

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

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

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Abstract

A field experiment was conducted to investigate appropriate fertilizer response models for winter wheat in saline-alkali soil areas of the Yellow River Delta. Four different nitrogen and phosphorus fertilizer application rates were established during the winter wheat growing season, and eight fertilizer response treatments were designed according to the “3414” experimental design to evaluate the fitting performance of four models: linear plus plateau, single-variable quadratic, square root, and bivariate quadratic. The results indicated that all four fertilizer response models achieved extremely significant fitting levels ($P < 0.01$). Among the single-variable fertilizer response models, the quadratic models for nitrogen and phosphorus demonstrated the best fitting performance, with maximum economic returns of 7,448.3 yuan · hm² and 7,357.7 yuan · hm², respectively, and corresponding optimal economic application rates of 254.4 kg · hm² and 98.6 kg · hm², respectively. Comparative analysis revealed that the bivariate quadratic model exhibited superior fitting performance, with optimal economic nitrogen and phosphorus application rates of 244.1 kg · hm² and 94.2 kg · hm², respectively, yielding an N:P fertilizer ratio of 2.6:1, economic benefit of 7,432.4 yuan · hm², nitrogen agronomic efficiency of 6.2 kg (grain) · kg⁻¹ (N), and phosphorus agronomic efficiency of 13.8 kg (grain) · kg⁻¹ (P O). Comprehensive analysis of goodness-of-fit, optimal economic fertilizer rates, economic benefits, fertilizer agronomic efficiency, and the limitations of single-variable models indicated that the bivariate quadratic fertilizer response model is optimal and represents the most suitable option for nitrogen and phosphorus fertilizer response models for winter wheat in saline-alkali soils of the Yellow River Delta.

Full Text

Preamble

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Comparison of fertilizer-effect models on winter wheat response to nitrogen and phosphorus fertilizers in saline soils in the Yellow River Delta*

SHAN Jingjing^{1,2}, CHEN Xiaobing^{1**}, YIN Chunyan^{1,2}, WEN Pei^{1,2}, YAN Kun¹, ZHANG Lihua¹, ZHANG Libin³, FU Xiqiang, SUN Haishuan

¹Key Laboratory of Coastal Zone Environmental Processes and Ecological Remediation / Yantai Institute of Coastal Zone Research, Chinese Academy of Sciences, Yantai 264003, China

²University of Chinese Academy of Sciences, Beijing 100049, China

³Dongying 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, inhibiting plant growth and crop yields in this region. Although fertilizer application can alleviate the adverse impacts of salinization on crops, little remains known about the performance of different fertilizer-effect models in simulating '3414' fertilizer experiments in winter wheat fields on saline soils. Among essential elements, nitrogen (N) and phosphorus (P) are usually the most important nutrients limiting plant growth in both saline and non-saline soils. This study employed four fertilizer-effect models to simulate the impacts of N and P fertilizers on wheat yield in a field experiment conducted in Lijin County, Shandong Province, aiming to select a suitable fertilizer-effect model for wheat cultivation in the Yellow River Delta's saline soils. Four levels of N and P fertilizers (N: 0 kg · hm⁻², 135 kg · hm⁻², 170 kg · hm⁻², 405 kg · hm⁻²; P: 0 kg · hm⁻², 53 kg · hm⁻², 105 kg · hm⁻², 157.5 kg · hm⁻²) were established across eight treatments based on the '3414' design to investigate the fitting performance of four fertilizer-effect models: linear plus plateau, unary quadratic, square root, and binary quadratic. To ensure model accuracy, the least squares method was used for statistical regression analysis. Results indicated that all four fertilizer-effect models achieved extremely significant fitting levels ($P < 0.01$). Among unary models, the unary quadratic model performed best, yielding maximum profits of ¥7,448.3 · hm⁻² and ¥7,357.7 · hm⁻², with optimal economic N and P rates of 254.4 kg · hm⁻² and 98.6 kg · hm⁻², respectively. Compared with unary models, the binary model was superior, recommending optimal economic N and P rates of 244.1 kg · hm⁻² and 94.2 kg · hm⁻², respectively, at an N:P ratio of 2.6:1. This model achieved an economic benefit of ¥7,432.4 · hm⁻², with agronomic efficiencies of 6.2 kg(grain) · kg⁻¹(N) for nitrogen and 13.8 kg(grain) · kg⁻¹(P O) for

phosphorus. Based on comprehensive analysis of goodness-of-fit, optimal economic fertilizer rates, economic benefits, fertilizer agronomic efficiency, and the limitations of unary models, the binary quadratic fertilizer-effect model proved optimal and should be considered the best choice for modeling N and P fertilizer effects on winter wheat in the Yellow River Delta's saline soils.

