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Genotypic Variation in Nutrient Uptake Requirements of Rice Using the QUEFTS Model

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Abstract: Nutrient requirements for single-season rice using the quantitative evaluation of the fertility of tropical soils (QUEFTS) model in China have been estimated in a previous study, which involved all the rice varieties; however, it is unclear whether a similar result can be obtained for different rice varieties. In this study, data were collected from field experiments conducted from 2016 to 2019 in Zhejiang Province, China. The dataset was separated into two parts: japonica/indica hybrid rice and japonica rice. To produce 1000 kg of grain, 13.5 kg N, 3.6 kg P, and 20.4 kg K were required in the above-ground plant dry matter for japonica/indica hybrid rice, and the corresponding internal efficiencies (IEs) were 74.0 kg grain per kg N, 279.1 kg grain per kg P, and 49.1 kg grain per kg K. For japonica rice, 17.6 kg N, 4.1 kg P, and 23.0 kg K were required to produce 1000 kg of grain, and the corresponding IEs were 56.8 kg grain per kg N, 244.6 kg grain per kg P, and 43.5 kg grain per kg K. Field validation experiments indicated that the QUEFTS model could be used to estimate nutrient uptake of different rice varieties. We suggest that variety should be taken into consideration when estimating nutrient uptake for rice using the QUEFTS model, which would improve this model.

Keywords: rice; genotypic variation; QUEFTS; internal efficiencies; nutrient requirements

1. Introduction

Rice (*Oryza sativa* L.) is one of the most important cereal crops for approximately half of the global population [1]. Fertilizer application has made tremendous contributions to increase the grain yield and maintain food security. However, most farmers apply N fertilizer in amounts that exceed the demand for rice growth, resulting in grain yield losses, low nutrient use efficiency, and even a negative effect on the environment [2,3]. Therefore, good nutrient management and fertilizer recommendation methods are expected to increase grain yield, improve nutrient use efficiencies, and reduce environmental risk simultaneously.

Estimating nutrient requirements is essential for nutrient management. However, nutrient requirements are difficult to determine based on limited data due to the high diversity in terms of soil fertility, nutrient supply, and climate conditions [4]. Recently, the quantitative evaluation of the fertility of tropical soils (QUEFTS) model was used to estimate the nutrient requirements for a target yield [5] and provide recommendations for fertilizer application [6]. To assess the relationship between grain yield and nutrient uptake in above-ground dry matter, the model uses a linear–parabolic–plateau function, taking the interactions among nitrogen (N), phosphorus (P), and potassium (K) into account [7,8]. In addition, The QUEFTS model uses a large number of nutrient uptake data, which could

avoid the problems resulting from the evaluation with limited data [7,9], thus providing a very useful tool for the application of site-specific nutrient management [10,11]. This model has been applied to rice [5,12,13], maize [6,11,14], wheat [6,15], winter oilseed rape [16], soybean [17], radish [18], potatoes [19], tea [20], and peanut [21].

Besides chemical fertilizer supply, another way to exploit the yield potential is to breed high-yield rice varieties [22]. Since the super rice program was launched in 1996 by the Ministry of Agriculture in China [23], over 130 super rice varieties, including japonica, indica, japonica hybrid, indica hybrid, and japonica/indica hybrid rice, have been released, as of 2019 [24]. Compared with other types of super rice, the number of japonica/indica hybrid rice varieties is relatively small, only accounting for 6.1% of the total (http://www.ricedata.cn/variety/superice.htm). However, the grain yield of japonica/indica hybrid rice could easily achieve more than 12 t ha^{-1} [24,25] and even over 15 t ha^{-1} [26] yield in field production, which is superior to that of indica hybrid varieties [27,28] and japonica varieties [24,29]. In addition, previous studies have revealed that japonica/indica hybrid rice varieties had higher dry matter accumulation, higher nutrient uptake, and better root morpho-physiology than other cultivars [24,29,30].

Recently, research on the relationship between grain yield and nutrient uptake of single-season rice—a cropping system in which rice is grown once a year—using the QUEFTS model in China was published by Xu et al. [5], with 886 samples from 2000 to 2013. However, grain yield and nutrient accumulation were different for modern high-yield rice varieties. It is unknown whether this result could also be obtained for different rice species, such as japonica/indica hybrid rice and inbred rice, and to guide nutrient management owing to the great difference in grain yield and nutrient uptake. Therefore, the purposes of this study were to (1) determine the relationship between grain yield and nutrient uptake and (2) evaluate nutrient uptakes of japonica/indica hybrid rice and japonica rice, simulated by the QUEFTS model.

2. Materials and Methods

2.1. Experimental Sites

Rice is the main cereal crop in Zhejiang Province, China. In 2018, it covered a total area of 0.65 million hectares, which produced 4.77 million tons of grain yield, and the sown area of single-season rice was 0.45 million hectares, which produced 3.53 million tons of rice grain (http://tjj.zj.gov.cn/col/col1525563/index.html). The japonica/indica hybrid rice, firstly bred by the Academy of Agricultural Science of Ningbo, Zhejiang Province, China, in 2005, covered a total area of 0.25 million hectares, accounting for 57.3% of sown area of single-season rice in 2017. Furthermore, as of 2017, japonica/indica hybrid rice had a total planting area of 1.58 million hectares [31].

