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Estimation of Watermelon Nutrient Requirements Based on the QUEFTS Model

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Abstract: Estimating balanced nutrient requirements for a watermelon plantation is essential to increase its fruit yield and nutrient use efficiency. This is vital for China, which produces 60% of world's watermelons with excessive fertilizer application. Therefore, datasets between 2000 and 2019 from field experiments in major watermelon producing regions across China were collected to assess relationships between fruit yield and nutrient uptake, and to estimate nitrogen (N), phosphorus (P), and potassium (K) requirements for a target yield using a modified Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) model. The results showed that the QUEFTS model predicted a linear increase in fruit yield to 60–70% of the total potential yield when balanced amounts of N, P, and K nutrients were absorbed. To produce 1000 kg of watermelon, 2.11 kg N, 0.27 kg P, and 2.69 kg K were required in shoot, and the corresponding internal efficiencies (IE) were 475, 3682, and 372 kg fruit per kg of N, P, and K, respectively. The modified QUEFTS model also simulated a balanced N, P, and K removal by fruit (accounting for 50.9%, 58.2%, and 66.4% of these nutrient accumulations in shoots, respectively). Field validation experiments further verified that the modified QUEFTS model could be used for estimating balanced nutrient requirements. Results from this study can provide practical guidance on fertilizer recommendations for improving fruit yield while preventing excessive or deficient nutrient supplies in China's watermelon plantations.

Keywords: QUEFTS model; watermelon; nutrient requirements; internal efficiency (IE)

1. Introduction

Watermelon (*Citrullus lanatus* (Thunb.) Matsum. et Nakai), one of the most important fruit crops, is widely cultivated and consumed around the world due to its juicy, sweet, taste and low price. Watermelon is abundant in beta-carotene, lycopene and polysaccharides, and is a source of antioxidants, which can be applied in the pharmaceutical and cosmetic industries [1–3]. Both the planting area and yield of watermelon in China have ranked first in the world for decades, and the total production is still increasing. According to the FAO (2018) [4], watermelon plantation area and yield in China were 1.5 million hectares and 63.0 million tons, which were equivalent to 47% and 61% of the world values, respectively. Chemical fertilizer, especially nitrogen (N), plays a dominant role in increasing watermelon yield and maintaining quality in China. However, to pursue higher yield and greater economic benefit, more and more fertilizers have been applied in watermelon plantations by Chinese farmers, resulting in a declining trend of fertilizer use efficiency in China [5]. It is well known that irrational fertilization is associated with negative impacts on crop yields, quality and the environment, including large amounts of residual fertilizer in soil that results in water pollution, and greenhouse gas emissions [6–8]. Therefore, a rational fertilizer recommendation is expected to address crop production and environmental issues simultaneously.

The estimation of crop nutrient requirements is crucial to crop nutrient management and fertilizer recommendation. Various methods of plant- and soil-based fertilizer recommendations have been applied to guide fertilization in numerous studies for crop nutrient management, such as chlorophyll meter, leaf color chart and soil testing [9–12]. Among them, soil testing, a soil-based fertilizer recommendation, has been used to increase crop yield and nutrient use efficiency since 2005 in China [13]. However, the heterogeneous soil and varied eco-environments of watermelon cultivation create great challenges and uncertainties for soil testing, which is hard to apply for accurately estimating the nutrient requirements of watermelons. In addition, due to numerous field sampling and laboratory analyses, soil testing is labor intensive and time consuming [12]. On the other hand, the plant-based fertilizer recommendation must estimate nutrient uptake to supplement the nutrients removed by the harvests [14,15]. Nutrient requirements of field-grown watermelons have been studied in China and other countries [16–18]. Most of these studies, however, were based on individual or few field trials to attain nutrient uptake parameters, and ignored the interactions among nutrients, which might not be suitable in a larger area [19,20]. Moreover, nutrient uptake (especially N, P) is affected by many factors, such as soil type, pH, organic matter, and soil microbes and their activity, and all of which are closely related to the bioavailability of nutrients, further causing the difference of nutrient supply in different regions [21]. Therefore, a systematic and balanced nutrient recommendation is vital to develop and sustain modern fertilization managements in agricultural systems without incurring human and environmental costs [22].

