the i^{th} study.

Each study was sequentially incorporated into the meta-analysis according to the time series, which is referred to as a cumulative meta-analysis. This approach can reflect the trend of the effect size and its 95% confidence interval over time. Subgroup analysis was carried out for different groups (influencing factors) to determine the source of the heterogeneity of the influencing factors on the results.

2.3.2 Regression analysis

Multiple linear regression analysis can be used to reveal potential nonlinear effects of numerical variables and can better explain the heterogeneity of NFA on cotton yield, DMA, and WUE in saline-alkali land. Nine numerical variables were selected from all subgroups, and multiple linear regression analysis was performed using these variables for the increased rate of yield, DMA, and WUE of cotton in saline-alkali land[36].

$$L=\alpha+\beta_1E+\beta_2D+\beta_3N+\beta_4B+\beta_5P+\beta_6E'+\beta_7T+\beta_8A \tag{11}$$

where, L represents the independent variable (the increase rate of the yield, DMA, and WUE of cotton); E represents the experimental period; D represents the planting density; N represents the nitrogen application rate; B represents the basal fertilizer proportion; P represents the average annual precipitation; E' represents the average annual evaporation; T represents the average annual temperature; A represents the average altitude; $\beta_{1\text{-}8}$ represent the coefficients of the variables.

Quantile regression analysis comprehensively describes the conditional distribution of the explanatory variables, and the error term does not require strong assumptions compared to the ordinary least squares method[37]. In this study, five quantiles, τ equals 0.10, 0.25, 0.50, 0.75, and 0.90 were selected. A model with eight numerical variables was constructed.

$$y_q(x_i)=x_i\beta_q \tag{12}$$

$$\min_{\beta_q}\sum_{i:y_i\geq x_i\beta_q}^{n}q|y_i-x_i\beta_q|+\sum_{i:y_i<x_i\beta_q}^{n}(1-q)|y_i-x_i\beta_q| \tag{13}$$

where, q represents the quantile of the distribution; $y_q(x_i)$ represents the linear function of x_i, β_q represents the regression coefficient of the q^{th} quantile, and i represents the number of variables. There were eight variables in this study, consistent with multiple linear regression.

2.3.3 Data processing

All data integration in this study was performed using Excel 2016 software, all data analysis was performed using the integrated development environment in the RStudio programming software, and all data visualization was performed using Origin 9.0 software.

3 Results

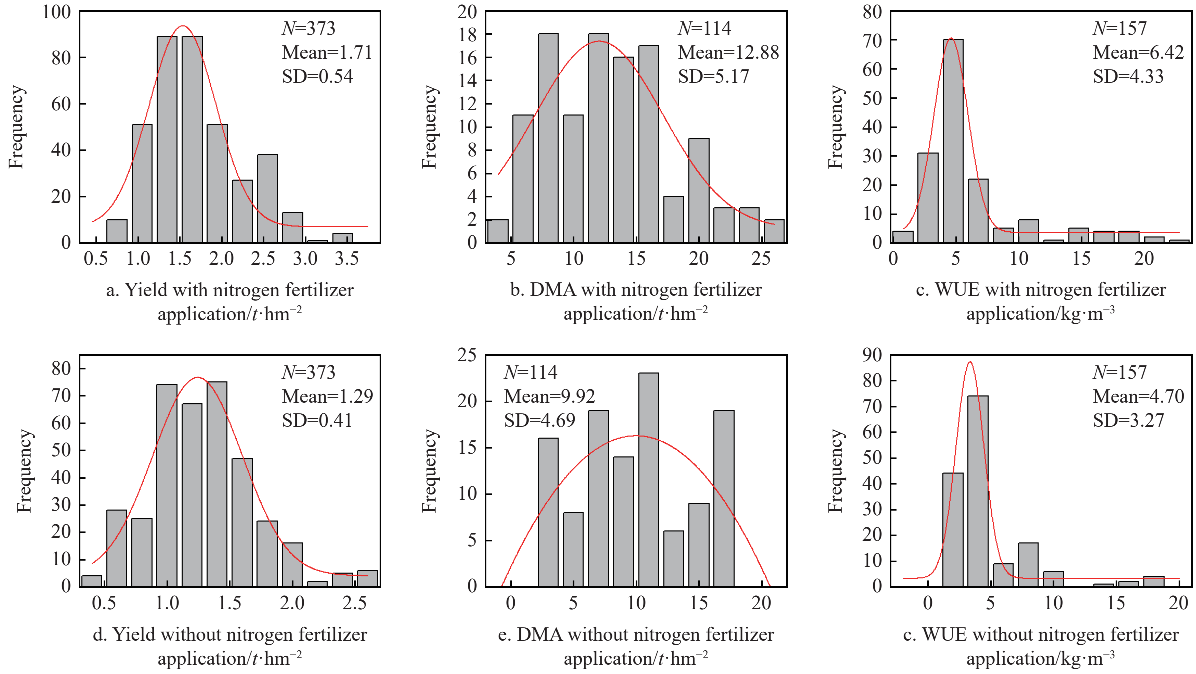
3.1 Comprehensive effects of NFA on cotton

The frequency distribution of the Gaussian function curve for the effect of NFA and no NFA on the cotton yield, DMA, and WUE in saline-alkali land is shown in Figure 1. The results showed that the data distribution was uniform, with an approximately normal distribution. There were large differences in the spatial and temporal variation in cotton yield, DMA, and WUE in saline-alkali land. NFA had a significant and positive effect on cotton production (Figure 2).

The results of the effect size analysis are listed in Table 1. A random-effects model (p<0.01) was used. The average yield increase rate after NFA to cotton in saline-alkali land was 34.11% (95% CI: 32.83%-35.40%), the average increase rate of DMA was 36.27% (95% CI: 33.26%-39.36%), and the average increase rate of WUE was 33.87% (95% CI: 30.06%-37.78%). According to the results of the publication bias test (Table 1) and the observation of the symmetry of the funnel plot, the data were evenly distributed. There was no publication bias for yield, DMA, and WUE (p>0.05). The combined effect of NFA on the yield, DMA, and WUE of cotton in saline-alkali land, and the 95% confidence intervals did not intersect zero. The results indicate that the effect of NFA on cotton in saline-alkali land is significant.