Keywords: Fertilizer-effect model; Nitrogen and phosphorus fertilizers; Optimal economic fertilizer rate; Winter wheat; Saline soil; Yellow River Delta

Introduction

According to incomplete statistics from UNESCO and FAO, saline soils worldwide cover an area of 950 million hectares [1]. Developing and improving these potential land resources into arable land represents a global challenge. In China's Yellow River Delta region, saline soils are extensively distributed [2], with Dongying City alone possessing nearly 530,000 hectares [3]. Influenced by both anthropogenic and natural environmental factors, soil salinization in this area is becoming increasingly severe [4]. Soils with salt content below 0.2% account for only 4.29% of the Yellow River Delta area [2], while lightly salinized soils with salt content between 0.1% and 0.3% can be readily reclaimed for cultivation [5]. Scientific development and utilization of these lands constitute an important component of the "Yellow River Delta Efficient Ecological Economic Zone" construction initiative.

Soil nutrient and salt conditions determine vegetation types and land use patterns in saline-alkali soils [6]; consequently, deep tillage, green manure application, and other soil management measures are commonly employed as saline soil improvement techniques [7-8]. Combined application of organic and inorganic fertilizers, as well as balanced N-P-K fertilization, can mitigate salt stress on crops and promote growth to some extent [9-11]. Rational and scientific fertilization not only optimizes fertilizer application rates but also improves fertilizer use efficiency, thereby protecting the agricultural ecological environment [12-15]. Fertilizer consumption in the Yellow River Delta region is substantial; in 2013, Dongying City consumed 160,000 tons of nitrogen fertilizer and [text incomplete] [16]. Excessive fertilization not only wastes resources and causes water eutrophication but also exacerbates soil salinization [17]. Fertilizer use efficiency in China remains relatively low, with N, P, and K utilization rates of 30%-35%, 10%-25%, and 35%-50%, respectively [18]; in saline soils, fertilizer use efficiency is even lower due to salt stress [19]. Achieving efficient fertilizer utilization in saline soils has long been a critical issue requiring resolution.

Current research on fertilization in saline soils primarily focuses on soil-crop interaction mechanisms, with few studies addressing fertilizer-effect mathematical models. 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. Estab-

lishing fertilizer-effect models enables determination of rational fertilizer rates and represents a primary approach for achieving quantitative fertilization both domestically and internationally [20-21]. Most fertilizer-effect experiments (particularly ‘3414’ experiments) have employed ternary quadratic fertilizer-effect models for simulation [22]; however, success rates are low [23], often resulting in data abandonment and loss. Without considering actual field conditions—for instance, in some northern regions where soils are not potassium-deficient—adopting ternary quadratic models may erroneously conclude potassium deficiency [24]. Moreover, even when ternary quadratic models fit successfully, unary and binary models are still needed for supplementation. Therefore, selecting appropriate fertilizer-effect models is crucial. Wang et al. [25] failed to successfully fit a N-P-K ternary quadratic fertilizer-effect model in a winter wheat (*Triticum aestivum*) ‘3414’ experiment, instead employing unary linear and quadratic models. Wang et al. [26] found that when investigating the relationship between winter wheat yield and nitrogen application rate, the linear plus plateau model was most suitable in the first year, while the quadratic polynomial model was more appropriate in the second year, indicating that model selection changes with environmental conditions even at the same location. Consequently, model selection must be determined based on experimental site conditions. Numerous studies have demonstrated that model selection varies with crops and nutrients [21]. Although previous research on fertilizer-effect models is abundant, few studies have addressed models under saline soil conditions. This experiment utilized saline soils from the Yellow River Delta region to investigate fertilizer-effect models for winter wheat through ‘3414’ experiments, aiming to identify optimal fertilizer rates and provide a basis for rational winter wheat fertilization in this region. Winter wheat is the primary grain crop in the Yellow River Delta [16]; establishing fertilizer-effect models for winter wheat in the region’s saline soils will facilitate scientific fertilization guidance. Calculating optimal fertilizer rates through models for fertilizer recommendations not only enables quantitative fertilization but also provides a scientific basis 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 is situated at approximately 6 m elevation within a north temperate monsoon climate zone. Annual precipitation is 542 mm, with uneven seasonal distribution—63.9% occurs from June to August, creating climatic characteristics of spring drought, summer flooding, and late autumn drought. The average 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 [3]. The average groundwater depth is 1.34 m, with mineralization of 15 g · L⁻¹. The experimental soil is sandy loam with particle distribution of 67% sand, 27% silt, and 6% clay; soil pH (1:5) is 8.59, bulk density is 1.3 g · cm⁻³; soil organic matter is 10.35 g · kg⁻¹, total nitrogen 0.958