Site-specific nutrient management (SSNM) has been originally applied to rice and mainly focused on the optimization of site-specific N management based on potential yield and yield response to fertilizer applications [23,24], which can effectively match nutrient supply and demand within a specific field in a particular cropping system. A modification of the Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) model has been advocated by SSNM to estimate field-specific N, P, and K recommendations [24–26]. The QUEFTS model is based on a large amount of field experimental data, which can effectively avoid the deviation of minimal data for nutrient estimation [27]. Furthermore, interactions among N, P, and K have been considered in this model, which can be used to accurately assess the relationship between crop yield and nutrient accumulation. The QUEFTS model can thus provide a practical tool for the application of SSNM [26,28,29].

The QUEFTS model has been adapted by different countries for various crops such as maize [15,30], rice [19,20], wheat [28,31], cassava [32], potato [33], and tea [34], but not yet for watermelon. We hypothesized that the QUEFTS model could be also applied to assess the nutrient requirements for watermelon plantations. The objectives of this study were thus to: (1) determine the relationships between fruit yield and nutrient uptake across diverse watermelon plantation environments; (2) quantify the balanced requirements of N, P, and K for watermelons using the QUEFTS model; and (3) evaluate the N, P, and K uptake of watermelons simulated by the QUEFTS model through field experiments.

2. Materials and Methods

2.1. Data Sources

The data sources were from field trials of the International Plant Nutrition Institute's China Program and published studies in the China Knowledge Resource Integrated Database (https://kns.cnki.net) between 2000 and 2019. The climate, soil fertility, watermelon varieties and agro-techniques were varied with different watermelon-producing regions across China. Field fertilizations were comprised of farmers' practices, optimal nutrient managements, nutrient omission treatments based on optimal nutrient management, and different rates of fertilizer treatments (Table 1). Field management practices except fertilizations were in accordance with the best local management practices.

Table 1. Fertilization rates in fields across China.

Province	Varieties	Fertilization Rates (kg/ha)			References
		N	P_2O_5	K_2O	
Gansu	Longkang 9	200	90–170	130–260	Ma et al. [35]
	Longkang 9	200	170	200	Du et al. [36]
	Jingxin 1	260	170	140–560	Zhang et al. [37]
	Longkang 9	200	170	260	Ma et al. [38]
Hubei	Jingxin 1	225	75–300	225	Chen et al. [39]
Jiangsu	Xiaolan	180	120	150–600	Dong et al. [40]
	Watermelon 8424	360	412	615	Zhao et al. [41]
Xinjiang	Xinyou 10	135	105	45–270	Wang et al. [42]
Ningxia	Xinong 8	150	150	75–300	Wang et al. [43]
Chongqing	Qilin	113–225	120	180–225	Li et al. [44]
Hebei	Tiandage	173–450	145–200	296–420	Li et al. [44]
	Tiandage	231	145	296	
	Tiandage	231–350	145–200	296–300	

2.2. Development of the QUEFTS Model

The yield of watermelon, harvest index (HI, kg fruit dry matter per kg shoot dry matter), N, P, and K uptake by the fruits and shoots, internal efficiency (IE, kg fruit per kg nutrient), and reciprocal internal efficiency (RIE, kg nutrient per 1000 kg fruit) were collated before the development of the QUEFTS model. Meanwhile, the data with <0.4 of harvest indexes (HI) were eliminated because they were treated as crops being exposed to abiotic or biotic stresses other than a nutrient supply [27,45]. To predict the balanced nutrient uptake for a certain yield target using the QUEFTS model, the core parameters of maximum accumulation (*a*), maximum dilution (*d*) and yield potential were the prerequisites. The *a* and *d* were the maximum accumulation and maximum dilution of nutrient levels, respectively, which defined the relationships between yield and nutrients uptake, and the values were calculated by excluding the upper and lower 2.5th, 5.0th, and 7.5th percentile of all measured IE data in the model. The potential yield was defined as the maximum yield attainable under the experiment conditions in this study. The steps of the QUEFTS model have been described in the previous studies [15,46]. In this study, simply, the processes combining the QUEFTS model with the solver model in Microsoft Office Excel estimated the balanced nutrient uptake under a certain target yield, simulated the balanced N, P, and K uptake curves under different target yields, and evaluated the relationships between nutrients uptake and yield.

2.3. Field Validation

On-farm field trials were conducted in Hebei province, China (37°73′01″ N, 115°70′23″ E) in 2019 to test the results predicted by the QUEFTS model. The soil basic properties are presented in Table 2. A completely randomized block design with three replications was applied to experiments. The plot area was 40 m^2 with a planting density of 0.5 m × 2 m. The dominant watermelon variety of Qilin was used in field experiments and was sown in mid-April.

