

## Modeling Nitrogen and Phosphorus Fertilizer Effects on Winter Wheat in Saline-Alkali Soils of the Yellow River Delta: A Postprint

**Authors:** Shan Jingjing, Chen Xiaobing, Yin Chunyan, Wen Pei, Yan Kun, Zhang Lihua, Zhang Libin, Fu Xiqiang, Sun Haishuan

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### Abstract

Through field experiments, suitable fertilizer response models for winter wheat in the saline-alkali soil region of the Yellow River Delta were studied. During the winter wheat growing season, four different nitrogen and phosphorus fertilizer application rates were established, and eight different fertilizer efficiency experimental treatments were designed according to the “3414” experimental design to investigate the fitting effects of four different models: linear plus plateau, univariate quadratic, square root, and bivariate quadratic. The results showed that the fitting results of all four fertilizer response models reached a highly significant level upon testing ( $P < 0.01$ ). Among the univariate fertilizer response models, the nitrogen and phosphorus univariate quadratic models exhibited the best fitting effect, with maximum economic returns of 7 448.3 yuan · hm<sup>2</sup> and 7 357.7 yuan · hm<sup>2</sup>, respectively, and optimal economic nitrogen and phosphorus application rates of 254.4 kg · hm<sup>2</sup> and 98.6 kg · hm<sup>2</sup>, respectively. Comparing univariate and bivariate models, the latter demonstrated better fitting performance, with optimal economic nitrogen and phosphorus application rates of 244.1 kg · hm<sup>2</sup> and 94.2 kg · hm<sup>2</sup>, respectively, corresponding to an N:P fertilizer ratio of 2.6 1, an economic benefit of 7 432.4 yuan · hm<sup>2</sup>, a nitrogen agronomic use efficiency of 6.2 kg(grain) · kg<sup>-1</sup>(N), and a phosphorus agronomic use efficiency of 13.8 kg(grain) · kg<sup>-1</sup>(P<sub>2</sub>O<sub>5</sub>). Based on comprehensive analysis of goodness of fit, optimal economic fertilizer application rates, economic returns, fertilizer agronomic use efficiency, and the limitations of univariate models, the bivariate quadratic fertilizer response model was determined to be optimal and can serve as the best choice for nitrogen and phosphorus fertilizer response models for winter wheat in saline-alkali soils of the Yellow River Delta region.

## Full Text

# Comparison of Fertilizer-Effect Models on Winter Wheat Response to Nitrogen and Phosphorus Fertilizers in Saline Soils in the Yellow River Delta

SHAN Jingjing<sup>1,2</sup>, CHEN Xiaobing<sup>1</sup>, YIN Chunyan<sup>1,2</sup>, WEN Pei<sup>1,2</sup>, YAN Kun<sup>1</sup>, ZHANG Lihua<sup>1</sup>, ZHANG Libin<sup>3</sup>, FU Xiqiang, SUN Haishuan

<sup>1</sup>Key Laboratory of Coastal Zone Environmental Processes and Ecological Remediation, Yantai Institute of Coastal Zone Research, Chinese Academy of Sciences, Yantai 264003, China; <sup>2</sup>University of Chinese Academy of Sciences, Beijing 100049, China; <sup>3</sup>Dongying Institute of Scientific and Technical Information, Dongying 257091, China; Shandong Huibangbohai Agricultural Development Co. Ltd., Dongying 257091, China