$\text{g} \cdot \text{kg}^{-1}$, available phosphorus $17.8 \text{ mg} \cdot \text{kg}^{-1}$, and available potassium $66.8 \text{ mg} \cdot \text{kg}^{-1}$. The surface soil (0-20 cm) contains total salts of $1.4 \text{ g} \cdot \text{kg}^{-1}$, Na $357 \text{ mg} \cdot \text{kg}^{-1}$, and Cl $533 \text{ mg} \cdot \text{kg}^{-1}$, classifying it as lightly salinized soil.

1.2 Experimental Design

The experiment implemented a subset of the ‘3414’ design, establishing a two-factor N and P trial with four levels each (0, 1, 2, 3). Level 0 represents no fertilizer application, level 2 represents the locally recommended optimal rate, level 1 = level 2 \times 0.5, and level 3 = level 2 \times 1.5 (representing excessive fertilization). Specific fertilizer rates are shown in Table 1. The experiment comprised eight treatments, each replicated four times, totaling 32 plots arranged in a completely randomized design, with each plot measuring 21 m^2 ($3 \text{ m} \times 7 \text{ m}$). Winter wheat was sown on October 22, 2015, with row spacing of 16 cm and seeding rate of $225 \text{ kg} \cdot \text{hm}^{-2}$. The basal-to-topdressing N ratio was 6:4, with all phosphorus applied as basal fertilizer. The winter wheat cultivar was ‘Shannong 24’, nitrogen fertilizer was urea (46% N), and phosphorus fertilizer was superphosphate (15% P O).

Irrigation was applied once during the winter wheat overwintering, jointing, and grain-filling stages, with other management practices consistent with conventional field production. All plots were harvested on June 14, 2016, with actual yields measured at maturity.

1.3.1 Unary Fertilizer Effect Models

Linear plus plateau model:

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

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

Unary quadratic model:

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

where: b is the linear term regression coefficient, c is the quadratic term regression coefficient, and y , x , and a are as defined above.

Square root model:

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

where: b is the square root term regression coefficient, c is the linear term regression coefficient, and y , x , and a 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 nitrogen and phosphorus application rates ($\text{kg} \cdot \text{hm}^{-2}$), respectively; f is the intercept, representing yield without fertilizer; a , b , c are quadratic term regression coefficients; and d , e are linear term regression coefficients.

1.4 Optimal Fertilizer Rate Calculation

Optimal N and P rates for each plot were determined using the marginal effect method for the unary quadratic, square root, and binary quadratic models, while the linear plus plateau model allowed direct calculation of optimal rates. The marginal effect principle calculates economically optimal fertilizer rates where marginal revenue equals marginal cost, i.e., $dy \cdot p_y = dx \cdot p_x$ (where p_x and p_y are fertilizer and winter wheat prices, respectively). This study used the 2016 winter wheat purchase price in Dongying City, Shandong Province ($\text{¥}1.27 \cdot \text{kg}^{-1}$), and actual market prices for fertilizers (urea: $\text{¥}1.6 \cdot \text{kg}^{-1}$; superphosphate: $\text{¥}2.4 \cdot \text{kg}^{-1}$).

1.5 Data Processing

Microsoft Excel and SAS statistical software were used for regression analysis based on the least squares principle [27], with ORIGIN and MATLAB software employed for graphing.

2.1 Unary and Binary Fertilizer Effect Models

During regression analysis, data from each replication were used instead of replication averages to avoid converting a replicated experiment into an unreplicated one, although both methods yield identical regression equations, the latter incorrectly inflates statistical test conclusions [28]. Treatments 2, 3, 6, and 8 were used to fit the nitrogen effect model at $105 \text{ kg} \cdot \text{hm}^{-2}$ phosphorus application rate, while treatments 4, 5, 6, and 7 were used to fit the phosphorus effect model at $270 \text{ kg} \cdot \text{hm}^{-2}$ nitrogen application rate. Specific fertilizer effect equations are presented in Table 2.