Table 2. Climate characters and soil basic properties (0–20 cm depth) of field sites in Hebei province, China.

Climate Type	Soil Type	pH (1:2.5)	Organic Matter (%)	Available N (mg/kg)	Olsen-P (mg/kg)	Available K (mg/kg)
Temperate	Fluvo-aquic	8.66	0.87	38.5	22.2	138.4

In the field sites, the fertilizer recommendation of watermelon was provided by the Nutrient Expert (NE) system. The NE system is a nutrient decision support system based on SSNM and a modified QUEFTS model developed by the International Plant Nutrition Institute [26,47]. The treatments included an FP (farmers' current practice), a balanced NE (fertilizer application based on Nutrient Expert), a balanced ST (fertilizer recommendation based on soil testing), NE(40%OF) (40% replacement of synthetic N fertilizer with organic N fertilizer), and a series of N treatments by adding or subtracting the N application rate and nutrient omission plots based on NE (Table 3). The fertilizer resources were urea (46% N), diammonium phosphate (46% P_2O_5 and 18% N), and potassium sulfate (50% K_2O). All P fertilizers were applied once as basal, while N and K fertilizer application was split into three: base fertilizer (mid-April) and two instances of top-dressing in late May and mid-June, which followed a ratio of 4:3:3 for N and 3:3:4 for K. The field management of weeds, pests, and diseases was controlled by adequate measurements during the watermelon growth.

Table 3. Description of fertilization and nutrient uptake for watermelon in field experiments in Hebei province, China.

Treatment	Yield (t/ha)	Fertilizer Application (kg/ha)			Nutrient Uptake (kg/ha)		
		N	P_2O_5	K_2O	N	P	K
NE − N	16.5	0	145	296	64.1	8.0	87.0
NE − 25%N	35.7	173	145	296	90.3	11.2	134.0
NE	38.1	231	145	296	96.9	13.0	139.4
NE + 25%N	40.7	289	145	296	97.1	11.7	122.9
NE + 50%N	40.0	347	145	296	88.4	10.6	117.8
NE − P	25.7	231	0	296	81.8	10.2	107.3
NE − K	22.0	231	145	0	62.2	6.7	88.1
NE (40%OF)	41.7	231	145	296	85.9	10.8	123.5
ST	33.9	250	150	300	65.3	8.4	90.2
FP	32.3	450	200	420	58.7	6.8	84.6

NE, fertilizer application based on Nutrient Expert; NE − 25%N, NE + 25%N, and NE + 50%N, adding or subtracting the N application rate based on NE; NE − N, NE − P, and NE − K, N/P/K omission plots based on NE; NE (40%OF), 40% replacement of synthetic N fertilizer with organic N fertilizer; ST, fertilizer recommendation based on soil testing; FP, farmers' current practice.

The shoots of the watermelon were manually harvested in early July. The harvested straw and fruit were oven-dried at 60 °C for determination of dry matter weight and N, P, and K concentrations. Parts of the straw and fruit were digested with H_2SO_4–H_2O_2 and N, P, and K concentrations were measured using the Kjeldahl method, vanadomolybdate yellow color method, and flame spectrophotometers, respectively [48]. The total N, P, and K accumulations were the products of the nutrient concentration multiplied with the plant dry weight.

The root mean square error (RMSE), normalized-RMSE (n-RMSE), and mean error (ME) were used to evaluate the QUEFTS model and the deviation between the measured and simulated data [33]. RMSE, n-RMSE and ME were calculated using the following formula:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (s_i - m_i)^2}{n}} \tag{1}$$

$$\text{nRMSE} = \frac{\text{RMSE}}{\overline{\text{m}}} \tag{2}$$

$$\text{ME} = \frac{\sum_{i=1}^{n}(s_i - m_i)}{n} \tag{3}$$

where s_i and m_i represent the values of simulated and measured nutrient uptake (kg/ha), respectively; n is the number of values; and $\overline{m}$ represents the average value of measured nutrient uptake (kg/ha). The equations of RMSE and ME measure the average discrepancy between the simulated and measured data with the same unit (kg/ha), while the n-RMSE equation does not consider the unit and enabled comparisons among values with different units [49]. The SPSS 20.0 software (SPSS Inc., Chicago, IL, USA) was utilized to analyze the significant differences between the means of simulated and observed values using the *t*-test at the 5% significance level. All charts were completed with Microsoft Office Excel (2013) software (Redmond, Washington, USA).