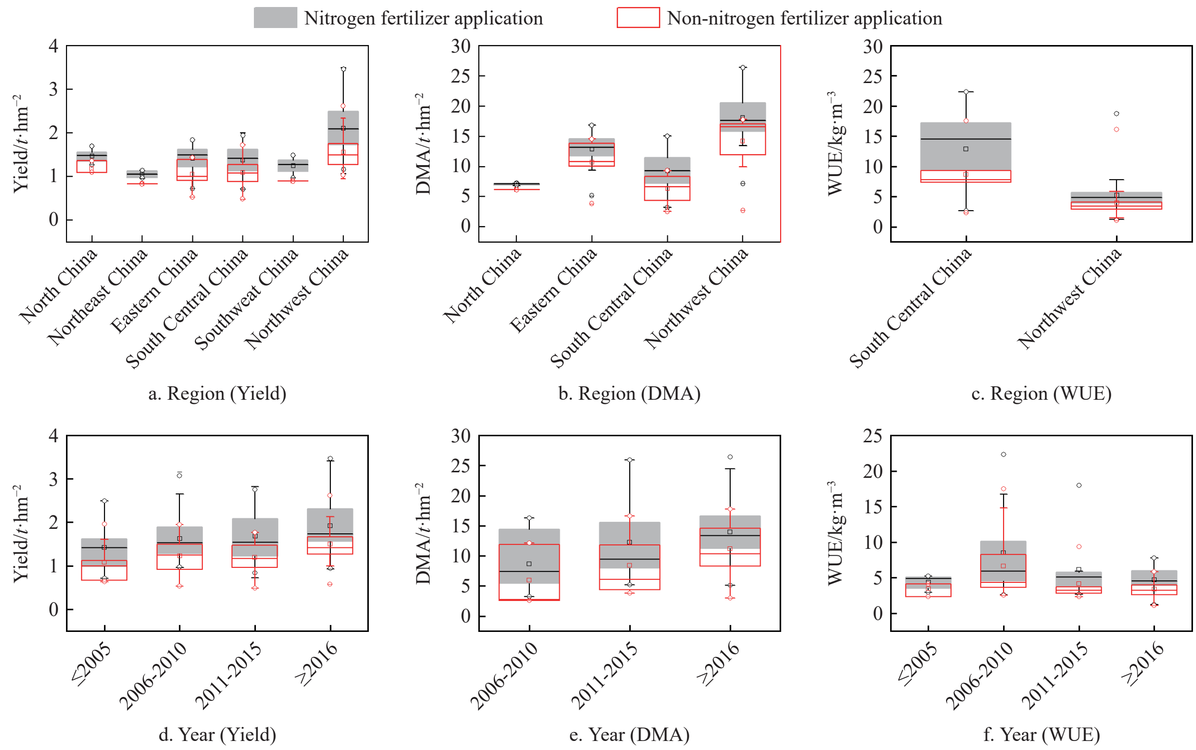
3.2 Cumulative meta-analysis of NFA to cotton

The average rates of increase in the yield, DMA, and WUE of cotton in saline-alkali land after NFA were subjected to a cumulative Meta-analysis based on the experimental year. (Figure 3). The results showed that since 2000, the cumulative average yield increase rate after NFA to cotton on saline-alkali land was 26.67%-37.09% compared with no NFA. The cumulative average yield increase rate showed a small fluctuation around the comprehensive average yield increase rate, and the fluctuation range gradually decreased over time. The cumulative average yield increase rate eventually approached the comprehensive average yield increase rate and remained stable. Since 2006, the average increase rate of the cumulative DMA of cotton was 36.53%-165.86% compared with no NFA. The average increase rate of the cumulative DMA showed a change from high to low, and the trend was stable. The average increase rate of DMA eventually approached the comprehensive average increase rate and remained stable. Since 2004, the cumulative average increase rate of WUE was 20.65%-37.85% compared with no NFA. The increase rate fluctuated before 2012 and approached the comprehensive average increase rate after 2012 and remained stable. The 95% confidence intervals of the cumulative average increase rate of the yield, DMA, and WUE



Note: NFA: Nitrogen fertilizer application; DMA: Dry matter accumulation; WUE: Water use efficiency. Same below.

Figure 1 Frequency distribution and the Gaussian function curve for yield, DMA and WUE of cotton in saline-alkali land



Note: The horizontal lines in the boxes and the lower and upper ends of the boxes indicate the 50th, 25th, and 75th percentiles, respectively. The dots inside and outside the box indicate the 1st and 99th percentile and outliers, respectively. The square dots inside and outside the box indicate the mean value.

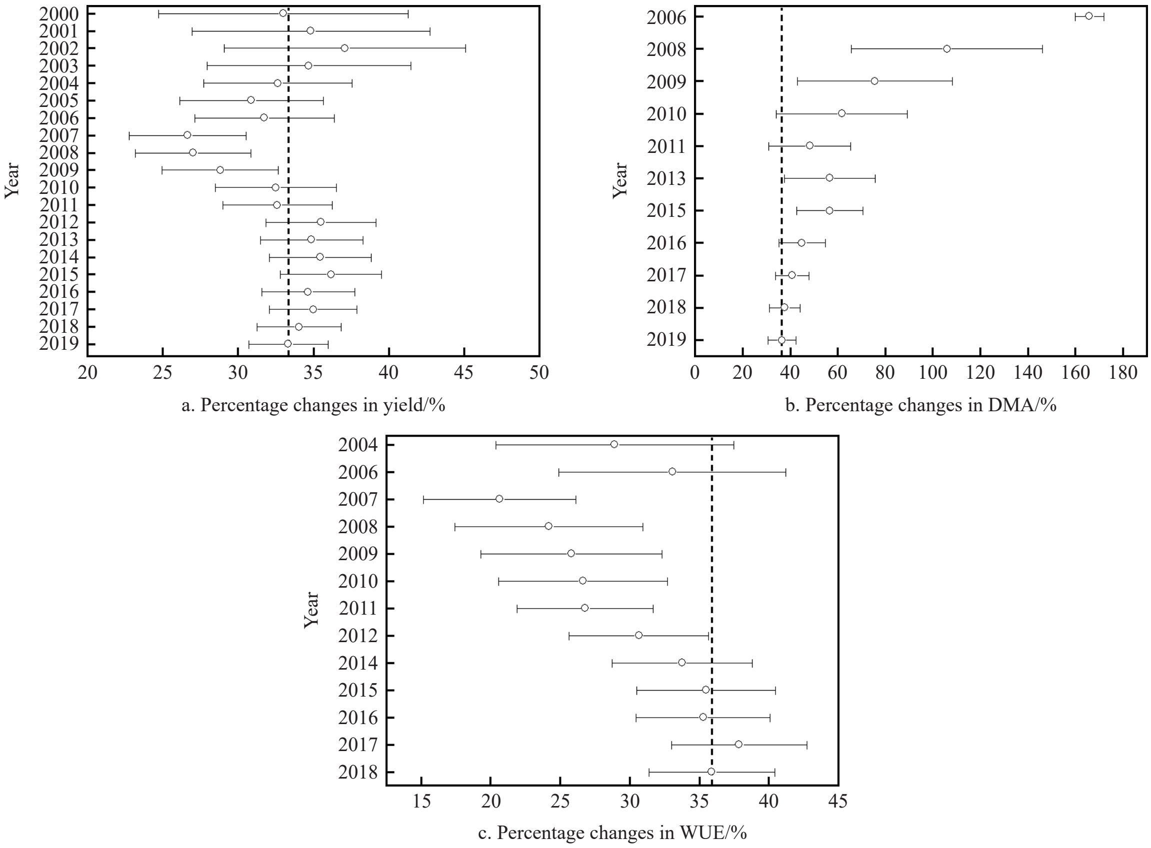
Figure 2 Spatial and temporal variation in cotton yield, DMA, and WUE in response to NFA in China

Table 1 Results of the comprehensive effect size analysis of NFA on the yield, DMA, and WUE of cotton in saline-alkali land

Item	Model	Increase rate/%	(95% CI)/%		Effect size test		Heterogeneity test		Publication bias test	
			Lower	Upper	Z	P	Q	P_Q	Z_B	P_B
Yield	REM	34.11	32.83	35.40	59.7153	<0.0001	12 286	<0.0001	−0.5453	0.5855
DMA	REM	36.27	33.26	39.36	27.0576	<0.0001	25 635	<0.0001	−0.9063	0.3648
WUE	REM	33.87	30.06	37.78	19.8041	<0.0001	15 644	<0.0001	1.1688	0.2425

Note: DMA: Dry matter accumulation; WUE: Water use efficiency. Same below; REM: Random effects model; Z is the statistic of the effect size test; P is the significance of the effect size test; Q is the statistic of heterogeneity test; P_Q is the estimated value of the overall heterogeneity; Z_B is the statistic of publication bias test; P_B is the p-value of publication bias test. The same as below.

became smaller over time. The results indicate that NFA has significantly increased cotton production in saline-alkali land in the past 20 years, and the cumulative effect has stabilized in recent years.