## Abstract

Salt-affected soils are widely distributed across the Yellow River Delta, where they inhibit plant growth and reduce crop yields. Although fertilizer application can alleviate the adverse impacts of salinization, the performance of different fertilizer-effect models in simulating “3414” fertilizer experiments for winter wheat in saline soils remains poorly understood. Nitrogen (N) and phosphorus (P) are the most critical nutrients limiting plant growth in both saline and non-saline soils. This study employed four fertilizer-effect models to simulate the effects of N and P fertilizers on wheat yield in a field experiment conducted in Lijin County, Shandong Province, aiming to identify the most suitable model for wheat cultivation in the Yellow River Delta’s saline soils. Four N and P fertilizer levels (N: 0, 135, 170, 405 kg·hm<sup>-2</sup>; P: 0, 53, 105, 157.5 kg·hm<sup>-2</sup>) were established across eight treatments based on the “3414” experimental design to evaluate the fit of four models: linear plus plateau, unary quadratic, square root, and binary quadratic. The least squares method was used for statistical regression analysis to ensure model accuracy. All four fertilizer-effect models achieved extremely significant fit levels ( $P < 0.01$ ). Among unary models, the unary quadratic model performed best, predicting maximum incomes of ¥7,448.3 hm<sup>-2</sup> and ¥7,357.7 hm<sup>-2</sup> with optimal economic N and P rates of 254.4 kg·hm<sup>-2</sup> and 98.6 kg·hm<sup>-2</sup>, respectively. The binary quadratic model outperformed unary models, recommending optimal economic N and P rates of 244.1 kg·hm<sup>-2</sup> and 94.2 kg·hm<sup>-2</sup> (N:P ratio = 2.6:1), with an economic benefit of ¥7,432.4 hm<sup>-2</sup>, agronomic efficiency of 6.2 kg(grain)·kg<sup>-1</sup>(N), and 13.8 kg(grain)·kg<sup>-1</sup>(P O). Based on goodness-of-fit, optimal economic fertilizer rates, economic returns, agronomic efficiency, and the limitations of unary models, the binary quadratic fertilizer-effect model proved optimal and is recommended as the best choice for N and P fertilizer management for winter wheat in the Yellow River Delta’s saline soils.

**Keywords:** Fertilizer-effect model; Nitrogen and phosphorus fertilizers; Opti-

mal economic fertilizer rate; Winter wheat; Saline soil; Yellow River Delta

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## Introduction

According to incomplete statistics from UNESCO and FAO, global salt-affected soils cover approximately 950 million hectares, representing a worldwide challenge for converting these potential lands into arable farmland. The Yellow River Delta region of China contains extensive saline soil distributions, with Dongying City alone possessing nearly 530,000 hectares. Influenced by both anthropogenic activities and natural environmental factors, soil salinization in this region is intensifying. Soils with salt content below 0.2% constitute only 4.29% of the Yellow River Delta area, while lightly salinized soils with salt content between 0.1% and 0.3% are more readily reclaimed for agricultural use. Scientific development and utilization of these lands are critical for constructing the “Yellow River Delta Efficient Ecological Economic Zone.”

Soil nutrient and salinity conditions determine vegetation types and land use patterns in saline soils, making soil management practices such as deep tillage and green manure application common amelioration strategies. Combined application of organic and inorganic fertilizers, as well as balanced N-P-K fertilization, can mitigate salt stress effects on crops and promote growth to some extent. Rational and scientific fertilization not only optimizes fertilizer application rates but also improves fertilizer use efficiency while protecting the agricultural ecological environment. Fertilizer consumption in the Yellow River Delta is substantial; in 2013, Dongying City consumed 160,000 tons of nitrogen fertilizer and significant amounts of phosphorus fertilizer. Excessive fertilization causes not only nutrient waste and water eutrophication but also exacerbates soil salinization. China’s fertilizer use efficiency remains relatively low, with N, P, and K utilization rates of 30-35%, 10-25%, and 35-50%, respectively, while saline soils exhibit even lower efficiencies due to salt stress.