3. Results and Discussion

3.1. Characteristics of Fruit Yield and Nutrient Uptake

The fruit yield of watermelon ranged from 6.48 t/ha to 99.1 t/ha, with an average of 46.7 t/ha (Table 4). The reason for these significant differences was the diversity of watermelon varieties, climate, and field management [50,51]. The average fruit yield in this study area was higher than the 41.7 t/ha in the whole China, and much higher than the world yield of 32.1 t/ha in 2018 [4]. The average nutrient harvest index, namely, the nutrient accumulation ratio of fruit/shoot, was 0.58, 0.66, and 0.70 for N, P, and K, respectively, indicating that 58%, 66%, and 70% of N, P, and K in shoot were stored in the fruit (Table 4).

Table 4. Descriptive characteristics statistics of all watermelon data, including fruit yield, harvest index (HI), N, P and K accumulation in fruit, straw and shoot dry matter, concentrations of N (N_c), P (P_c), and K (K_c) in fruit and straw, and nutrient harvest index (kg nutrient in fruit per kg nutrient in shoot dry matter).

Parameter	Unit	*n* [1]	Mean	SD [2]	Minimum	25%Q [3]	Median	75%Q	Maximum
Fruit yield	t/ha	446	46.7	20.3	6.48	31.7	45.8	59.7	99.1
Harvest index	kg/kg	386	0.72	0.11	0.33	0.65	0.75	0.80	0.95
N_c in fruit	g/kg	388	15.8	3.64	7.34	13.6	15.2	17.6	31.6
P_c in fruit	g/kg	384	2.35	0.77	0.97	1.86	2.20	2.58	5.67
K_c in fruit	g/kg	388	25.2	8.99	8.04	19.9	23.0	27.4	66.7
N in fruit	kg/ha	390	55.0	27.0	6.55	35.2	53.2	70.8	144
P in fruit	kg/ha	380	7.86	3.92	0.90	5.19	7.64	9.89	21.7
K in fruit	kg/ha	383	84.2	41.0	9.88	58.0	80.8	103	237
N_c in straw	g/kg	380	24.5	3.84	11.8	22.3	24.1	26.4	38.0
P_c in straw	g/kg	380	2.38	0.76	0.48	1.99	2.27	2.63	10.1
K_c in straw	g/kg	380	22.6	9.84	1.69	15.4	21.2	28.2	65.4
N in straw	kg/ha	385	38.2	19.6	6.88	25.6	34.8	46.6	175
P in straw	kg/ha	385	3.75	2.76	0.65	2.41	3.17	4.47	40.9
K in straw	kg/ha	385	35.1	22.2	2.86	19.3	29.1	44.6	154
N in shoot DM [4]	kg/ha	404	92.7	34.5	20.8	71.1	90.0	110	287
P in shoot DM	kg/ha	391	11.6	4.64	2.18	8.61	11.2	13.9	31.4
K in shoot DM	kg/ha	400	117	48.0	21.4	82.7	111	142	295
N harvest index	kg/kg	387	0.58	0.16	0.14	0.46	0.59	0.70	0.94
P harvest index	kg/kg	379	0.66	0.15	0.16	0.58	0.69	0.78	0.94
K harvest index	kg/kg	380	0.70	0.16	0.20	0.61	0.73	0.82	0.96

n [1], number of observations. SD [2], standard deviation. Q [3], quartile. DM [4], dry matter.

The average N, P, and K concentrations in fruit were 15.8 g/kg, 2.35 g/kg, and 25.2 g/kg, respectively, while those in straw were 24.5 g/kg, 2.38 g/kg, and 22.6 g/kg, respectively (Table 4). However, due to the wide range of field environments, different watermelon varieties, and field management practices [14], there were widely varied N, P, and K concentrations of fruit (7.34–31.6 g/kg, 0.97–5.67 g/kg, and 8.04–66.7 g/kg, respectively) and straw (11.8–38.0 g/kg, 0.48–10.1 g/kg, and 1.69–65.4 g/kg) (Table 4).

The average accumulations of N, P, and K in the shoot dry matter were 92.7, 11.6, and 117 kg/ha, respectively (Table 4). We observed that K concentration in watermelon fruit was higher than that in straw, which indicated the importance of K among the three macronutrients of N, P, and K for watermelon production. Thus, K management should be optimized to ensure a high yield, the same as banana and cassava crops [32,52].