Note: The error bars represent the 95% confidence intervals. The dotted line represents the composite average improvement rate.

Figure 3 Results of the cumulative meta-analysis of the effects of NFA on the yield, DMA, and WUE of cotton in saline-alkali land

3.3 Effects of planting management factors

3.3.1 Experimental period

The increased rates of the yield, DMA, and WUE of cotton in saline-alkali land after NFA were all significantly affected by the experimental period. (Figure 4). The yield increase rate rose with an increase in the number of years after the experiment, but the rate remained stable in the first 2 years at 30.75% (95% CI: 27.86%-33.71%) and 31.23% (95% CI: 25.80%-36.90%). In the third and fourth year of NFA experiment, the yield rate increased rapidly to 44.20% (95% CI: 33.67%-55.55%) and 64.08% (95% CI: 47.98%-80.98%), respectively (Figure 4a). The increase rate of DMA was opposite to the increase rate of the yield, decreasing from 39.11% (95% CI: 32.46%-46.10%) in the first year to 20.62% (95% CI: 16.44%-24.97%) in the second year (Figure 4b). The rate of increase in WUE increased slightly with the number of years in the experimental period, from 34.06% (95% CI: 28.98%-39.33%) to 43.53% (95% CI: 35.35%-52.21%) (Figure 4c).

3.3.2 Planting density

The effect of the planting density on the increased rate of the cotton yield and WUE in saline-alkali land remained stable after NFA, but the effect on the increased rate of DMA showed substantial changes (Figure 4). The highest yield increase rate was 47.21% (95% CI: 41.00%-53.68%), and the lowest was 20.85% (95% CI: 18.34%-23.42%). The NFA increased the yield of cotton in saline-alkali land the most at the lowest and highest planting densities. The yield increase rate remained stable at planting densities between 100 000 and 250 000 plants/hm^2 (Figure 4a). The increase rate of DMA decreased steadily with an increase in the planting density from 45.34% (95% CI: 34.66%-56.86%) to 37.71% (95% CI: 26.56%-49.84%) to 24.38% (95% CI: 18.71%-30.33%). (Figure 4b). The improvement rate of WUE remained stable when the planting density was below 250 000 plants/hm^2 which was 35.84% (95% CI: 26.62%-45.73%) and 33.74% (95% CI: 27.71%-40.05%). When the planting density exceeded 250 000 plants/hm^2, the improvement rate increased slightly to 41.92% (95% CI: 33.50%-50.86%) (Figure 4c).

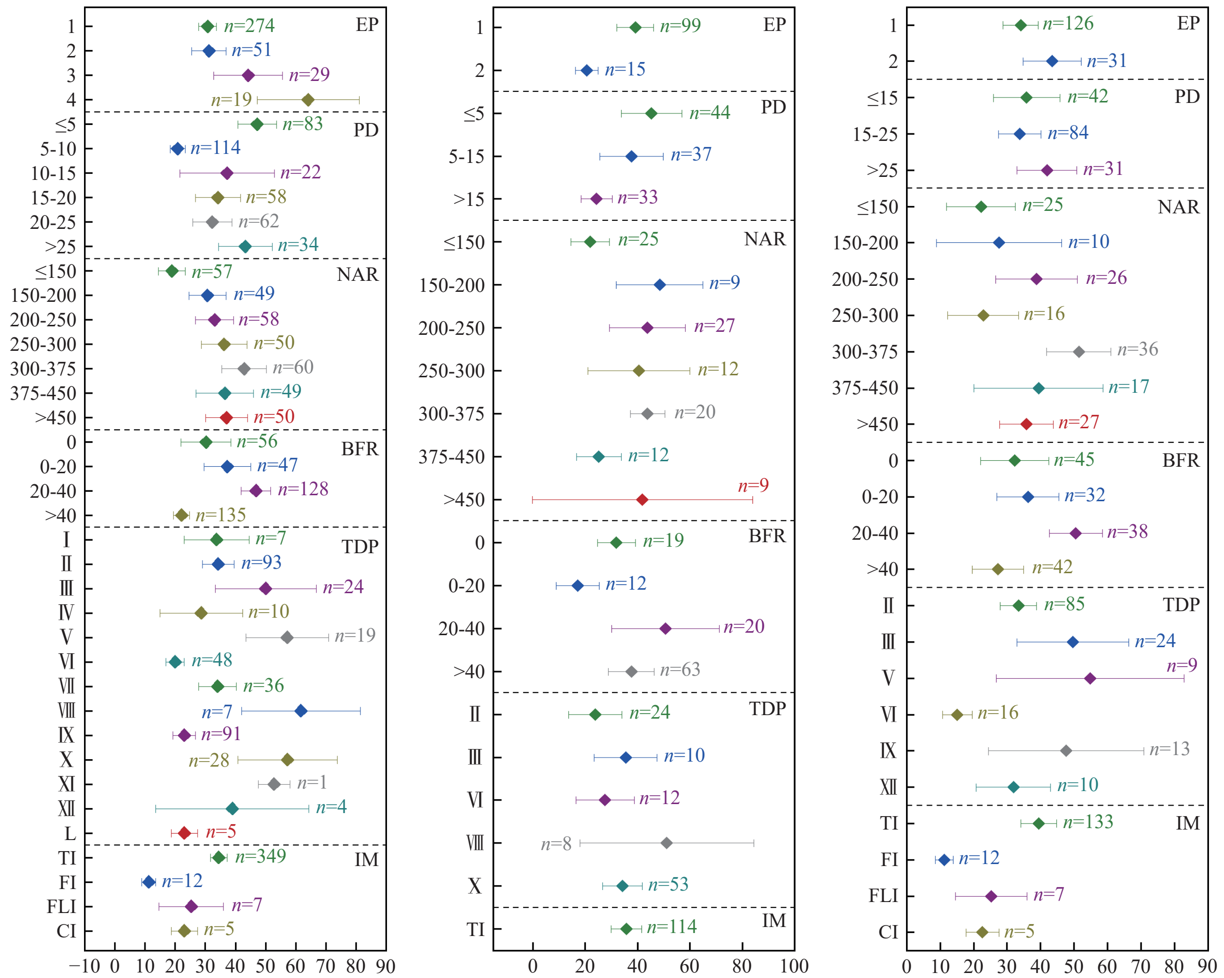
3.3.3 Nitrogen application rate

The nitrogen application rate affected the increase rate of the yield, DMA, and WUE, which increased and then decreased (Figure 4). The yield increase reached the peak value of 42.88% (95% CI: 35.89%-50.22%) at a nitrogen application rate of 300-375 kg/hm^2 (Figure 4a). After excluding unstable results and data obtained from very small sample sizes, it was concluded that the peak value of 43.84% (95% CI: 28.01%-50.40%) of the increase rate of DMA occurred at a nitrogen application rate of 300-375 kg/hm^2 (Figure 4b). The increase rate of the WUE reached a peak value of 51.39% (95% CI: 42.39%-60.98%) at a nitrogen application rate of 300-375 kg/hm^2 (Figure 4c). It was concluded that a nitrogen application rate of 300-375 kg/hm^2 resulted in the largest increase rates of the yield, DMA, and WUE of cotton in saline-alkali land.

3.3.4 Basal fertilizer proportion

The increase rate of the yield, DMA, and WUE of cotton in saline-alkali land showed an increase from no basal fertilizer to 40% basal fertilizer, reaching the peak at 20%-40% basal fertilizer, followed by a decrease at greater than 40% basal fertilizer (Figure 4).