Most research on saline soil fertilization has focused on soil-crop interaction mechanisms, with few studies addressing fertilizer-effect models from a mathematical perspective. Fertilizer-effect models (empirical models) are regression models based on field experimental results and biostatistics that describe the quantitative relationship between fertilizer application rates and crop yields. These models enable determination of rational fertilizer rates and represent the primary approach for achieving quantitative fertilization both domestically and internationally. Most “3414” fertilizer experiments have employed ternary quadratic models, though with low success rates that often lead to data abandonment. Moreover, applying ternary quadratic models without considering actual field conditions (e.g., K-sufficient soils in northern regions) can yield erroneous conclusions about potassium deficiency. Even when ternary quadratic models fit successfully, unary and binary models are still needed for supplementation, making appropriate model selection crucial. Previous studies have shown

that model selection varies with environmental conditions, crops, and nutrients. While numerous studies have examined fertilizer-effect models, few have investigated them under saline soil conditions. This study utilized saline soils from the Yellow River Delta to investigate fertilizer-effect models for winter wheat through “3414” experiments, aiming to identify optimal fertilizer rates to provide a scientific basis for rational fertilization in the region. Winter wheat is the primary grain crop in the Yellow River Delta, and establishing fertilizer-effect models for this crop in saline soils will facilitate scientific fertilization guidance. Using models to calculate optimal fertilizer rates enables not only quantitative fertilization but also provides scientific support for future soil nutrient management.

### 1.1 Study Area Description

The field experiment was conducted in October 2015 at Bohai Farm, Dingluo Town, Lijin County, Dongying City, Shandong Province (37°41' 17.25 N, 118°36' 03.76 E). The farm, situated at approximately 6 m elevation, lies in a north temperate monsoon climate zone. Annual precipitation is 542 mm with uneven seasonal distribution, as June-August rainfall accounts for 63.9% of the annual total, creating climatic patterns of spring drought, summer flooding, and late autumn drought. The mean annual temperature is 12.3°C, with 10°C accumulated temperature of 4,183°C, a frost-free period of 203 days, and annual sunshine duration of 2,712.9 hours. The average groundwater depth is 1.34 m with mineralization of 15 g · L<sup>-1</sup>. The experimental soil is sandy loam with particle distribution of 67% sand, 27% silt, and 6% clay. Soil pH (1:5 water extraction) is 8.59, bulk density is 1.3 g · cm<sup>-3</sup>, organic matter content is 10.35 g · kg<sup>-1</sup>, total nitrogen is 0.958 g · kg<sup>-1</sup>, available phosphorus is 17.8 mg · kg<sup>-1</sup>, and available potassium is 66.8 mg · kg<sup>-1</sup>. The surface soil (0-20 cm) contains total salts of 1.4 g · kg<sup>-1</sup>, Na of 357 mg · kg<sup>-1</sup>, and Cl of 533 mg · kg<sup>-1</sup>, classifying it as lightly salinized soil.

### 1.2 Experimental Design

The experiment implemented a partial “3414” design, establishing a two-factor experiment with N and P, each at four levels (0, 1, 2, 3). Level 0 represents no fertilizer application, level 2 represents the locally recommended optimal rate, level 1 equals 0.5 × level 2, and level 3 equals 1.5 × level 2 (excessive fertilization). Specific fertilizer rates are shown in . Eight treatments were established, each replicated four times, totaling 32 plots arranged in a completely randomized design with individual plot areas of 21 m<sup>2</sup> (3 m × 7 m). Winter wheat (cv. ‘Shannong 24’) was sown on October 22, 2015, at a row spacing of 16 cm and seeding rate of 225 kg · hm<sup>-2</sup>. Nitrogen fertilizer (urea, 46% N) was applied as 60% basal and 40% topdressing, while phosphorus fertilizer (superphosphate, 15% P O) was applied entirely as basal fertilizer. Irrigation was applied once during the wintering, jointing, and grain-filling stages, with other management practices following conventional field methods. All plots were harvested on June

14, 2016, for yield measurement.

### 1.3.1 Unary Fertilizer Effect Models

Three unary models were evaluated:

#### 1. Linear plus plateau model:

$$y = \begin{cases} a + bx & (x \leq C) \\ P & (x > C) \end{cases}$$

where  $y$  is grain yield ( $\text{kg} \cdot \text{hm}^{-2}$ ),  $x$  is fertilizer rate ( $\text{kg} \cdot \text{hm}^{-2}$ ),  $a$  is the intercept (yield without fertilizer),  $b$  is the regression coefficient,  $C$  is the intersection point between the linear and plateau phases, and  $P$  is the plateau yield ( $\text{kg} \cdot \text{hm}^{-2}$ ) when fertilizer rate reaches  $C$ .