Regression analyses of measured N, P, and K uptake and watermelon fruit yield showed a good linear relationship (Figure 1). There were significant differences between nutrient accumulation and yield ($p < 0.01$), with $R^2 = 0.60, 0.55, 0.59$ for N, P, and K, respectively. These results demonstrated that watermelon fruit yield was obviously affected by N, P, and K supplies. Therefore, an accurate fertilization based on yield responses should be further improved to make the watermelon production system simpler and more robust.

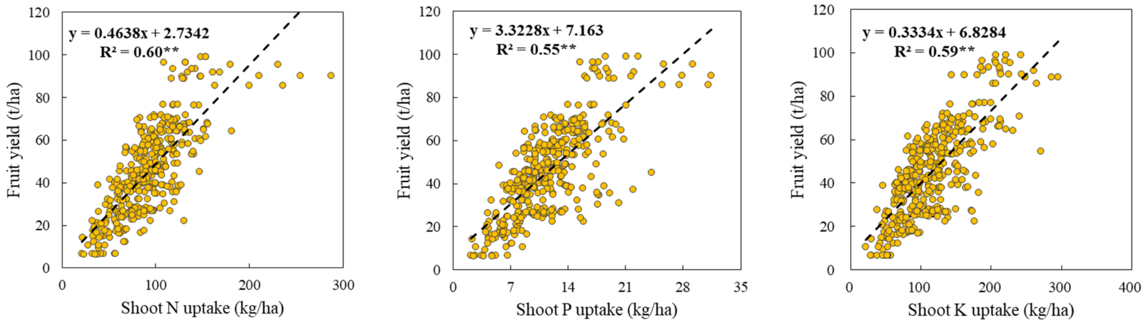

Figure 1. Relationships between observed fruit yield and N, P, and K uptake in the shoot dry matter at all sites in watermelon production areas in China. Dotted line represents the linear regression line. Two asterisks (**) represent the significance at the 0.01 level.

3.2. Internal Efficiency and Reciprocal Internal Efficiency

In this study, the measurements of IE and RIE were based on the analysis of several treatments, including optimal nutrient treatment, omission plots, and farmers' practices. The average IE of N, P, or K were 490, 3971, or 397 kg fruit yield per kg N, P, or K uptake for all watermelon data, respectively, equivalent to an N:P:K ratio of 1.2:10.0:1.0 in shoot DM (Table 5). The IE values varied tremendously, with a range of 116 to 1026 kg/kg for N, 979 to 8620 kg/kg for P, and 103 to 847 kg/kg for K (Table 5). These results indicated that nutrition management practices had a great influence on IE values. Additionally, due to the diversities of plant growth characteristics and other factors, the IEs of N, P, and K were greater than other crops such as maize [30], soybean [14], peanut [53], and potato [33].

Table 5. Descriptive statistics of the internal efficiency of N, P, and K (IE, kg fruit per kg nutrient) and its reciprocal internal efficiency (RIE, kg nutrient per 1000 kg fruit) for watermelon grown in China.

Parameter	Unit	*n* [1]	Mean	SD [2]	Minimum	25%Q [3]	Median	75%Q	Maximum
IE-N	kg/kg	404	490	148	116	381	499	585	1026
IE-P	kg/kg	391	3971	1261	979	3023	4026	4851	8620
IE-K	kg/kg	400	397	127	103	302	408	491	847
RIE-N	kg/t	404	2.30	0.99	0.97	1.71	2.01	2.63	8.59
RIE-P	kg/t	391	0.29	0.12	0.12	0.21	0.25	0.33	1.02
RIE-K	kg/t	400	2.87	1.24	1.18	2.04	2.45	3.32	9.74

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

RIE showed the opposite trend from IE (Table 5). To produce 1000 kg fruit, 2.30 kg N, 0.29 kg P, and 2.87 kg K were required (Table 5), which corresponded to the demand for N and K being approximately eight and ten times that for P during the growth of watermelon, respectively. The higher RIEs of N and K were related to the higher yield levels [14].

3.3. Selection of Data for Adapting the QUEFTS Model

To determine the maximum accumulation (YA) and maximum dilution (YD) borderlines using the QUEFTS model, HI data that were less than 0.4 were excluded, because a lower HI indicated that plant growth was influenced by limitation factors other than nutrients [19,54]. As shown in Figure 2, only one HI observation was below 0.4. For all watermelon data, HI in this study ranged from 0.33 to 0.95 with an average of 0.72 (Figure 2), which was similar to the HI values in potato plantations [33].