The peak increase rate of the proportion of basal fertilizer for the cotton yield, DMA, and WUE was 46.80% (95% CI: 42.05%-51.73%) (Figure 4a), 50.70% (95% CI: 32.60%-71.24%) (Figure 4b), and 50.50% (95% CI: 42.99%-58.42%) (Figure 4c), respectively.



a. Percentage changes in yield/% b. Percentage changes in DMA/% c. Percentage changes in WUE/%

Note: EP, PD, NAR, BFR, TDP, and IM represent the experimental period (year), planting density (10 000 plants/hm²), nitrogen application rate (kg/hm²), basal fertilizer proportion (%), top-dressing program, and irrigation method, respectively. TI, FI, FLI, and CI denote trickle irrigation, furrow irrigation, flood irrigation, and check irrigation, respectively. The error bars represent the 95% confidence intervals, and n represents the number of data sets.

Figure 4 Effects of planting management factors on the response of cotton yield, DMA, and WUE to NFA in saline-alkali land

3.3.5 Top-dressing program

The top dressing programs are listed in Table 2. Its effect on the increase rate of the yield, DMA, and WUE of cotton was shown in Figure 4. The three groups of top-dressing programs with the most significant effect on the yield increase rate were Ⅷ, Ⅹ, and Ⅴ, which increased by 61.67% (95% CI: 44.11%-81.36%), 57.21% (95% CI: 42.30%-73.69%), and 57.13% (95% CI: 44.50%-70.86%), respectively (Figure 4a). The three groups of top-dressing programs with the most significant effect on the DMA rate were Ⅷ, Ⅲ, and Ⅹ, and the corresponding improvement rates were 51.13% (95% CI: 23.95%-84.28%), 35.43% (95% CI: 24.32%-47.52%) and 34.23% (95% CI: 27.12%-41.72%), respectively (Figure 5b). The three groups of top-dressing programs with the most significant effect on the WUE improvement rate were Ⅴ, Ⅲ, and Ⅸ, and the corresponding improvement rates were 54.81% (95% CI: 31.00%-82.92%), 49.68% (95% CI: 34.64%-66.41%), and 47.61% (95% CI: 27.53%-70.83%), respectively (Figure 4c).

Table 2 Top-dressing program in different growth stages during the growing period

Number	Bud stage	Initial flowering stage	Flower boll stage	Full boll stage	Boll opening stage
Ⅰ	×	×	×	×	×
Ⅱ	√	√	√	√	√
Ⅲ	√	√	√	×	×
Ⅳ	√	√	√	√	×
Ⅴ	×	√	×	√	×
Ⅵ	×	×	√	×	×
Ⅶ	×	×	√	×	√
Ⅷ	√	×	√	√	×
Ⅸ	×	√	×	×	×
Ⅹ	×	√	√	×	×
Ⅺ	√	√	√	×	√
Ⅻ	√	√	×	×	×
L	×	√	√	√	×

Note: Ⅰ, Ⅱ…L represent 13 different top-dressing programs. √ means top-dressing at the growth stage, × means no top-dressing at the growth stage.

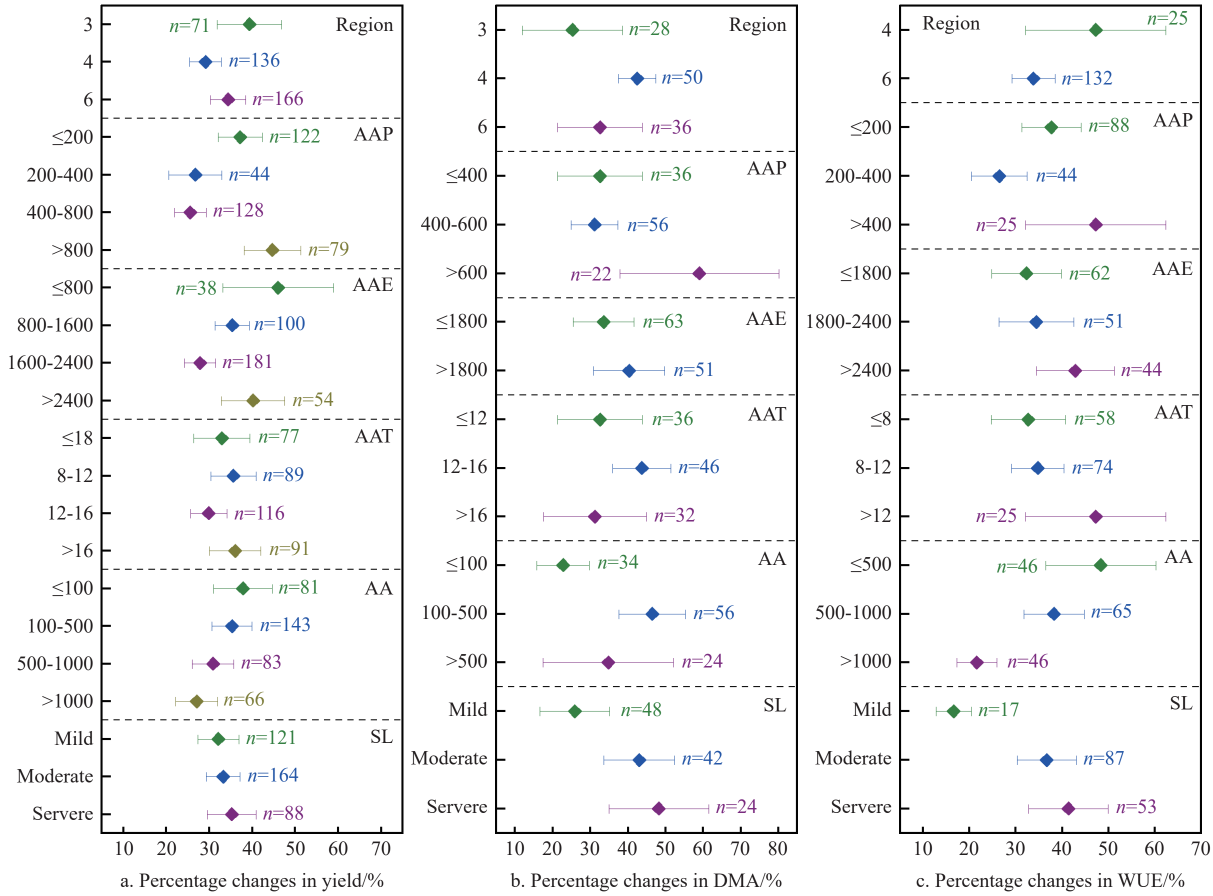
3.3.6 Irrigation practices

There were significant differences in the effects of irrigation practices on cotton yield and WUE after NFA (Figures 4a and 4c). Drip irrigation had the largest effect on cotton yield (34.47% (95% CI: 31.72%-37.29%)) and WUE (39.47% (95% CI: 34.39%-44.46%)), followed by diffuse and border irrigation. Furrow irrigation resulted in the least improvements (11.26% (95% CI: 8.94%-13.62%) and 11.18% (95% CI: 8.59%-13.84%), respectively).

3.4 Effects of environmental factors

3.4.1 Experimental site

Since the amount of data available for conducting subgroup analysis in North China, Northeast China, and Southwest China was too small the stability of the analysis results was poor. Data from North China and Southwest China were included in South Central China, and data from Northeast China were included in Eastern China according to the location distribution characteristics of their test sites when conducting subgroup analysis. NFA had the highest yield increase in East China (40.17% (95% CI: 32.64%-48.13%)), followed by Northwest China (34.35% (95% CI: 30.37%-38.44%)), and the lowest yield increase in South China (29.32% (95% CI: 25.33%-33.42%)) (Figure 5a). The DMA increase rates of cotton in Eastern China, South Central China, and Northwest China were 25.23% (95% CI: 13.17%-38.58%), 49.50% (95% CI: 41.94%-57.46%), and 32.54% (95% CI: 22.14%-43.81%), respectively (Figure 5b). The DMA increase rate was significantly higher in South Central China than in Northwest China and Eastern China. The WUE increase rates of cotton in the central-southern and northwestern regions were 47.27% (95% CI: 33.51%-62.45%) and 33.82% (95% CI: 29.28%-38.51%), respectively (Figure 5c), and significant effects occurred in both regions.