Table 2 shows that R^2 values for unary N and P fertilizer effect equations followed the order: linear plus plateau model > unary quadratic model > square root model > 0.5, with all F-test P values < 0.01. This indicates that winter wheat grain yield was extremely significantly correlated with N and P application rates, meaning these models adequately reflected the relationship between fertilizer rate and yield. Comparing N and P fertilizer effect equations, the latter showed higher R^2 values, demonstrating superior fitting performance for phosphorus compared to nitrogen.

The fitted curves for unary N and P fertilizer effect models are shown in Figures 1a [Figure 1: see original paper] and 1b. The N and P linear plus plateau models showed inflection points at $162.0 \text{ kg} \cdot \text{hm}^{-2}$ and $64.5 \text{ kg} \cdot \text{hm}^{-2}$, respectively, beyond which yields stabilized rather than continuing to increase with fertilizer rate. The unary quadratic models reached maximum yields at N and P rates of $292.3 \text{ kg} \cdot \text{hm}^{-2}$ and $106.6 \text{ kg} \cdot \text{hm}^{-2}$, respectively. Unlike the linear plus plateau model, the quadratic model simulated yield decreases at excessive fertilizer rates, while the former showed no such trend. The square root models reached maximum yields at N and P rates of $323.7 \text{ kg} \cdot \text{hm}^{-2}$ and $90.1 \text{ kg} \cdot \text{hm}^{-2}$, respectively. These fitted curves resembled the linear plus plateau model, but showed relatively slower yield increases at higher fertilizer rates. The N square root model approached zero yield change at high application rates, while the P model exhibited a yield decline trend.

Under the experimental site' s fertility conditions, the relationship between fertilizer rates and yield formed by N and P application was:

$$y = 4,472.222 + 6.2025x_1 + 18.4126x_2 + 0.0309x_1x_2 - 0.0161x_1^2 - 0.1278x_2^2$$

This fitted equation had an R^2 value of 0.7058, with F-test $P < 0.01$, indicating an extremely significant correlation between winter wheat grain yield and N-P application rates. According to this model' s fitted curve (Figure 1c), yield showed a clear maximum under the influence of both N and P factors, corresponding to N and P rates of $296.5 \text{ kg} \cdot \text{hm}^{-2}$ and $107.9 \text{ kg} \cdot \text{hm}^{-2}$, respectively.

2.2 Optimal Fertilizer Rates and Economic Returns

Maximum yield fitting results for unary and binary models are presented in Table 3. For nitrogen, the unary quadratic model predicted the highest grain yield, followed by the linear plus plateau and square root models; however, profit ranking was linear plus plateau model > unary quadratic model > square root model, with corresponding N rates following square root model > unary quadratic model > linear plus plateau model. For phosphorus, the unary quadratic model predicted the highest grain yield, followed by the square root and linear plus plateau models; profit ranking was unary quadratic model > linear plus plateau model > square root model, with corresponding P rates following unary quadratic model > square root model > linear plus plateau model.

Comparing unary and binary models, the binary model' s maximum yield was $24.4 \text{ kg} \cdot \text{hm}^{-2}$ and $55.7 \text{ kg} \cdot \text{hm}^{-2}$ lower than the former two models. However, considering economic benefits, maximum yield does not correspond to maximum profit; thus, model selection cannot be based solely on maximum yield but must also consider final returns using marginal effect analysis.

Table 4 shows that for nitrogen, the linear plus plateau model yielded the highest profit, followed by the unary quadratic and square root models, with optimal economic N rates following unary quadratic model > square root model > linear plus plateau model. The linear plus plateau model' s profit was only $\text{¥}14 \cdot \text{hm}^{-2}$