Field experiments were conducted in Huzhou, Hangzhou, Jiaxin, Shaoxin, Jinhua, Taizhou, Ningbo, and Quzhou City of Zhejiang Province from 2016 to 2019 (Figure 1). The japonica/indica hybrid rice is mainly grown from early or mid-May to late October or early November, whereas japonica rice is mainly grown from mid- or late May to late October. The total growth duration of japonica/indica hybrid rice could reach 160–170 days, while that of japonica rice was about 145–155 days [24,28]. Soil physical-chemical properties, climate characteristics, and rice varieties for each experimental site are shown in Tables S1–S3, respectively.

2.2. Data Sources

The datasets for this study were collected from the field experiments conducted by our group from 2016 to 2019. Grain yield, nutrient concentrations in grain and straw, nutrient accumulation, and harvest index (HI, kg grain per kg total above-ground dry matter) were collected and analyzed to evaluate the relationship between grain yield and nutrient uptake. The experimental sites contained variable nutrient management practices, including farmers' practice, optimal practice treatment, a series of nutrient

omission treatments based on optimal fertilization treatments, long-term experiments, and different rates of fertilizer treatments.
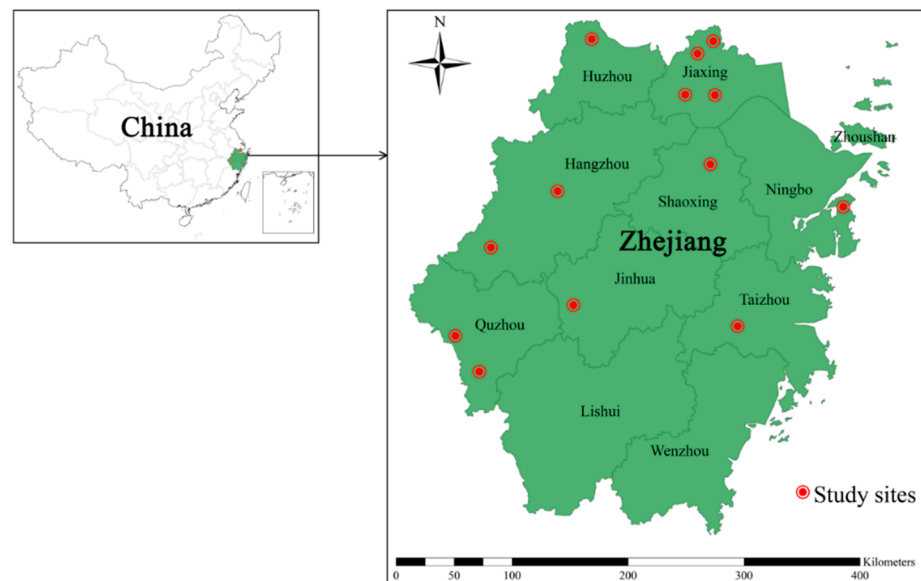

Figure 1. Distribution of experimental sites for rice in Zhejiang Province, China.

2.3. Model Development

We analyzed the grain yield and nutrient uptake of different rice varieties, with exclusion of the data with harvest index (HI) values less than 0.4 kg kg^{-1}, which were considered to be from a crop that was exposed to other stresses rather than the nutrient supply during the growing season [7]. Internal efficiency (IE), defined as the amount of grain yield produced per unit of nutrient accumulated in the above-ground plant dry matter [8], is used to evaluate the ability of a crop to transform nutrients into economic yield [32]. The QUEFTS model assumes that the IE is the same until the yield reaches about 70–80% of potential yield [33]. In addition, the 2.5, 5.0, and 7.5 percentiles of all the IE data were used as the maximum accumulation (*a*) and the maximum dilution (*d*) to define the envelope functions [7]. These *a* and *d* values were then used as parameters to estimate the nutrient requirements through the application of the QUEFTS model. The steps of the QUEFTS model have been described previously [6,15]. Additionally, the nutrient uptake under different potential and target yields was estimated using the solver model in Microsoft Office Excel. The key steps were, briefly, as follows: (a) selecting suitable data that fulfil the boundary conditions of the model; (b) defining the two borderlines of N, P, and K corresponding to the maximum and minimum nutrients accumulation in plant; and (c) simulating curves of optimum N, P, and K uptake at different potential or target yields.

2.4. Field Validation

The field validation experiments were conducted in Jinhua City and Hangzhou City in 2018 and 2019 as the field experiments performed in 2016 and 2017 to construct the QUEFTS model. Rice varieties were the same as those shown in Table S3. The fertilizers used in this study were urea (46% N), superphosphate (12% P$_2$O$_5$), and potassium chloride (60% K$_2$O) as N fertilizer, P fertilizer, and K fertilizer, respectively. The application rate was 300 kg N ha^{-1}, 105 kg P$_2$O$_5$ ha^{-1}, and 180 kg K$_2$O ha^{-1}. Nitrogen fertilizer was applied at the pre-transplanting stage, the early tillering stage, and the panicle initiation stage with a ratio of 5:3:2. P and K fertilizers were applied as basal fertilizers on the day before transplanting. Plant samples taken at the maturity stage were separated into stem and panicle and were oven-dried at 70 °C for 3 days to a constant weight. The N, P, and K concentrations were determined using the Kjeldahl method, vanadium molybdate yellow colorimetry, and flame photometry, respectively [34].