Note: AAP, AAE, AAT, AA, and SL represent average annual precipitation (mm), average annual evaporation (mm), average annual temperature (°C), average altitude (m), and salinity level, respectively. Regions 3, 4, and 6 represent Eastern China, South Central China, and Northwest China, respectively. The error bars represent the 95% confidence intervals, and n represents the number of data sets.

Figure 5 Effects of environmental factors on the response of cotton yield, DMA, and WUE to NFA in saline-alkali land

3.4.2 Climate effects

The effect of the annual average precipitation on the increase rate of the cotton yield, DMA, and WUE decreased and then increased (Figure 5). The yield increase rate was the largest when the annual average precipitation exceeded 800 mm. There was no significant difference in the yield increase rate between annual average precipitation of less than 200 mm (37.18% (95% CI: 32.26%-42.29%)) and annual average precipitation of 800 mm (44.67% (95% CI: 38.40%-51.23%)) under NFA (Figure 5a). NFA has the greatest impact on the DMA (58.98% (95% CI: 40.30%-80.15%)) when the precipitation exceeds 600 mm (Figure 5b). The WUE increase rate was the largest (47.27% (95% CI: 33.51%-62.45%)) when the precipitation exceeded 400 (Figure 5c). The yield increase rate first decreased and then increased with a rise in the average annual evaporation, while the DMA increase rate and the WUE increase rate showed a small increase (Figure 5). As the annual average temperature increased, the yield increase rate fluctuated slightly, but there was no significant difference between the different temperate groups (Figure 5a). The DMA increase rate first increased and then decreased, reaching the maximum value of 43.66% (95% CI: 36.33%-51.39%) at 12°C-16°C (Figure 5b). The WUE improvement rate remained stable when the temperature did not exceed 12°C and reached the maximum (47.27% (95% CI: 33.51%-62.45%)) when the temperature was higher than 12°C (Figure 5c).

3.4.3 Average altitude

As the average altitude increased, the effect of NFA on the increase rate of cotton yield and WUE in saline-alkali land decreased, while the DMA increase rate first increased and then decreased (Figure 5). The yield and WUE increase rates were the largest (37.80% (95% CI: 31.28%-44.61%) and 48.35% (95% CI: 37.36%-60.22%)) at an altitude of less than 100 m. The yield and WUE increase rates were the smallest (27.07% (95% CI: 22.37%-31.95%) and 21.57% (95% CI: 17.41%-25.89%)) when the altitude exceeded 1000 m. The DMA increase rate was the largest at 100-500 m altitude (46.42% (95% CI: 38.11%-55.22%)).

3.4.4 Salinity level

The yield increase rate of cotton increased slightly as the salinity increased from low to high, but there was no significant difference in the increase rate. The rates were 32.10% (95% CI: 27.47%-36.92%), 33.24% (95% CI: 29.42%-37.16%), and 35.22% (95% CI: 29.74%-40.90%) for the three salinity levels (Fig. 5a). The increase rates of DMA and WUE showed a large increase from low salinity (25.86% (95% CI: 17.25%-35.12%) and 16.56% (95% CI: 12.86%-20.38%)) to moderate salinity (42.98% (95% CI: 34.15%-52.38%) and 36.68% (95% CI: 30.62%-43.03%)). A small increase occurred as the salinity changed from moderate to high. The maximum increase rates were 48.17% (95% CI: 36.00%-61.45%) for DMA and 41.37% (95% CI: 33.28%-49.95%) for WUE (Figure 5b and 5c).

3.5 Regression results of the effects of NFA on cotton

3.5.1 Multiple linear regression

The results of the multiple linear regression analysis showed (Table 3) that EP, PD, NAR, BFR, and AAP significantly affected

Table 3 Multiple linear regression results of the increased rate of yield, DMA, and WUE of cotton in saline-alkali land under nitrogen application

Items	Dependent variable	Estimate	Beta	SE	*t*	*p*	Sign.
Yield	*α* (Intercept)	−0.611		0.180	−3.391	0.001	***
	β_1 (E)	0.043	0.196	0.012	3.642	0.000	***
	β_2 (D)	0.006	0.310	0.002	3.414	0.001	***
	β_3 (N)	0.000	0.162	0.000	3.233	0.001	**
	β_4 (B)	−0.001	−0.143	0.001	−2.616	0.009	**
	β_5 (P)	0.000	0.443	0.000	4.942	0.000	***
	β_6 (E’)	−0.000	−0.004	0.000	−0.056	0.956	NS
	β_7 (T)	−0.001	−0.025	0.003	−0.342	0.733	NS
	β_8 (A)	−0.000	−0.060	0.000	−0.991	0.323	NS
DMA	*α* (Intercept)	−1.744		0.694	−2.514	0.014	*
	β_1 (E)	0.008	0.011	0.065	0.121	0.904	NS
	β_2 (D)	−0.003	−0.103	0.005	−0.616	0.539	NS
	β_3 (N)	0.000	0.245	0.000	2.760	0.007	**
	β_4 (B)	−0.001	−0.062	0.002	−0.416	0.678	NS
	β_5 (P)	0.001	0.776	0.000	3.883	0.000	***
	β_6 (E’)	0.000	0.357	0.000	2.702	0.008	**
	β_7 (T)	−0.007	−0.173	0.006	−1.108	0.270	NS
	β_8 (A)	0.000	0.328	0.000	2.087	0.039	*
WUE	*α* (Intercept)	−0.377		0.334	−1.127	0.261	NS
	β_1 (E)	0.043	0.136	0.025	1.689	0.093	NS
	β_2 (D)	−0.001	−0.039	0.003	−0.339	0.735	NS
	β_3 (N)	0.000	0.087	0.000	1.032	0.304	NS
	β_4 (B)	−0.000	−0.031	0.001	−0.285	0.776	NS
	β_5 (P)	−0.001	−0.586	0.000	−2.412	0.017	*
	β_6 (E’)	0.000	0.499	0.000	4.304	0.000	***
	β_7 (T)	0.007	0.086	0.009	0.774	0.440	NS
	β_8 (A)	−0.001	−0.951	0.000	−4.305	0.000	***

Note: Estimate and Beta denote the unstandardized and standardized regression coefficients, respectively. *, **, and *** indicate significance levels of $p<0.05$, $p<0.01$, and $p<0.001$, respectively; NS indicates not significant.

the yield. EP, PD, NAR, and AAP had positive effects, and BFR had negative effects. NAR, AAP, AAE, and AA had significant and positive effects on DMA. AAP, AAE, and AA had significant effects on WUE; AAE had positive effects, and AAP and AA had negative effects.