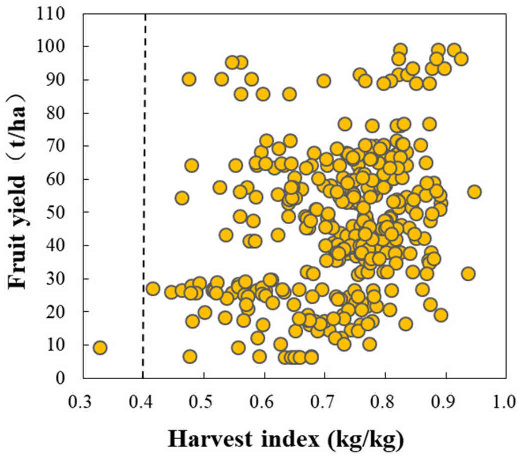

Figure 2. Distribution of fruit yield and harvest index (HI) of watermelon. The dotted line was used to exclude the value of HI < 0.4.

The constants of *a* and *d* represented the internal efficiency at maximum accumulation and maximum dilution of a nutrient. To define the sensitivity of the model, maximum attainable yield (90 t/ha) was set to the potential yield [55,56], and the relationship between fruit yield and nutrient uptake was estimated using the QUEFTS model excluding the upper and lower 2.5th (set I), 5.0th (set II), and 7.5th (set III) percentiles of all IE data (Figure 3). The nutrient requirements calculated by the QUEFTS model were similar for the two smaller sets (Table 6). To guarantee a certain confidence level of the model, however, set II (which included more than 90% of the data) was used to estimate balanced nutrient uptake and the relationship between fruit yield and nutrient accumulation, which was different from previous reports [19,28,57]. The constant *a* and *d* of N, P, and K were 265 and 731, 1935 and 6044, and 199 and 595 kg/kg for all watermelons (Table 6), respectively. Other crops, such as radish, showed that the constant *a* and *d* of N, P, and K were 241 and 845, 1069 and 4480, and 171 and 879 kg/kg, respectively [58].

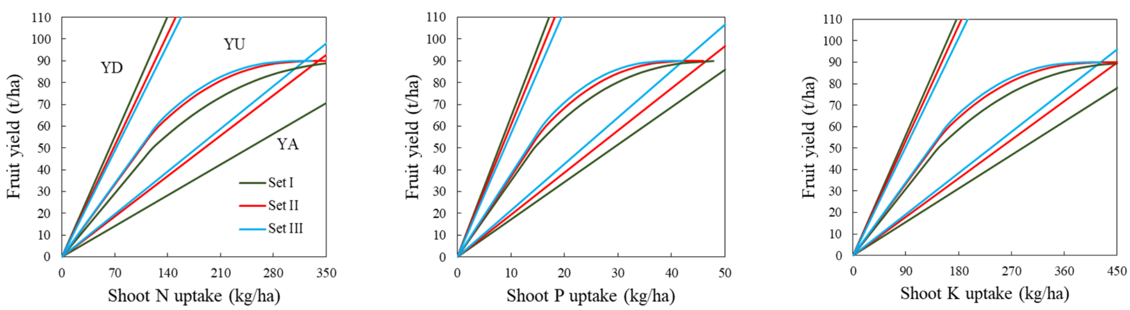

Figure 3. Relationships between fruit yield and nutrient uptake of watermelon at different sets of constants *a* and *d*. Set I, II, and III excluded the upper and lower 2.5th, 5.0th, and 7.5th percentiles of all internal efficiency (IE) data, respectively. YD, YA, and YU represented the maximum dilution, maximum accumulation, and balanced uptake of N, P, or K in the shoot, respectively. The yield potential was set at 90 t/ha.

Table 6. Envelope coefficients relating fruit yield to the maximum accumulation (*a*) and maximum dilution (*d*) of N, P and K in the shoot dry matter of all watermelon. Constants *a* and *d* were calculated by excluding the upper and lower 2.5th (set I), 5.0th (set II), and 7.5th (set III) percentiles of all nutrient efficiency data of the combined dataset.