The values of root mean square error (RMSE) and normalized root mean square error (n-RMSE) were used to evaluate the deviation between the simulated data and observed data. Computation of the deviation statistics was as follows:

$$\text{RMSE} = \sqrt{\frac{\sum\limits_{i=1}^{n}(s_i - m_i)^2}{n}} \qquad (1)$$

$$\text{n-RMSE} = \frac{\text{RMSE}}{\overline{m}} \qquad (2)$$

where s_i represents the simulated value, m_i represents the measured value, n represents the number of observed data, and $\overline{m}$ represents the average of observed data.

2.5. Statistical Analysis

SPSS 17.0 software (IBM Corp., Armonk, NY, USA) was used to analyze the significance of the difference between the means of observed nutrient uptake and simulated nutrient uptake using the Student's *t*-test at the 0.05 significance level. Principal component analysis (PCA) was applied to visualize the distribution of the difference between japonica/indica hybrid rice and japonica rice using R project (Version 4.0.2). The calculation of the PCs also allowed to verify the existence of relationships among the variables.

3. Results

3.1. Grain Yield and Nutrient Uptake

The grain yield varied between japonica/indica hybrid rice and japonica rice. The average grain yields of japonica/indica hybrid rice and japonica rice were 9.92 and 8.02 t ha^{-1}, respectively, and ranged from 4.37 to 13.85 t ha^{-1} and from 3.74 to 11.60 t ha^{-1}, respectively (Table 1). Average straw yield was 9.57 t ha^{-1}, ranging from 4.26 to 15.18 t ha^{-1} for japonica/indica hybrid rice, while the average straw yield of japonica rice was 8.92 t ha^{-1}, ranging from 3.78 to 15.97 t ha^{-1}. The average HI of japonica/indica hybrid rice was 0.51 kg kg^{-1}, with a range from 0.39 to 0.62 kg kg^{-1}, while the average HI of japonica rice was 0.46 kg kg^{-1}, with a range from 0.37 to 0.56 kg kg^{-1}.

For the japonica/indica hybrid rice, the average concentrations of N, P, and K in grain were 0.93%, 0.25%, and 0.20%, respectively, while those in straw were 0.65%, 0.14%, and 2.04%, respectively. The average N, P, and K uptake in grain was 92.0 kg, 24.7, and 19.1 kg ha^{-1}, respectively, while that in straw was 63.9, 14.9, and 189.3 kg ha^{-1}, respectively. The average N, P, and K uptake in total above-ground dry matter was 155.9, 39.7, and 208.4 kg ha^{-1}, respectively. For the japonica rice, the average concentrations of N, P, and K in grain were 1.07%, 0.26%, and 0.23%, respectively, while those in straw were 0.76%, 0.19%, and 1.99%, respectively. The average N, P, and K uptake in grain was 89.5, 21.2, and 17.8 kg ha^{-1}, respectively, while that in straw was 70.9 kg, 17.6, and 166.9 kg ha^{-1}, respectively. The average N, P, and K uptakes in total above-ground dry matter were 160.5, 38.8, and 184.7 kg ha^{-1}, respectively.

To visualize the difference between japonica/indica hybrid rice and japonica rice, PCA was applied to a data matrix made up of the parameters from Table 1. The extracted first two PCs explained 70.1% of total variance (Figure 2).

Table 1. Characteristics of grain yield and nutrient uptake of japonica/indica hybrid rice and japonica rice.