3.5.2 Quantile regression

The effect sizes of the cotton yield, DMA, and WUE under NFA were analyzed by regression for the 10th, 25th, 50th, 75th, and 90th quantiles (see Appendix Tables A2-A4). The results showed that PD and AAP had significant positive effects on yield for all quantiles, whereas AAE, AAT, and AA had no significant effects for any quantiles. EP had significant positive effects for the 10th, 25th, and 50th quantiles, NAR had significant positive effects for all quantiles except for the 10th quantile, and BFP had significant negative effects for the 75th and 90th quantiles. NAR and AAP had positive effects on DMA for all quantiles, whereas PD, BFP, and AAE had no significant effects for any quantiles. EP had a significant positive effect only for the 50th quantile. AAT had a significant positive effect only for the 90th quantile. AA had a significant positive effect for all quantiles except the 50th quantile. AAE had a significant positive effect on WUE for all quantiles, whereas NAR had no significant effect for any quantiles. PD and AAT had significant negative and positive effects only for the 90th quantile.

4 Discussion

This study evaluated the effects of NFA on the yield, DMA, and WUE of cotton in saline-alkali land in different regions in China and for different climatic conditions and planting management measures. The result showed that NFA significantly improved cotton yield, DMA, and WUE, with average increase rates of 34.11%, 36.27%, and 33.87%, respectively (Table 1). Shi et al.[38] showed that DMA affects cotton yield. The stem diameter and plant height of cotton tended to increase with an increase in the nitrogen application rate[39]. A suitable amount of nitrogen and an appropriate top-dressing period improve the formation and growth of vegetative organs in cotton, as well as the nutrient distribution, thereby improving the cotton yield[40-42]. Constant evapotranspiration and an increase in the DMA and yield of cotton improve the WUE. An appropriate amount of nitrogen fertilizer can also improve soil quality, soil fertility, and resource utilization efficiency[43,44].

4.1 Effect of planting management factors on cotton

The continuous use of drip irrigation under the film to control the salt in saline-alkali land can effectively reduce the salinity of the plow layer over time. Liu et al.[45] demonstrated that drip irrigation under the film saves water, conserves moisture, suppresses salt, and ensures precise irrigation. These measures reduce the salt concentration of the plow layer, increase production, and improve WUE[46,47]. The low average improvement rate of the DMA may be attributed to the low sample size in the second year of the experiment. It is also possible that drip irrigation was used under the film for many years before the experiment, resulting in increased salinity of the deep soil layer. As the groundwater level rises, the soil undergoes secondary salinization, resulting in a relatively low average DMA increase rate[21,48].

The effect of the planting density on the average increase rate of the yield and WUE showed that "two ends are large, and the middle is small". The results showed that a low or high planting density improves the average increase rate of the yield and WUE after NFA, but the effect is unstable. Wang et al.[49] showed that the planting density significantly affected crop growth[50], but a very low or high planting density reduced the crop yield[51,52]. Therefore, a high yield increase rate does not necessarily imply a higher yield but only indicates that the NFA has a positive effect at the same planting density[53]. However, at a planting density of 100 000 to 250 000 plants/hm^2, the effect of NFA on the average increase rate of the cotton yield and WUE remained stable (Figure 4a). The decrease in the average increase rate of DMA is attributed to the continuous increase in planting density, the increasing difference in the proportion of the vegetative and reproductive organs of cotton, and a nutrient imbalance[51,54-56].

An appropriate amount of nitrogen fertilizer can improve the photosynthetic rate of cotton, which improves nutrient absorption and DMA, resulting in a stable and high yield and improving WUE[14]. However, an excessive amount of nitrogen fertilizer results in a low resource utilization rate threatens the ecological health of farmland, and reduces cotton yield, DMA, and WUE[22,57]. The effects of NFA on the cotton parameters (Figure 4) confirm these findings. It was found that the optimal amount of NFA for cotton in saline-alkali land was 300-375 kg/hm^2. This amount ensures a high cotton yield and maintains the ecological health of farmland.

Li et al.[58] found that an appropriate ratio of basal fertilizer could delay the senescence of cotton leaves and ensure the formation of photosynthetic products in the later stages of cotton growth, improving cotton production. The basal application ratio of the nitrogen fertilizer and the NFA amount showed a similar change trend (Figure 4). The effect of the proportion of the basal fertilizer on the average increase rate of the yield, DMA, and WUE indicated that a ratio of 20%-40% was the optimal amount. Significant differences were observed in the responses of cotton in saline-alkali land to the top-dressing program[22]. After excluding results obtained from studies with small sample sizes, it was concluded that the top-dressing programs with the most significant effects were Ⅲ, Ⅴ, Ⅷ, and Ⅹ. Table 2 lists that these four top-dressing programs do not carry out top-dressing during the boll opening stage. It was concluded that Ⅷ was the best top-dressing program, i.e., the application of nitrogen fertilizer at the cotton bud, flower boll, and full boll stages. Ahmed et al.[59] demonstrated that the nitrogen content in the soil at the seedling stage of cotton was high when all of the nitrogen fertilizer was applied as a basal fertilizer. However, the amount was insufficient to meet the needs of cotton growth and development in the later growth period. The number of effective bolls, the number of completed bolls, and the boll quality of cotton can be significantly improved by multiple fertilizer applications[23,25]. The results of our meta-analysis and regression analysis confirm this result.

4.2 Effect of environmental factors on cotton

The cotton yield, DMA, and WUE in response to NFA may be affected by different planting management practices, climatic conditions, altitudes, and soil textures. The research results showed that the average yield increase rates were relatively large in Eastern China and Northwest China. The average DMA increase rate was large in South Central China and Northwest China, and the NFA in these regions significantly increased the WUE of cotton. Northwest China is far away from the ocean and has low annual precipitation, high evaporation, and high soil salinity. Since irrigation and fertilization can be controlled, the application of nitrogen fertilizer can substantially improve the physical and chemical properties of the soil in Northwest China and increase the soil nutrient content required for cotton growth and the soil's organic carbon content. Thus, NFA can improve soil quality and WUE of cotton under drought stress[60-62]. East China and South Central China are located in the subtropical monsoon climate zone, an area with opposite conditions to Northwest China. The annual precipitation is the highest in the country, the climate is humid, agricultural production is not limited by water resources, and the soil nutrient content is relatively high. Applying an appropriate amount of nitrogen fertilizer to meet the nutritional needs of cotton at different growth stages can increase yield, DMA, and WUE by promoting the growth of cotton roots. The interaction between the nitrogen fertilizer and the sufficient amount of water in the region increases cotton yield and improves cotton quality[63-65]. The effects of nitrogen fertilizer on the yield, DMA, and WUE of cotton in the two distinct climate types in Northwest China, East China, and South Central China correspond to the trend of the annual average precipitation, the annual average evaporation, and the annual average temperature. As the salinity increased, the average increase rate of the cotton yield, DMA, and WUE increased in a small range, indicating that NFA is crucial for increasing cotton production in saline-alkali land.

4.3 Limitations

Although this meta-analysis provided theoretical information on controlled-release NFA to cotton in saline-alkali land, it has several limitations. For example, the published literature did not provide sufficient detail, the experimental conditions were not clearly described in some articles. The effect of NFA on cotton production in saline-alkali land is also influenced by the initial soil fertility, However, most of the published articles have designed NFA treatments in terms of nutrients required for crop growth and development without considering the initial fertility. The data collected cannot be used for the analysis and evaluation of the effect of NFA on cotton production by different initial soil fertility levels. The data set that can support the analysis and evaluation can only meet the necessary needs of this study but does not adequately represent the full range of evaluation of the effects of nitrogen fertilizer application by other factors. In addition, the cotton yield, DMA, and WUE in saline-alkali land are affected by multiple factors and their interactions. This study only selected the most typical factors for analysis. It is recommended to collect more detailed and comprehensive data in future experiments to facilitate the integration between studies and obtain valid statistics.