Nutrients	Set I		Set II		Set III	
	a (2.5th)	*d* (97.5th)	*a* (5th)	*d* (95th)	*a* (7.5th)	*d* (92.5th)
N	202	789	265	731	280	696
P	1719	6417	1935	6044	2133	5656
K	173	623	199	595	213	563

3.4. Estimating the Balanced Nutrient Uptakes

The balanced nutrient requirements were calculated by the QUEFTS model under different potential yields from 30 to 90 t/ha with the Set II *a* and *d* values (Figure 4a–c). The highest yield potential of 90.0 t/ha was set to run the QUEFTS model for estimating the balanced nutrient requirements because the fruit yield rarely exceeded this potential yield in China [44]. The model predicted a linear increase in fruit yields if nutrients were taken up in balanced amounts, until the yield reached about 60–70% of the potential yield. When target yield exceeded 70% of the potential yield, more nutrients were required to increase yield (meaning a decline of IE) until the yield target approached potential yield. There were great differences in the balanced N, P, and K uptake requirements for targeted yields because of the potential yields (Figure 4).

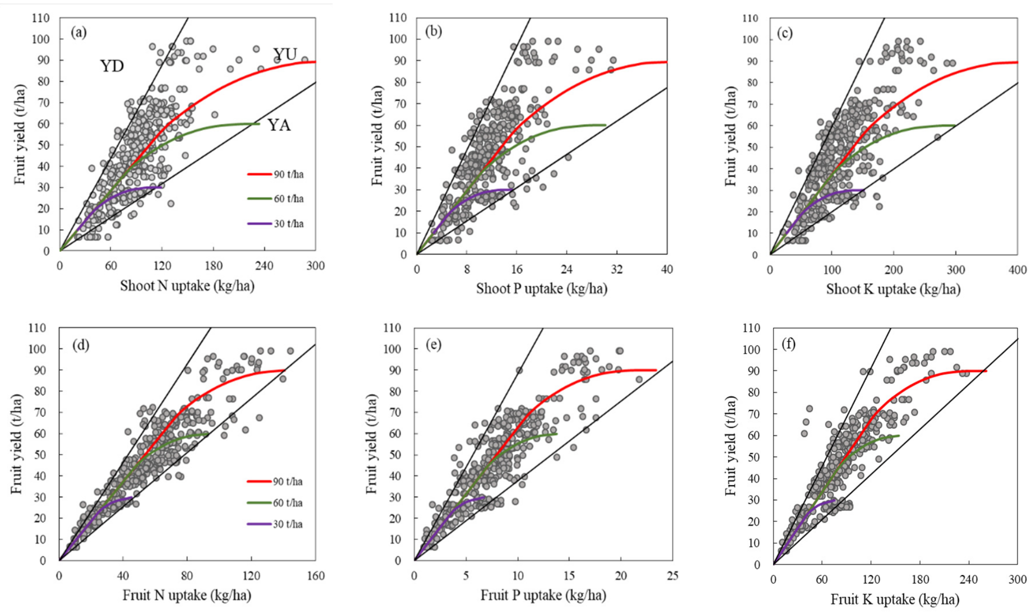

Figure 4. Relationships between fruit yield and N, P, and K accumulation in the shoot dry matter (**a**–**c**) and fruit (**d**–**f**) under different potential yields predicted by the Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) model. YD, YA, and YU represent the maximum dilution, maximum accumulation, and balanced uptake of N, P, and K in the shoot dry matter or in the fruit dry matter, respectively. These parameters were calculated by the QUEFTS model after excluding the upper and lower 5th percentiles of all internal efficiency data (HI ≥ 0.4). The potential yield ranged from 30 to 90 t/ha.

The QUEFTS model predicted the balanced nutrient accumulation of 2.1 kg N, 0.3 kg P, and 2.7 kg K per 1000 kg fruit when the yield reached about 60–70% of the potential yield, and the corresponding IE values for N, P, and K were 475, 3682, and 372 kg/kg for watermelon (Table 7). The optimal N:P:K ratios in shoot were about 7.81:1.00:9.96 (Table 4), while the ratios of mean measured NPK uptake from filed experiments were 7.99:1.00:10.09 (Table 7). These differences were because the estimated nutrient from the model was a balanced nutrient requirement [15,25,27]. In this study, some observations of N, P, and K uptake were not close to the balanced nutrient uptake thresholds as predicted by the QUEFTS model (Figure 4a–c), indicating the deficient and excessive use of nutrients, further reflecting the imbalanced application of N, P, and K fertilizers in the main watermelon-producing regions. This was mainly due to the fact that the N, P, and K fertilizers were not applied according to the indigenous supply of nutrients in the soil or plant demand in many nutrient management practices or treatments, including farmers' practices and nutrient omission treatments, in field experiments in the watermelon database [58].