Parameter [1]	Unit	Japonica/Indica Hybrid Rice					Japonica Rice				
		n [2]	Mean	SD [3]	Minimum	Maximum	n	Mean	SD	Minimum	Maximum
Grain yield	t ha^{-1}	683	9.92	1.66	4.37	13.85	508	8.02	1.67	3.74	11.60
Straw yield	t ha^{-1}	683	9.57	2.20	4.26	15.18	508	8.92	2.10	3.78	15.97
HI	kg kg^{-1}	683	0.51	0.04	0.39	0.62	508	0.46	0.04	0.37	0.56
(N) in grain	%	683	0.93	0.18	0.18	1.47	508	1.07	0.23	0.67	2.05
(P) in grain	%	518	0.25	0.04	0.03	0.44	382	0.26	0.04	0.14	0.40
(K)in grain	%	518	0.20	0.04	0.06	0.43	382	0.23	0.06	0.05	0.46
(N) in straw	%	683	0.65	0.22	0.13	1.27	508	0.76	0.21	0.24	1.50
(P) in straw	%	518	0.14	0.05	0.04	0.33	382	0.19	0.04	0.06	0.28
(K) in straw	%	518	2.04	0.48	0.48	4.50	382	1.99	0.48	0.81	4.29
N uptake grain	kg ha^{-1}	683	92.0	24.8	22.2	155.6	508	89.5	28.4	26.8	171.0
P uptake grain	kg ha^{-1}	518	24.7	6.4	2.9	44.6	382	21.2	6.8	9.2	43.6
K uptake grain	kg ha^{-1}	518	19.1	6.1	5.5	40.1	382	17.8	6.2	3.3	33.0
N uptake straw	kg ha^{-1}	683	63.9	24.5	11.8	151.9	508	70.9	27.2	11.6	152.1
P uptake straw	kg ha^{-1}	518	14.9	5.9	3.4	34.2	382	17.6	6.0	6.0	40.7
K uptake straw	kg ha^{-1}	518	189.3	50.9	73.5	309.2	382	166.9	58.0	56.8	385.0
Plant N	kg ha^{-1}	683	155.9	46.2	49.7	280.7	508	160.5	53.3	44.9	295.1
Plant P	kg ha^{-1}	518	39.7	11.6	13.4	68.6	382	38.8	12.1	15.6	68.1
Plant K	kg ha^{-1}	518	208.4	54.6	84.0	348.4	382	184.7	62.5	65.9	410.3
NHI	kg kg^{-1}	683	0.60	0.07	0.39	0.84	508	0.55	0.06	0.39	0.76
PHI	kg kg^{-1}	518	0.64	0.08	0.17	0.84	382	0.55	0.06	0.38	0.78
KHI	kg kg^{-1}	518	0.09	0.02	0.03	0.17	382	0.09	0.02	0.03	0.16

[1] (N), concentration of N; (P), concentration of P; (K), concentration of K. [2] n, number of observations. [3] SD, standard deviation.
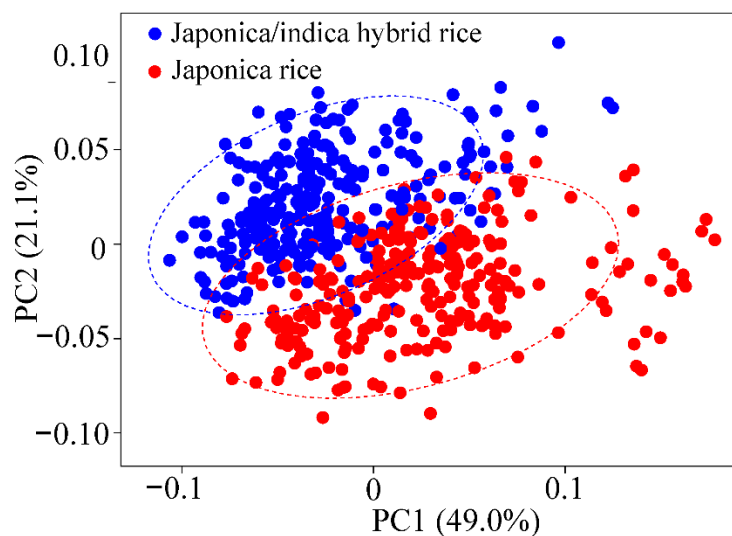
Figure 2. Principal component analysis (PCA) of the difference between japonica/indica hybrid rice and japonica rice based on the parameters in Table 1.

3.2. Internal Efficiency (IE) and Reciprocal Internal Efficiency (RIE)

IE (kg grain per kg nutrient) and reciprocal internal efficiency (RIE) (nutrient uptake requirement per ton of grain yield) were used to estimate the relationship between grain yield and nutrient uptake in the above-ground dry matter. The average IEs of N, P, and K for japonica/indica hybrid rice were 67.3, 265.7, and 46.4 kg kg^{-1}, respectively (Table 2). For japonica rice, the average IEs of N, P, and K were 53.3, 212.5, and 41.3 kg kg^{-1}, respectively. To produce 1000 kg of grain, the average N, P, and K requirements were 15.8, 3.9, and 23.4 kg for japonica/indica hybrid rice, respectively, and 19.6, 4.9, and 26.5 kg for japonica rice, respectively.

Table 2. Internal efficiency (IE) and reciprocal internal efficiency (RIE) of N, P, and K for japonica/indica hybrid rice and japonica rice.

| Data Set	Parameter	Unit	n [1]	Mean	SD [2]	25%Q [3]	Median	75%Q
Japonica/indica hybrid rice	IE-N	kg kg^{-1}	683	67.3	17.1	54.5	64.4	77.2
	IE-P	kg kg^{-1}	518	265.7	59.1	223.5	255.4	306.0
	IE-K	kg kg^{-1}	518	46.4	14	37.5	45.0	52.2
	RIE-N	kg t^{-1}	683	15.8	3.7	12.9	15.5	18.4
	RIE-P	kg t^{-1}	518	3.9	0.8	3.3	3.9	4.5
	RIE-K	kg t^{-1}	518	23.4	6.8	19.2	22.2	26.7
Japonica rice	IE-N	kg kg^{-1}	508	53.3	11.4	45.8	52.7	59.0
	IE-P	kg kg^{-1}	382	212.5	44.9	180.9	202.5	229.9
	IE-K	kg kg^{-1}	382	41.3	12.9	33.1	40.0	47.7
	RIE-N	kg t^{-1}	508	19.6	4.2	16.9	19.0	21.8
	RIE-P	kg t^{-1}	382	4.9	0.9	4.4	4.9	5.5
	RIE-K	kg t^{-1}	382	26.5	8.2	20.9	25.0	30.2

[1] n, number of observations. [2] SD, standard deviation. [3] Q, quartile.