5 Conclusions

A meta-analysis and regression analysis were conducted to quantify the effect of NFA under different planting management and environments on cotton yield, DMA, and WUE in saline-alkali land in China. NFA increased the average yield, DMA and WUE by 34.11%, 36.27%, and 33.87%, respectively. Control NFA of 300-375 kg/hm^2, BFR of 20%-40%, and TDP at the cotton bud stage, flowering boll stage, and full boll stage had the best effect on cotton yield, DMA, and WUE. The best response to NFA was observed in the planting in improved saline-alkali land for many years, and Eastern, South Central, and Northwest China (areas with AAP≤200 mm or >800 mm and AAE≤800 mm or >2400 mm), and with drip irrigation, and planting density of 100 000 to 250 000 plants/hm^2. Regression analysis showed that EP, PD, NAR, and AAP had significant positive effects on yield under NFA, and PD and AAP had positive effects for all quantiles. NAR, AAP, AAE, and AA had significant positive effects on DMA under NFA, and NAR and AAP had positive effects for all quantiles. For WUE under NFA, there was an AAE significant positive effect for all quantiles. The results quantify the impact of NFA on cotton production, which can make a certain contribution to nitrogen fertilizer input in the cotton industry and ensure sustainable agricultural development.

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Appendix

Table A1 Subgroup division of the data set

Subgroup	Division						
	1	2	3	4	5	6	7
Region^{YDW}	North China	Northeast China	Eastern China	South Central China	Southwest China	Northwest China	
EP/year^{YDW}	1	2	3	4			
AAP/mm^{Y}	≤200	200-400	400-800	>800			
AAP/mm^{D}	≤400	400-600	>600				
AAP/mm^{W}	≤200	200-400	>400				
AAE/mm^{Y}	≤800	800-1600	1600-2400	>2400			
AAE/mm^{D}	≤1800	>1800					
AAE/mm^{W}	≤1800	1800-2400	>2400				
AAT/°C^{Y}	≤8	8-12	12-16	>16			
AAT/°C^{D}	≤12	12-16	>16				
AAT/°C^{W}	≤8	8-12	>12				
AA/m^{Y}	≤100	100-500	500-1000	>1000			
AA/m^{D}	≤100	100-500	>500				
AA/m^{W}	≤500	500-5000	>1000				
SL^{YDW}	mild	moderate	severe				
PD/(10 000 plants·hm^{-2})^{Y}	≤5	5-10	10-15	15-20	20-25	>25	
PD/(10 000 plants·hm^{-2})^{D}	≤5	5-15	>15				
PD/(10 000 plants·hm^{-2})^{W}	≤15	15-25	>25				
NAR/(kg·hm^{-2})^{YDW}	≤150	150-200	200-250	250-300	300-375	375-450	>450
BFR/%^{YDW}	0	0-20	20-40	40-60	60-80	80-100	7-100
IM^{YDW}	trickle irrigation	furrow irrigation	flood irrigation	check irrigation			

Note: The superscripts Y, D, and W represent the subgroup's interval divisions related to the yield, dry matter accumulation, and water use efficiency, respectively. YDW indicates that the subgroup interval division is the same for the three factors. EP, AAP, AAE, AAT, AA, SL, PD, NAR, BFR, and IM represent the experimental period (year), average annual precipitation (mm), average annual evaporation (mm), average annual temperature (ºC), average altitude (m), salinity level, planting density (10 000 plants/hm^2), nitrogen application rate (kg/hm^2), basal fertilizer proportion (%), and irrigation method, respectively.

Table A2 Quantile regression analysis of cotton yield increase rate under nitrogen fertilizer application

Model	Dependent variable	Estimate	Beta	SE	*t*	*p*	Sign.
Model 1 (Q10th)	α (Intercept)	−0.468		0.129	−3.619	0.000	***
	β_1 (E)	0.053	−0.240	0.009	6.201	0.000	***
	β_2 (D)	0.003	0.130	0.001	1.997	0.047	*
	β_3 (N)	0.000	0.050	0.000	1.378	0.169	NS
	β_4 (B)	−0.000	−0.005	0.004	−0.135	0.893	NS
	β_5 (P)	0.000	0.254	0.000	3.945	0.000	***
	β_6 (E')	0.000	0.078	0.000	1.639	0.102	NS
	β_7 (T)	0.001	0.025	0.002	0.473	0.636	NS
	β_8 (A)	0.000	0.063	0.000	1.438	0.151	NS
Model 2 (Q25th)	α (Intercept)	−0.564		0.134	−4.203	0.000	***
	β_1 (E)	0.047	0.210	0.009	5.225	0.000	***
	β_2 (D)	0.005	0.252	0.001	3.736	0.000	***
	β_3 (N)	0.000	0.088	0.000	2.357	0.019	*
	β_4 (B)	0.000	0.035	0.000	0.854	0.394	NS
	β_5 (P)	0.000	0.398	0.000	5.954	0.000	***
	β_6 (E')	−0.000	−0.071	0.000	−1.433	0.153	NS
	β_7 (T)	−0.002	−0.060	0.002	−1.081	0.280	NS
	β_8 (A)	0.000	0.047	0.000	1.035	0.301	NS
Model 3 (Q50th)	α (Intercept)	−0.854		0.201	−4.246	0.000	***
	β_1 (E)	0.041	0.187	0.013	3.105	0.002	**
	β_2 (D)	0.009	0.474	0.002	4.676	0.000	***
	β_3 (N)	0.000	0.217	0.000	3.863	0.000	***

	β_4 (B)	−0.001	−0.075	0.001	−1.228	0.220	NS
	β_5 (P)	0.000	0.567	0.000	5.665	0.000	***
	β_6 (E')	−0.000	−0.130	0.000	−1.761	0.079	NS
	β_7 (T)	0.000	−0.005	0.003	−0.064	0.949	NS
	β_8 (A)	−0.000	−0.030	0.000	−0.434	0.665	NS
Model 4 (Q75th)	α (Intercept)	−0.314		0.296	−1.063	0.289	NS
	β_1 (E)	0.024	0.109	0.020	1.227	0.221	NS
	β_2 (D)	0.012	0.610	0.003	4.097	0.000	***
	β_3 (N)	0.000	0.276	0.000	3.342	0.001	**
	β_4 (B)	−0.003	−0.302	0.001	−3.348	0.001	**
	β_5 (P)	0.000	0.623	0.000	4.234	0.000	***
	β_6 (E')	−0.000	−0.086	0.000	−0.793	0.428	NS
	β_7 (T)	−0.001	−0.025	0.005	−0.210	0.834	NS
	β_8 (A)	−0.000	−0.182	0.000	−1.817	0.070	NS
Model 5 (Q90th)	α (Intercept)	−0.238		0.258	−0.922	0.357	NS
	β_1 (E)	0.013	0.061	0.017	0.783	0.434	NS
	β_2 (D)	0.007	0.360	0.003	2.773	0.006	**
	β_3 (N)	0.000	0.284	0.000	3.943	0.000	***
	β_4 (B)	−0.004	−0.388	0.001	−4.938	0.000	***
	β_5 (P)	0.000	0.606	0.000	4.718	0.000	***
	β_6 (E')	0.000	0.069	0.000	0.729	0.466	NS
	β_7 (T)	−0.001	−0.013	0.004	−0.119	0.906	NS
	β_8 (A)	−0.000	−0.163	0.000	−1.874	0.062	NS

Table A3 Quantile regression analysis of cotton dry matter accumulation increase rate under nitrogen fertilizer application