#### 2. Unary quadratic model:

$$y = a + bx + cx^2$$

where  $b$  and  $c$  are linear and quadratic regression coefficients, respectively, and  $y$ ,  $x$ , and  $a$  are as defined above.

#### 3. Square root model:

$$y = a + b\sqrt{x} + cx$$

where  $b$  is the square root term coefficient,  $c$  is the linear term coefficient, and other variables are as defined above.

### 1.3.2 Binary Fertilizer Effect Model

Binary quadratic model:

$$y = f + ax_1 + bx_2 + cx_1^2 + dx_2^2 + ex_1x_2$$

where  $y$  is grain yield ( $\text{kg} \cdot \text{hm}^{-2}$ ),  $x_1$  and  $x_2$  are N and P fertilizer rates ( $\text{kg} \cdot \text{hm}^{-2}$ ),  $f$  is the intercept (yield without fertilizer),  $a$ ,  $b$ ,  $c$  are quadratic regression coefficients, and  $d$ ,  $e$  are linear regression coefficients.

### 1.4 Optimal Fertilizer Rate Calculation

Optimal N and P rates for the unary quadratic, square root, and binary quadratic models were determined using marginal analysis, where marginal revenue equals marginal cost ( $dy \cdot p_y = dx \cdot p_x$ , with  $p_x$  and  $p_y$  representing fertilizer and wheat prices, respectively). For the linear plus plateau model, optimal rates were calculated directly. Wheat price was set at  $\text{¥}1.27 \text{ kg}^{-1}$  (2016 Shandong purchase price), with fertilizer prices at  $\text{¥}1.6 \text{ kg}^{-1}$  for urea and  $\text{¥}2.4 \text{ kg}^{-1}$  for superphosphate.

## 1.5 Data Processing

Microsoft Excel and SAS statistical software were used for regression analysis based on the least squares principle. ORIGIN and MATLAB software were used for graphical visualization.

### 2.1 Unary and Binary Fertilizer Effect Models

During regression analysis, data from each replication were used instead of treatment means to avoid pseudoreplication, which would incorrectly inflate statistical significance. Treatments 2, 3, 6, and 8 were used to fit the N effect model at 105 kg · hm<sup>-2</sup> P rate, while treatments 4, 5, 6, and 7 were used to fit the P effect model at 270 kg · hm<sup>-2</sup> N rate. The resulting fertilizer effect equations are presented in .

All unary N and P models showed R<sup>2</sup> values > 0.5, with linear plus plateau > unary quadratic > square root, and all were highly significant (P < 0.01), indicating strong correlations between wheat grain yield and N/P application rates. Phosphorus models exhibited higher R<sup>2</sup> values than nitrogen models, suggesting better fit for phosphorus.

The fitted curves for N and P unary models are shown in [Figure 1a: see original paper] and [Figure 1b: see original paper]. The linear plus plateau models reached plateaus at 162.0 kg · hm<sup>-2</sup> N and 64.5 kg · hm<sup>-2</sup> P, beyond which yields stabilized. The unary quadratic models predicted maximum yields at 292.3 kg · hm<sup>-2</sup> N and 106.6 kg · hm<sup>-2</sup> P, with yield decline beyond these rates—unlike the linear plus plateau model. The square root models predicted maximum yields at 323.7 kg · hm<sup>-2</sup> N and 90.1 kg · hm<sup>-2</sup> P, showing slower yield increases at higher fertilizer rates. The N square root model approached zero yield increase at high rates, while the P model showed a yield decline trend.

The binary quadratic model for this soil fertility condition was:

$$y = 4472.222 + 6.2025x_1 + 18.4126x_2 + 0.0309x_1x_2 - 0.0161x_1^2 - 0.1278x_2^2$$

with R<sup>2</sup> = 0.7058 (P < 0.01), indicating highly significant correlation. The fitted surface ([Figure 1c: see original paper]) showed a clear yield peak at 296.5 kg · hm<sup>-2</sup> N and 107.9 kg · hm<sup>-2</sup> P.