3.3. Selection of Data for Running the QUEFTS Model

The constant *a* and *d* values of N, P, and K were calculated by excluding the upper and lower 2.5 (I), 5 (II), and 7.5 (III) percentiles of IEs for japonica/indica hybrid rice and japonica rice (HI ≥ 0.4 kg kg^{-1}) (Table 3). The nutrient requirements in the above-ground plant dry matter for japonica/indica hybrid rice and japonica rice at a target yield of 13 t ha^{-1} were calculated based on Set I, Set II, and Set III (Figure 3).

Table 3. Envelope coefficients of the maximum accumulation (*a*) and maximum dilution (*d*) of N, P, and K in the above-ground dry matter of japonica/indica hybrid rice and japonica rice.

Datasets	Nutrients	Set I		Set II		Set III	
		a (2.5)	*d* (97.5)	*a* (5)	*d* (95)	*a* (7.5)	*d* (92.5)
Japonica/indica hybrid rice	N	43	110	45	101	47	95
	P	173	389	187	362	191	350
	K	25	84	28	74	29	67
Japonica rice	N	34	82	36	75	39	69
	P	155	334	162	309	165	290
	K	22	75	24	63	25	58
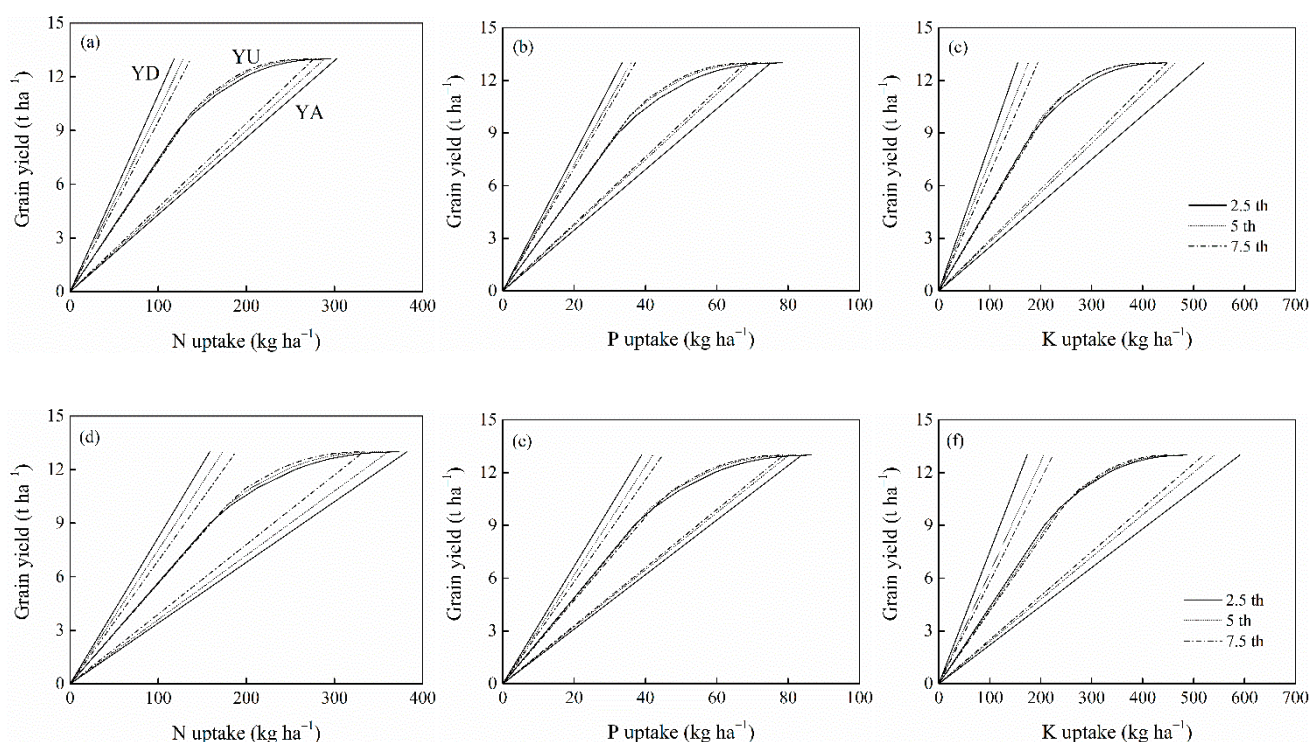
Figure 3. The nutrient requirements of japonica/indica hybrid rice (**a–c**) and japonica rice (**d–f**) simulated by the quantitative evaluation of the fertility of tropical soils (QUEFTS) models based on Set I, Set II, and Set III (HI $\geq$ 0.4 kg kg^{-1}). The yield potential of rice was set at 13 t ha^{-1}. YD, YU, and YA represent the maximum dilution, balanced uptake of nutrient in plant dry matter, and maximum accumulation, respectively.