Model	Dependent variable	Estimate	Beta	SE	*t*	*p*	Sign.
Model 1 (Q10th)	α (Intercept)	−0.048		0.268	−0.180	0.858	NS
	β_1 (E)	0.034	0.048	0.025	1.347	0.181	NS
	β_2 (D)	0.002	0.077	0.002	1.190	0.237	NS
	β_3 (N)	0.000	0.183	0.000	5.360	0.000	**
	β_4 (B)	0.001	0.053	0.001	0.933	0.353	NS
	β_5 (P)	0.000	0.251	0.000	3.253	0.002	**
	β_6 (E')	0.000	0.021	0.000	0.419	0.676	NS
	β_7 (T)	−0.019	−0.475	0.002	−7.874	0.000	***
	β_8 (A)	0.000	−0.389	0.000	−6.417	0.000	***
Model 2 (Q25th)	α (Intercept)	−0.251		0.427	−0.589	0.557	NS
	β_1 (E)	0.052	0.074	0.040	1.291	0.199	NS
	β_2 (D)	0.004	0.133	0.003	1.298	0.197	NS
	β_3 (N)	0.000	0.267	0.000	4.899	0.000	***
	β_4 (B)	0.002	0.156	0.001	1.710	0.090	NS
	β_5 (P)	0.000	0.255	0.000	2.072	0.041	*
	β_6 (E')	0.000	0.081	0.000	0.993	0.323	NS
	β_7 (T)	−0.019	−0.495	0.004	−5.149	0.000	***
	β_8 (A)	0.000	−0.409	0.000	−4.239	0.000	***
Model 3 (Q50th)	α (Intercept)	−1.869		0.496	−3.767	0.000	***
	β_1 (E)	0.093	0.133	0.047	1.999	0.048	*
	β_2 (D)	0.002	0.061	0.004	0.506	0.614	NS
	β_3 (N)	0.000	0.248	0.000	3.917	0.000	***
	β_4 (B)	0.001	0.075	0.001	0.709	0.480	NS
	β_5 (P)	0.000	0.564	0.000	3.943	0.000	***
	β_6 (E')	0.000	0.150	0.000	1.590	0.115	NS
	β_7 (T)	−0.015	−0.371	0.004	−3.320	0.001	**
	β_8 (A)	0.000	0.039	0.000	0.349	0.728	NS
Model 4 (Q75th)	α (Intercept)	−3.901		0.673	−5.798	0.000	***
	β_1 (E)	0.030	0.043	0.063	0.475	0.635	NS
	β_2 (D)	0.002	0.067	0.005	0.414	0.680	NS
	β_3 (N)	0.000	0.270	0.000	3.139	0.002	**
	β_4 (B)	−0.001	−0.072	0.002	−0.502	0.617	NS
	β_5 (P)	0.001	1.027	0.000	5.299	0.000	***
	β_6 (E')	0.000	0.215	0.000	1.672	0.097	NS

	β_7 (T)	0.002	0.051	0.006	0.336	0.737	NS
	β_8 (A)	0.001	0.857	0.000	5.628	0.000	***
	α (Intercept)	−3.502		0.326	−10.745	0.000	***
	β_1 (E)	−0.231	−0.330	0.031	−7.523	0.000	***
	β_2 (D)	0.003	0.082	0.003	1.046	0.298	NS
	β_3 (N)	0.000	0.263	0.000	6.322	0.000	***
Model 5 (Q90th)	β_4 (B)	−0.001	−0.064	0.001	−0.924	0.358	NS
	β_5 (P)	0.001	1.038	0.000	11.059	0.000	***
	β_6 (E’)	0.000	0.098	0.000	1.582	0.117	NS
	β_7 (T)	0.027	0.685	0.003	9.327	0.000	***
	β_8 (A)	0.001	1.515	0.000	20.547	0.000	***

Table A4 Quantile regression analysis of cotton water use efficiency increase rate under nitrogen fertilizer application

Model	Dependent variable	Estimate	Beta	SE	`	*p*	Sign.
	α (Intercept)	−0.221		0.252	−0.875	0.383	NS
	β_1 (E)	0.033	0.107	0.019	1.756	0.081	NS
	β_2 (D)	−0.001	−0.049	0.002	−0.569	0.570	NS
	β_3 (N)	0.000	0.077	0.000	1.217	0.226	NS
Model 1 (Q10th)	β_4 (B)	0.001	0.123	0.001	1.517	0.131	NS
	β_5 (P)	0.000	−0.338	0.000	−1.846	0.067	NS
	β_6 (E’)	0.000	0.268	0.000	3.062	0.003	**
	β_7 (T)	0.011	0.136	0.007	1.614	0.109	NS
	β_8 (A)	0.000	−0.330	0.000	−1.979	0.050	NS
	α (Intercept)	0.226		0.280	0.806	0.421	NS
	β_1 (E)	0.049	0.155	0.021	2.305	0.023	*
	β_2 (D)	−0.003	−0.106	0.002	−1.104	0.271	NS
	β_3 (N)	0.000	0.068	0.000	0.959	0.339	NS
Model 2 (Q25th)	β_4 (B)	0.002	0.212	0.001	2.361	0.020	*
	β_5 (P)	−0.001	−0.661	0.000	−3.245	0.001	**
	β_6 (E’)	0.000	0.306	0.000	3.146	0.002	**
	β_7 (T)	0.006	0.069	0.008	0.737	0.462	NS
	β_8 (A)	0.000	−0.669	0.000	−3.614	0.000	***
	α (Intercept)	−0.287		0.398	−0.721	0.472	NS
	β_1 (E)	0.073	0.234	0.030	2.445	0.016	*
	β_2 (D)	−0.000	−0.003	0.004	−0.024	0.981	NS
	β_3 (N)	0.000	0.011	0.000	0.107	0.915	NS
Model 3 (Q50th)	β_4 (B)	0.000	0.026	0.001	0.201	0.841	NS
	β_5 (P)	−0.001	−0.508	0.000	−1.759	0.081	NS
	β_6 (E’)	0.000	0.394	0.000	2.862	0.005	**
	β_7 (T)	0.008	0.095	0.011	0.718	0.474	NS
	β_8 (A)	0.000	−0.877	0.000	−3.342	0.001	**
	α (Intercept)	−0.053		0.333	−0.160	0.873	NS
	β_1 (E)	0.045	0.145	0.025	1.808	0.073	NS
	β_2 (D)	−0.004	−0.145	0.003	−1.273	0.205	NS
	β_3 (N)	0.000	0.070	0.000	0.838	0.404	NS
Model 4 (Q75th)	β_4 (B)	0.000	−0.035	0.001	−0.329	0.743	NS
	β_5 (P)	−0.001	−0.785	0.000	−3.246	0.001	**
	β_6 (E’)	0.000	0.739	0.000	6.402	0.000	***
	β_7 (T)	0.003	0.035	0.009	0.319	0.751	NS
	β_8 (A)	−0.001	−1.454	0.000	−6.607	0.000	***
	α (Intercept)	0.351		0.224	1.567	0.119	NS
	β_1 (E)	0.021	0.066	0.017	1.232	0.220	NS
	β_2 (D)	−0.011	−0.428	0.002	−5.589	0.000	***
	β_3 (N)	0.000	−0.086	0.000	−1.535	0.127	NS
Model 5 (Q90th)	β_4 (B)	−0.002	−0.188	0.001	−2.620	0.010	**
	β_5 (P)	−0.002	−1.499	0.000	−9.223	0.000	***
	β_6 (E’)	0.000	1.078	0.000	13.890	0.000	***
	β_7 (T)	0.019	0.236	0.006	3.155	0.002	**
	β_8 (A)	−0.001	−2.087	0.000	−14.117	0.000	***

Note: *, **, and *** indicate significant levels of p<0.05, p<0.01, and p<0.001, respectively.

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