higher than the unary quadratic model, but its optimal economic N rate was $92.4 \text{ kg} \cdot \text{hm}^{-2}$ lower. If profit is the sole objective, both linear plus plateau and unary quadratic models are suitable for nitrogen. In this experiment, the linear plus plateau model achieved the highest profit of $\text{¥}7,462.3 \cdot \text{hm}^{-2}$, with an optimal economic N rate of $162.0 \text{ kg} \cdot \text{hm}^{-2}$. For phosphorus, the unary quadratic model yielded the highest profit, followed by the square root and linear plus plateau models, with corresponding P rates following unary quadratic model > square root model > linear plus plateau model. Although the linear plus plateau model showed good fit, comprehensive economic analysis indicated the unary quadratic model provided the highest profit ($\text{¥}7,357.7 \cdot \text{hm}^{-2}$) with an optimal economic P rate of $98.6 \text{ kg} \cdot \text{hm}^{-2}$. Therefore, among unary models, the linear plus plateau and unary quadratic models are suitable for nitrogen, while the unary quadratic model is optimal for phosphorus.

Comparing unary and binary quadratic models, the binary model's maximum profit was $\text{¥}15.8 \cdot \text{hm}^{-2}$ and $\text{¥}74.8 \cdot \text{hm}^{-2}$ lower than the former two models, while optimal economic N and P rates were $10.3 \text{ kg} \cdot \text{hm}^{-2}$ and $4.4 \text{ kg} \cdot \text{hm}^{-2}$ lower, respectively. This indicates minimal differences in maximum profit and optimal rates between unary and binary quadratic models; however, the latter incorporates N and P as variables in a single equation, accounting for N-P interactions.

2.3 Fertilizer Agronomic Efficiency

Fertilizer agronomic efficiency is a crucial indicator of fertilizer use efficiency, calculated as [29]:

$$\text{Nitrogen agronomic efficiency} = \frac{\text{Grain yield with N} - \text{Grain yield without N}}{\text{N application rate}}$$

Figure 2 [Figure 2: see original paper] demonstrates that agronomic efficiency decreased linearly with increasing fertilizer rate, with correlation coefficients reaching significant levels. Significant differences existed between levels 1 and 3 for both N and P treatments, while level 2 did not differ significantly from other levels. Nitrogen agronomic efficiencies for levels 1-3 were $8.2 \text{ kg}(\text{grain}) \cdot \text{kg}^{-1}(\text{N})$, $5.2 \text{ kg}(\text{grain}) \cdot \text{kg}^{-1}(\text{N})$, and $3.1 \text{ kg}(\text{grain}) \cdot \text{kg}^{-1}(\text{N})$, respectively, with level 1 being 2.6 times that of level 3. Phosphorus agronomic efficiencies for levels 1-3 were $18.3 \text{ kg}(\text{grain}) \cdot \text{kg}^{-1}(\text{P O})$, $12.8 \text{ kg}(\text{grain}) \cdot \text{kg}^{-1}(\text{P O})$, and $6.5 \text{ kg}(\text{grain}) \cdot \text{kg}^{-1}(\text{P O})$, respectively, with level 1 being 2.8 times that of level 3. Overall, nitrogen agronomic efficiency was lower than phosphorus agronomic efficiency. These results indicate that increasing N and P application rates reduces fertilizer agronomic efficiency, but phosphorus use efficiency remains higher than nitrogen.

Based on the linear relationship between fertilizer rate and use efficiency, agronomic efficiencies at optimal rates recommended by different models can be determined. For the N and P linear plus plateau, unary quadratic, and square root

models, agronomic efficiencies at optimal economic rates were 7.7, 6.0, and 7.2 $\text{kg}(\text{grain}) \cdot \text{kg}^{-1}(\text{N})$ for nitrogen, and 17.2, 13.3, and 16.63 $\text{kg}(\text{grain}) \cdot \text{kg}^{-1}(\text{P O})$ for phosphorus, respectively. For the N-P binary quadratic model, agronomic efficiencies were 6.2 $\text{kg}(\text{grain}) \cdot \text{kg}^{-1}(\text{N})$ and 13.8 $\text{kg}(\text{grain}) \cdot \text{kg}^{-1}(\text{P O})$. These results show that the linear plus plateau model achieved the highest fertilizer use efficiency, while unary and binary quadratic models showed nearly identical efficiencies.