Set I was used to estimate the relationship between grain yield and nutrient requirements due to the larger range of variability. For japonica/indica hybrid rice, the values of *a* and *d* were 43 and 110 for N, 173 and 389 for P, and 25 and 84 for K, respectively. For japonica rice, the values of *a* and *d* were 34 and 82 for N, 115 and 334 for P, and 22 and 75 for K, respectively.

3.4. Genotypic Variations in Nutrient Requirements

At a yield potential of 13 t ha^{-1}, the nutrient requirements of japonica rice were higher than those of japonica/indica hybrid rice in above-ground dry matter, which means japonica rice needs relatively more nutrients compared with japonica/indica hybrid rice to obtain the same grain yield in the range of 0 to 13 t ha^{-1} based on Set I (Figure 4). To produce 1000 kg grain, japonica/indica hybrid rice required 13.5 kg N, 3.6 kg P, and 20.4 kg K in a ratio of 3.8:1.0:5.7 and japonica rice required 17.6 kg N, 4.1 kg P, and 23.0 kg K in a ratio of 4.3:1.0:5.6 (Figure 5).
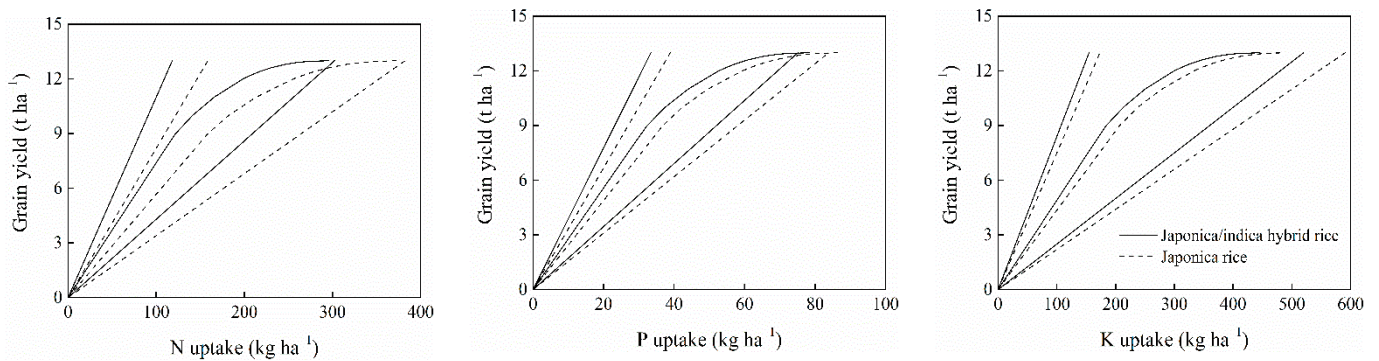
Figure 4. The nutrient requirements of japonica/indica hybrid rice and japonica rice in above-ground dry matter at a grain yield of 13 t ha^{-1}, based on Set I.
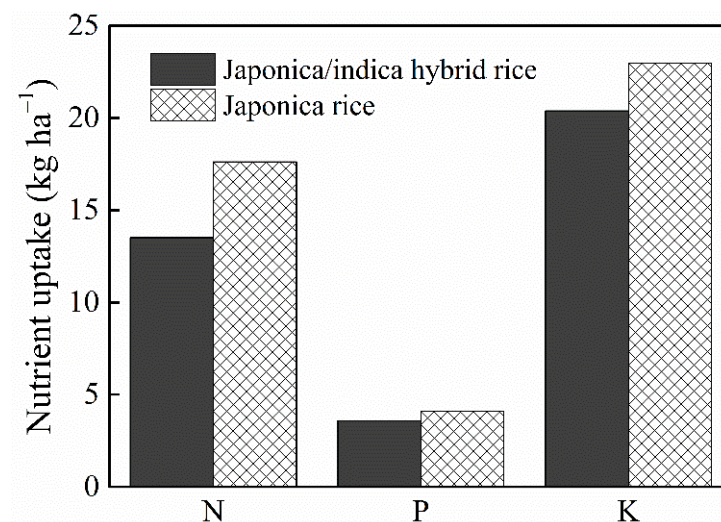

Figure 5. The nutrient requirements of japonica/indica hybrid rice and japonica rice in above-ground dry matter to produce 1000 kg of grain.

3.5. Estimating N, P, and K Requirements

The grain yield potentials were set as ranging from 9 to 15 t ha^{-1} for japonica/indica hybrid rice and japonica rice (Figure 6). The QUEFTS model predicted a linear increase in grain yield if N, P, and K were taken up in a balanced manner until actual yield reached about 60–70% of yield potential. Nutrient uptake for japonica rice was almost distributed under the nutrient absorption curve of japonica/indica hybrid rice (Figure 6a–c), indicating that japonica rice requires more nutrients than does japonica/indica hybrid rice to achieve the same yield.