### 2.2 Optimal Fertilizer Rates and Economic Returns

Maximum yield predictions from each model are summarized in . For nitrogen, the unary quadratic model predicted highest grain yield, followed by linear plus plateau and square root models, though economic returns ranked: linear plus plateau > unary quadratic > square root, with corresponding N rates: square root > unary quadratic > linear plus plateau. For phosphorus, the unary quadratic model also predicted highest yield, followed by square root and linear plus plateau, with returns: unary quadratic > linear plus plateau > square root, and P rates: unary quadratic > square root > linear plus plateau.

Comparing unary and binary models, the binary model predicted slightly lower maximum yields ( $24.4 \text{ kg} \cdot \text{hm}^{-2}$  and  $55.7 \text{ kg} \cdot \text{hm}^{-2}$  less) but higher economic returns, demonstrating that maximum yield does not correspond to maximum profit. Marginal analysis is therefore essential for model comparison.

presents optimal economic rates and returns. For nitrogen, the linear plus plateau model yielded highest returns ( $\text{¥}7,462.3 \text{ hm}^{-2}$ ) at  $162.0 \text{ kg} \cdot \text{hm}^{-2} \text{ N}$ , just  $\text{¥}14 \text{ hm}^{-2}$  higher than the unary quadratic model but requiring  $92.4 \text{ kg} \cdot \text{hm}^{-2}$  less N. Both models are viable for nitrogen management. For phosphorus, the unary quadratic model provided highest returns ( $\text{¥}7,357.7 \text{ hm}^{-2}$ ) at  $98.6 \text{ kg} \cdot \text{hm}^{-2} \text{ P}$ , making it the preferred unary model for phosphorus.

Comparing unary and binary quadratic models, the binary model's returns were only  $\text{¥}15.8 \text{ hm}^{-2}$  and  $\text{¥}74.8 \text{ hm}^{-2}$  lower, with optimal rates  $10.3 \text{ kg} \cdot \text{hm}^{-2} \text{ N}$  and  $4.4 \text{ kg} \cdot \text{hm}^{-2} \text{ P}$  lower than unary models. The small differences in returns and optimal rates, combined with the binary model's ability to account for N-P interactions, make it superior for saline soils.

### 2.3 Fertilizer Agronomic Efficiency

Agronomic efficiency, a key indicator of fertilizer use efficiency, was calculated as:

$$\text{Nitrogen agronomic efficiency} = \frac{\text{Yield with N} - \text{Yield without N}}{\text{N rate}}$$

[Figure 2: see original paper] shows that agronomic efficiency decreased linearly with increasing fertilizer rates (significant correlation). N and P rates at levels 1 and 3 differed significantly, while level 2 did not differ from others. Agronomic efficiency values were  $8.2$ ,  $5.2$ , and  $3.1 \text{ kg}(\text{grain}) \cdot \text{kg}^{-1}(\text{N})$  for N levels 1-3, with level 1 being  $2.6\times$  higher than level 3. For phosphorus, values were  $18.3$ ,  $12.8$ , and  $6.5 \text{ kg}(\text{grain}) \cdot \text{kg}^{-1}(\text{P O})$ , with level 1 being  $2.8\times$  higher than level 3. Phosphorus efficiency consistently exceeded nitrogen efficiency.

Based on the linear relationship between fertilizer rate and efficiency, agronomic efficiencies at optimal economic rates were: N— $7.7$ ,  $6.0$ , and  $7.2 \text{ kg}(\text{grain}) \cdot \text{kg}^{-1}(\text{N})$  for linear plus plateau, unary quadratic, and square root models; P— $17.2$ ,  $13.3$ , and  $16.6 \text{ kg}(\text{grain}) \cdot \text{kg}^{-1}(\text{P O})$  for corresponding models. The binary quadratic model predicted  $6.2 \text{ kg}(\text{grain}) \cdot \text{kg}^{-1}(\text{N})$  and  $13.8 \text{ kg}(\text{grain}) \cdot \text{kg}^{-1}(\text{P O})$ . Linear plus plateau models showed highest efficiency, while unary and binary quadratic models showed nearly identical efficiencies.