3 Discussion and Conclusion

Evaluating fertilizer-effect models requires consideration of both statistical fitting performance and the efficiency of recommended fertilizer rates [30]. Larger R^2 values indicate better fit. Zeng et al. [30] found that when simulating winter wheat nitrogen unary models, R^2 values ranked as linear plus plateau model > unary quadratic model > square root model. Wang et al. [26] similarly reported linear plus plateau model > unary quadratic model. Meng et al. [31] found that when simulating winter wheat N-P models, R^2 values showed binary quadratic model > unary quadratic model, and $\text{N} > \text{P}$ (for unary quadratic models). Cerrato et al. [32] reported linear plus plateau model > unary quadratic model > square root model when simulating corn nitrogen unary models. In this study, under salt stress, winter wheat N-P model R^2 values still followed binary quadratic model > linear plus plateau model > unary quadratic model > square root model, but for unary models, $\text{P} > \text{N}$. These findings demonstrate that while salinity does not affect model fitting performance, phosphorus fitting is superior to nitrogen in saline soils. Therefore, it can be inferred that in high-salinity areas, model fitting performance remains optimal for binary quadratic and unary linear plus plateau models. As fertilizer rates increased, the nitrogen square root model showed progressively slower yield increases; however, under salt stress, the phosphorus square root model exhibited a yield decline trend. This may be because nitrogen rates in this experiment did not reach levels causing yield reduction, though other causes cannot be excluded and require further experimental verification.

In low-salinity areas, Zeng et al. [30] found the linear plus plateau model optimal for winter wheat nitrogen, with an optimal N rate of $119.6 \text{ kg} \cdot \text{hm}^{-2}$. In contrast, this experiment on saline soil showed the linear plus plateau model's optimal N rate was $162.0 \text{ kg} \cdot \text{hm}^{-2}$, consistent with saline soil management practices requiring increased nitrogen application to alleviate salt stress [33]. In soils with total salts [text incomplete] [34], unary quadratic N-P models for carrots (*Daucus carota*) were simulated and experimentally validated to provide highest returns. Since suitable fertilizer models vary by crop [21], and given this experimental site's total salt content of $1.4 \text{ g} \cdot \text{kg}^{-1}$, winter wheat nitrogen models with higher returns were linear plus plateau and unary quadratic models, while phosphorus showed highest returns with the unary quadratic model.

Wang et al. [11] used quadratic polynomial models to determine that winter wheat-maize rotation achieved maximum yield at $763 \text{ kg} \cdot \text{hm}^{-2}$ N rate with-

out considering economic returns. In this experiment, maximum yield did not correspond to maximum profit; therefore, marginal effect analysis was used to compare model profits, concluding that nitrogen suits linear plus plateau and unary quadratic models, while phosphorus suits the unary quadratic model. Since differences in maximum profit and optimal rates between unary and binary quadratic models were minimal, and the latter incorporates N-P interactions by including both nutrients as variables, the binary quadratic model is also suitable for saline soils, consistent with Mao et al. [35] proposing that quadratic models are most appropriate for simulating fertilizer-effect equations.

Excessive salinity inhibits soil nitrification, affecting nitrogen utilization [36]. In this study area, high N and P application rates significantly reduced fertilizer agronomic efficiency, with optimal rates from all models falling between levels 2 and 3. Although recommended optimal rates did not achieve maximum fertilizer use efficiency, they provided highest returns while maintaining relatively high efficiency. In low-salinity areas (total salt $0.56 \text{ g} \cdot \text{kg}^{-2}$), nitrogen use efficiency at optimal rates from the linear plus plateau model was 1.3 times that of the unary quadratic model [30]. In this experiment, linear plus plateau model efficiencies were 1.28 and 1.29 times those of the unary quadratic model for nitrogen and phosphorus, respectively. Thus, the relationship between fertilizer use efficiencies among different models appears unaffected by salinity.

Different researchers have reached varying conclusions regarding optimal models. Wang et al. [21] suggested the linear plus plateau model is suitable for the Huang-Huai-Hai region, while Guan [27] proposed that quadratic models suit soils with low baseline fertility, and square root models suit high-fertility soils. In summary, the Yellow River Delta saline soil region, affected by salt stress, requires relatively higher fertilizer inputs than conventional farmland. Under conditions ensuring high goodness-of-fit, the N-P binary quadratic model represents the most suitable choice for this region's soil conditions.