3.6. QUEFTS Model Validation

We analyzed the observed nutrient uptake and simulated nutrient uptake for two field experiments in Jinhua City and Hangzhou City in 2018–2019 to validate the QUEFTS model (Figure 7). The values of RMSE and n-RMSE were used to evaluate the deviation between the simulated data and observed data. The RMSE values of N, P, and K were 19.4, 5.8, and 36.2 kg ha^{-1}, respectively, while the n-RMSE values of N, P, and K were 11.7%, 13.8%, and 15.6%, respectively.
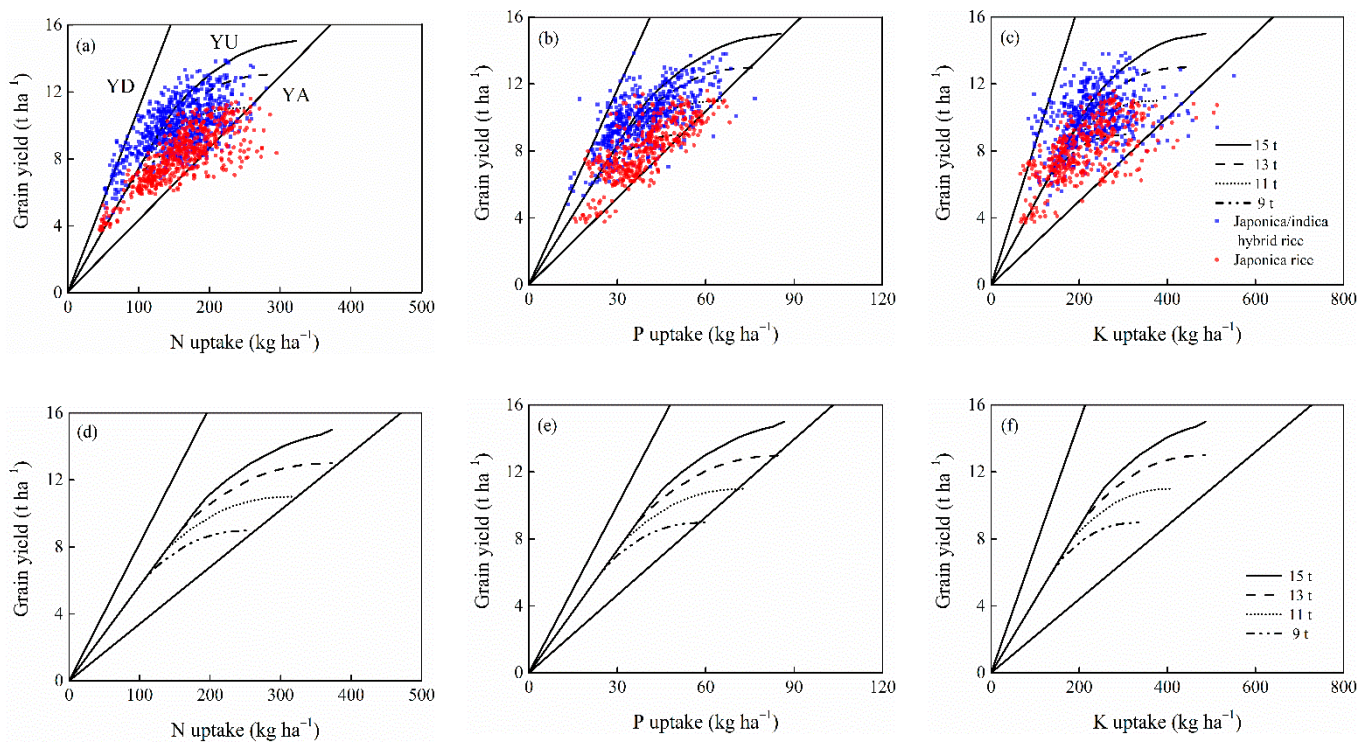
Figure 6. Relationship between grain yield and nutrient uptake in total above-ground plant dry matter under different yield potentials simulated by the QUEFTS model for japonica/indica hybrid rice (**a–c**) and japonica rice (**d–f**). YD, YU, and YA represent the maximum dilution, balanced uptake of nutrient in plant dry matter, and maximum accumulation, respectively. The yield potential ranged from 9 to 15 t ha^{-1}.
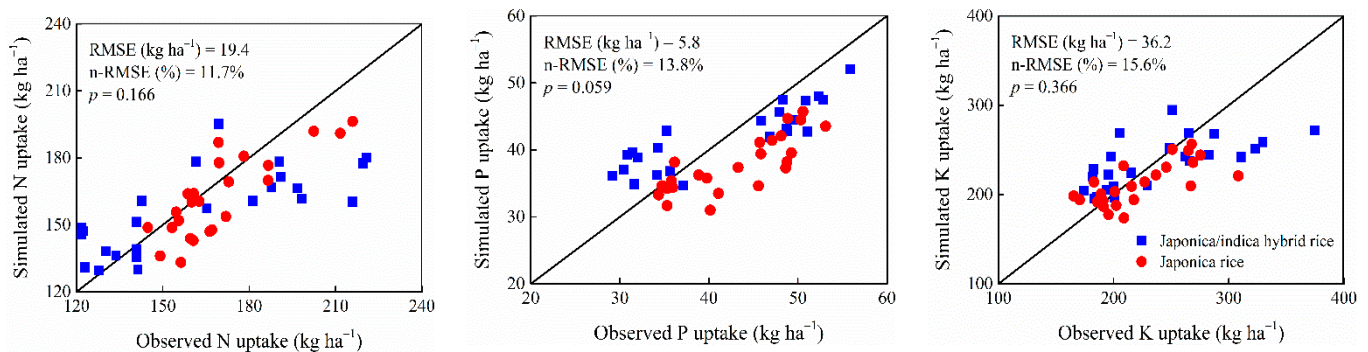

Figure 7. Relationships between the observed nutrient uptake and simulated nutrient uptake for japonica/indica hybrid rice and japonica rice. The observed data are from the field experiments conducted in Jinhua City and Hangzhou City in 2018 and 2019, respectively. The simulated data were derived from the QUEFTS model.