### 3 Discussion and Conclusion

Model evaluation requires consideration of both statistical fit and fertilizer savings. Higher  $R^2$  indicates better fit. Previous studies on winter wheat N models in non-saline soils reported  $R^2$  rankings of linear plus plateau  $>$  unary quadratic  $>$  square root. Similar rankings were found for corn and other crops. Our study

confirmed these rankings under salt stress, with binary quadratic > linear plus plateau > unary quadratic > square root, though phosphorus models outperformed nitrogen models in the unary category. This suggests that while salinity doesn't alter relative model performance, phosphorus fertilization is more predictable than nitrogen in saline soils.

The square root model showed slower yield increases at high N rates, while the P model exhibited yield decline, possibly because N rates never reached yield-depressing levels or due to other factors requiring further investigation.

In low-salinity regions, optimal N rates from linear plus plateau models were  $119.6 \text{ kg} \cdot \text{hm}^{-2}$ , whereas our saline soil study recommended  $162.0 \text{ kg} \cdot \text{hm}^{-2}$  N, consistent with the need for higher N application to mitigate salt stress in saline soils. Studies on other crops have also found quadratic models to provide highest returns. In our lightly salinized soil ( $1.4 \text{ g} \cdot \text{kg}^{-1}$  total salts), linear plus plateau and unary quadratic models performed well for nitrogen, while unary quadratic was best for phosphorus.

Maximum yield did not correspond to maximum profit in our study, necessitating marginal analysis. For single-nutrient studies, unary quadratic models are suitable, but for N-P interaction studies, binary quadratic models are superior as they account for nutrient interactions while maintaining similar predictive accuracy. This aligns with recommendations that quadratic models are most appropriate for fertilizer response simulation.

High salinity inhibits soil nitrification and reduces nitrogen utilization. Our results show that high N and P rates significantly decreased agronomic efficiency, with optimal rates from all models falling between levels 2 and 3. While these optimal rates didn't achieve maximum efficiency, they provided the highest economic returns while maintaining relatively high efficiency. In low-salinity soils, linear plus plateau N efficiency was  $1.3\times$  higher than unary quadratic; our saline soil study found ratios of  $1.28\times$  for N and  $1.29\times$  for P, suggesting that relative efficiency relationships among models are not affected by salinity.

Different researchers have recommended different optimal models based on regional conditions. The Yellow River Delta's saline soils require higher fertilizer inputs than normal farmland. Considering goodness-of-fit, optimal economic rates, returns, and agronomic efficiency, the binary quadratic model is most appropriate for this region's conditions.

Winter wheat yield response to N and P fertilization in the Yellow River Delta can be described by linear plus plateau, unary quadratic, square root, and binary quadratic models. Integrating model fit, optimal economic rates, returns, and agronomic efficiency, unary quadratic models are suitable for single-nutrient studies, while binary quadratic models are optimal for studying N-P interactions. Since N and P are typically applied together in the Yellow River Delta, the binary quadratic model is the superior choice. For lightly salinized soils, the binary quadratic model recommends optimal economic rates of  $244.1 \text{ kg} \cdot \text{hm}^{-2}$  N and  $94.2 \text{ kg} \cdot \text{hm}^{-2}$  P (N:P = 2.6:1), yielding  $\text{¥}7,432.4 \text{ hm}^{-2}$  economic benefit, 6.2

kg(grain) · kg<sup>-1</sup>(N) nitrogen agronomic efficiency, and 13.8 kg(grain) · kg<sup>-1</sup>(P O) phosphorus agronomic efficiency. Annual adjustments based on current grain and fertilizer prices can provide more accurate, locally adapted recommendations for scientific fertilization guidance.

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