Winter wheat fertilizer rate-yield relationships in the Yellow River Delta can be described by linear plus plateau, unary quadratic, square root, and binary quadratic models. Comprehensive consideration of goodness-of-fit, optimal economic fertilizer rates, economic returns, and fertilizer agronomic efficiency indicates that the unary quadratic model is appropriate for single-nutrient studies, while the binary quadratic model is optimal for investigating N-P dual factors. Since N and P fertilizers are typically applied together in the Yellow River Delta, the binary quadratic model is the superior choice. In lightly salinized soils, the binary quadratic model recommends optimal economic N and P rates of $244.1 \text{ kg} \cdot \text{hm}^{-2}$ and $94.2 \text{ kg} \cdot \text{hm}^{-2}$, respectively (N:P ratio = 2.6:1), achieving an economic benefit of $\text{¥}7,432.4 \cdot \text{hm}^{-2}$, nitrogen agronomic efficiency of $6.2 \text{ kg}(\text{grain}) \cdot \text{kg}^{-1}(\text{N})$, and phosphorus agronomic efficiency of $13.8 \text{ kg}(\text{grain}) \cdot \text{kg}^{-1}(\text{P O})$. Based on annual fluctuations in grain and fertilizer prices, this model can be used to calculate more realistic optimal economic fertilizer rates for the region, facilitating scientific fertilization guidance.

References

- [1] Wang Z Q, Zhu S Q, Yu R P, et al. *Salt-affected Soils of China*[M]. Beijing: Science Press, 1993: 1-3
- [2] Guo B. The research on saline-alkali soil grading and governance of the Yellow River Delta based on the RS and GIS[D]. Ji' nan: Shandong Normal University, 2015: 9-10
- [3] Wang J R. Dongying Soil[R]. Dongying: Dongying Soil and Fertilizer Station, 1988: 3-5
- [4] Li B H, Zhao G X, Dong C, et al. Dynamic and driving force analysis of salinized land in the Yellow River Delta based on RS and GIS[J]. *Journal of Natural Resources*, 2011, 26(2): 310-318
- [5] Wu Z F, Zhao S L, Zhang X L. Studies on interrelation between salt vegetation and soil salinity in the Yellow River Delta[J]. *Acta Phytocologica Sinica*, 1994, 18(2): 184-193
- [6] Wang H M, Li Z H, Song G B, et al. The correlation among vegetation distribution, land use type and soil character in Yellow River Delta[J]. *Acta Scientiarum Naturalium Universitatis NeiMongol*, 2006, 37(1): 69-75
- [7] Zhang J F, Zhang X D, Zhou J X, et al. World resources of saline soil and main amelioration measures[J]. *Research of Soil and Water Conservation*, 2005, 12(6): 28-30
- [8] Zhou H P, Zhang L X, Yu F, et al. Review and prospect of saline land improvement in China[J]. *Modern Agricultural Science and Technology*, 2007, (11): 159-161
- [9] Cui S B, Qian X Q, Wang Z Y. The comprehensive benefits of green manure applied in the low yield farmland of rice-wheat rotation in saline soil of HuaiBei[J]. *Chinese Journal of Soil Science*, 1995, 26(2): 78-81
- [10] Chen X D, Zhao B, Gu J T, et al. Effects of nitrogen application rates and ratio on grain yield and quality of feed barley in Jianghuai wheat region[J]. *Acta Agriculturae Boreali-Sinica*, 2014, 29(S1): 280-283
- [11] Wang L Y, Xiao H, Cheng W J, et al. Effects of different fertilization mode on crops yield and soil fertility in coastal saline soil[J]. *Acta Agriculturae Boreali-Sinica*, 2016, 31(5): 71-74
- [12] Li J G, Pu L J, Zhu M, et al. The present situation and hot issues in the salt-affected soil research[J]. *Acta Geographica Sinica*, 2012, 67(9): 1233-1245
- [13] Li H G, He W T, Duan X H, et al. Techniques of alkalized soil improvement and rational fertilization for rice on Qianjin Farm in Ningxia Province[J]. *Acta Agriculturae Boreali-Occidentalis Sinica*, 2009, 18(5): 217-222
- [14] Deng L Q, Liu Z P, Cheng A W, et al. Effects of N and P fertilizers on sunflower grown in different saline soil on coast[J]. *Chinese Journal of Oil Crop Sciences*, 2002, 24(4): 61-64
- [15] Zeng W Z, Xu C, Huang J S, et al. Interactive effect of salinity and nitrogen application on sunflower growth[J]. *Transactions of the CSAE*, 2014, 30(3): 86-94
- [16] Dongying Statistics Department. Dongying Statistical Yearbook—Agriculture, Forestry, Animal, Husbandry and Fishery[DB/OL]. [2015-05-12].