4. Discussion

In the present study, there were considerable variations in grain yield and nutrient concentrations of straw and grain, regardless of the rice genotypes (Table 1). In terms of grain yield and nutrient concentrations, the lower data were mainly from the omission plots for N, P, and K, while the higher data were derived from long-term high fertilization rates. This high variability in grain yield and nutrient uptake reflected the wide range of soil and weather conditions and fertilizer management, which provided a reliable database for evaluating the IEs of different rice varieties.

Differences in grain yield and nutrient uptake could be observed between the two rice genotypes (Table 1). The average yield of japonica/indica hybrid rice was higher than

that of japonica rice because of the relatively longer growth period of japonica/indica hybrid rice [24,28]. Nutrient concentrations of japonica rice were higher than those of japonica/indica hybrid rice, except for the concentration of K in straw. However, similar nutrient uptake in the plant dry matter was observed. Additionally, determination of *a* and *d* of nutrients was one of the most important parameters to run this model. The *a* and *d* values of japonica rice were lower than those of japonica/indica hybrid rice (Table 3 and Figure 4), indicating that more nutrients were required to produce the same yield for japonica rice. The *a* and *d* values were much different from those reported by Das et al. [13], Buresh et al. [12], and Xu et al. [5], which were related to different rice varieties, soil and climate conditions, and fertilizer management, thus resulting in different grain yield and nutrient uptake.

The RIEs simulated by the model were the same until the targeted yield reached 60%-70% of the yield potential, and then increased when the targeted yield beyond that, as has been found in previous studies [5,15,20]. In this study, the RIEs of japonica rice were higher than those of japonica/indica hybrid rice (Figure 5), resulting from the combination of higher nutrient concentrations and lower HI.

For single-season rice in China, Xu et al. [5] had estimated the nutrient requirements of 14.8 kg N, 3.8 kg P, and 15.0 kg K to produce 1000 kg of grain. The RIEs of N and P were higher than those of japonica/indica hybrid rice and lower the those of japonica rice in the current study. This difference could be due to the dataset reported by Xu et al. [5] which involved the combined estimation of nutrient uptake of all the rice genotypes, including japonica rice and hybrid rice, while in this study, the nutrient uptake of each rice genotype was estimated separately. Moreover, the experimental sites reported by Xu et al. [5] were mainly located in the northeast and northwest of China, which are dominated by cool temperate or temperate climates, unlike Zhejiang Province in this study, which is dominated by subtropical monsoon climate. This climate difference could be another reason for the difference in RIEs of N and P. However, the RIE of K was lower than both japonica/indica hybrid rice and japonica rice, which was mainly attributed to the high K fertilizer application (180 kg K_2O ha^{-1}) in the current study. Thus, for rice in China, variety should be taken into consideration when estimating nutrient uptake using the QUEFTS model, such as high yielding hybrid rice and relative low yielding conventional rice, although K uptake values of japonica/indica hybrid rice and japonica rice in the current study were higher than that reported by Xu et al. [5], so as to improve the QUEFTS model.

Field validation results showed that the observed nutrient uptake was distributed closely around the 1:1 line (Figure 7), suggesting that the simulated data were consistent with the observed data, which was in line with [5,15,20]. In addition, no significant differences were observed between the observed and simulated data ($p > 0.05$). It confirmed that the nutrient uptake of different rice varieties can be appropriately predicted by the QUEFTS model at a targeted yield.

5. Conclusions

There was a wide variation in grain yield and nutrient uptake, regardless of the rice genotypes. We found obvious differences in nutrient uptake across japonica/indica hybrid rice and japonica rice. The QUEFTS model predicted a linear relationship between target yield and nutrient uptake until the target yield reached about 60–70% of the potential yield. The nutrient requirements of japonica rice were relatively greater than those of japonica/indica hybrid rice. To produce 1000 kg of grain, 13.5 kg N, 3.6 kg P, and 20.4 kg K were required for japonica/indica hybrid rice and 17.6 kg N, 4.1 kg P, and 23.0 kg K for japonica rice. Field validation indicated that the QUEFTS model could be used to estimate nutrient uptake of different rice varieties at a certain targeted yield. Rice variety should be taken into consideration when estimating nutrient uptake using the QUEFTS model, which would help to improve this model. Moreover, the datasets should be expanded to include more rice varieties, such as japonica rice variety, indica rice variety, japonica

hybrid variety, indica hybrid variety, and japonica/indica hybrid rice variety. Different agricultural environmental conditions and cropping systems are also recommended for future research.

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