<http://www.dystjj.gov.cn/dytj/Columns/19374178653.shtml>

- [17] Wang Y Q, Peng Z P, Xue S C, et al. Effect of excessive fertilization on soil ecological environment in the facility farmland[J]. *Journal of Agro-Environment Science*, 2005, 24(S1): 81-84
- [18] Yang Q L, Sang L M, Sun J R, et al. Current situation of fertilizer use in china and the method to improve chemical fertilizer utilization efficiency[J]. *Journal of Shanxi Agricultural Sciences*, 2011, 39(7): 690-692
- [19] Guo S X, Gong Y S. Effect of different salinity and nitrogen on water and nitrogen use efficiency of spinach[J]. *Chinese Journal of Soil Science*, 2011, 42(4): 906-910
- [20] Zhang M Q, Li J, Kong Q B, et al. Progress and prospect of the study on crop-response-to-fertilization function model[J]. *Acta Pedologica Sinica*, 2016, 53(6): 1343-1356
- [21] Wang X R, Chen X P, Zhang F S, et al. Application of fertilization model for fertilizer recommendation in China[J]. *Plant Nutrition and Fertilizer Science*, 1998, 4(1): 67-74
- [22] Wang S R, Chen X P, Gao X Z, et al. Study on simulation of “3414” fertilizer experiments[J]. *Plant Nutrition and Fertilizer Science*, 2002, 8(4): 409-413
- [23] Sun Y X, Guo Y S, Yu S Z, et al. Establishing phosphorus and potassium fertilization recommendation index based on the “3414” field experiments[J]. *Plant Nutrition and Fertilizer Science*, 2009, 15(1): 197-203
- [24] Zhang F S. *Soil Testing and Fertilization Recommendation*[M]. Beijing: China Agricultural University Press, 2011: 86-90
- [25] Wang S H, Sun Y M, Feng Z J, et al. Fertilizer effect of “3414” experiment on winter wheat in Tangshan[J]. *Journal of Hebei Agricultural Sciences*, 2009, 13(9): 1-2
- [26] Wang X M, Jie X L, Chen S L, et al. Verification of fertilization model and recommended fertilization in the crop rotation of winter wheat and summer maize[J]. *Journal of Anhui Agricultural Sciences*, 2008, 36(10): 4181-4184
- [27] Guan N. Function model of multi-fertilization effect[D]. Changchun: Jilin Agricultural University, 2012: 2-5
- [28] Shen J B, Mao D R. *Research Methods of Plant Nutrition*[M]. 3rd ed. Beijing: China Agricultural University Press, 2011: 86-90
- [29] Shukla A K, Ladha J K, Singh V K, et al. Calibrating the leaf color chart for nitrogen management in different genotypes of rice and wheat in a systems perspective[J]. *Agronomy Journal*, 2004, 96(6): 1606-1621
- [30] Zeng C L, Wang X R, Chen X P, et al. Study on the select of nitrogen fertilization models for winter wheat and the effects of it on result of fertilizing nitrogen[J]. *Journal of Jiangnan University*, 2000, 17(3): 8-12
- [31] Meng Z F, Li F, Meng X, et al. Study on optimal supplying rates of N, P and K for winter wheat in fluvo-aquic soil by “3414” experiment[J]. *Shandong Agricultural Sciences*, 2010, (10): 71-74
- [32] Cerrato M E, Blackmer A M. Comparison of models for describing corn yield response to nitrogen fertilizer[J]. *Agronomy Journal*, 1990, 82(1): 138-143
- [33] Wu R, Li Y N. Effect of salinity and nitrogen interaction on the growth of

- wheat[J]. *Water Saving Irrigation*, 2013, (5): 8-10
- [34] Chen X B, Zhang H J, Zhao H Y, et al. Mathematical model and optimization scheme for river west corridor processing type carrot N, P, K fertilizer formulation[J]. *Journal of Shenyang Agricultural University*, 2007, 38(4): 540-543
- [35] Mao D R, Zhang C D. Study on fertilization model and experimental design in recommended fertilization[J]. *Chinese Journal of Soil Science*, 1991, 22(5): 216-218
- [36] Min W, Hou Z A, Liang Y C, et al. Effects of soil salinity level and nitrogen rate on urea-N transformation in grey desert soil[J]. *Chinese Journal of Soil Science*, 2012, 43(6): 1372-1379

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