Table 7. Internal efficiency (IE), the reciprocal internal efficiency (RIE) of N, P, and K in the shoot and fruit, and removal ratio at different target yields simulated by the QUEFTS model for watermelon in China with a potential yield of 90 t/ha.

Yield (t/ha)	Shoot IE (kg/kg) [1]			Shoot RIE (kg/t) [2]			Fruit RIE (kg/t) [3]			Nutrients Harvest Index (kg/kg) [4]		
	N	P	K	N	P	K	N	P	K	N	P	K
10	475	3682	372	2.11	0.27	2.69	1.07	0.16	1.78	0.51	0.58	0.66
20	475	3682	372	2.11	0.27	2.69	1.07	0.16	1.78	0.51	0.58	0.66
30	475	3682	372	2.11	0.27	2.69	1.07	0.16	1.78	0.51	0.58	0.66
40	475	3682	372	2.11	0.27	2.69	1.07	0.16	1.78	0.51	0.58	0.66
50	475	3682	372	2.11	0.27	2.69	1.07	0.16	1.78	0.51	0.58	0.66
60	468	3631	366	2.14	0.28	2.73	1.07	0.16	1.78	0.50	0.57	0.65
70	435	3371	340	2.30	0.30	2.94	1.08	0.16	1.79	0.47	0.54	0.61
80	390	3021	305	2.57	0.33	3.28	1.17	0.17	1.95	0.46	0.52	0.60
90	253	1960	198	3.96	0.51	5.05	1.75	0.26	2.90	0.44	0.50	0.57

[1] Amount of fruit yield produced per unit of nutrient accumulated in the shoot dry matter; [2] Expressed as kilogram of shoot nutrient requirement (including stems, leaves, and fruits) to produce one ton of fruit yield; [3] Expressed as kilogram of fruit nutrient requirements to produce one ton of fruit yield; [4] Expressed as the ratios of nutrient in the fruits to the shoots.

Fruit nutrient requirements were also simulated by the QUEFTS model, because nutrients being removed in harvested fruit and/or other plant parts had to be returned to soil through fertilization for maintaining soil fertility [14]. The model calculated fruit nutrient removal by excluding the upper and lower five percentiles of all IE values (HI ≥ 0.4) under different potential yields (30–90 t/ha) (Figure 4d–f). The balanced nutrient removals from fruits were 1.1 kg N, 0.2 kg P, and 1.8 kg K to product 1000 kg of fruit, indicating that about 50.9% N, 58.2% P, and 66.4% K were removed from the shoots of watermelons (Table 7). The nutrient HI calculated by the QUEFTS model (Table 7) were lower than the average observed values of nutrient HI (Table 4), indicating that the presence of luxury nutrient consumption throughout the watermelon growth cycle in situations of excessive fertilization and adequate indigenous nutrient supply [33]. These results confirmed the importance of assessing nutrient uptake requirement for rational fertilizer applications. Taking into account the fruit nutrient uptake can therefore provide practical guidance for the appropriate fertilization and avoiding of fertilizer waste [30].

3.5. Model Validations

Observed and simulated nutrient uptakes were analyzed in this study from experiments in watermelon-producing regions of Hebei in 2019 to test the QUEFTS model. The root mean square error (RMSE), normalized-RMSE (n-RMSE) and mean error (ME) were used to evaluate the QUEFTS model [33]. The reference data used for validations were experimental data from field trials where fertilizer rates were recommended by the NE system [26]. The RMSE, n-RMSE and ME values were 25.85 kg/ha, 26.8%, and 4.45 kg/ha for N, 3.18 kg/ha, 27.2%, and 1.38 kg/ha for P, and 30.72 kg/ha, 24.9%, and 4.80 kg/ha for K, respectively (Figure 5). The p values for N, P, and K were 0.574, 0.156, and 0.654, respectively (Figure 5), suggesting that there were no significant differences between the observed and model values and they fitted well with each other. However, a few of such N, P, and K uptake values were not close to the 1:1 threshold (Figure 5), which might be attributed to the diversities of soil properties, soil microbial population and fertilizer type (organic or synthetic fertilizer) [59]. In validation trials, organic fertilizer combined with synthetic or inorganic fertilizer application significantly increased nutrient uptake and fruit yield compared to conventional fertilization (Table 3). This was due to the fact that organic or inorganic fertilization changed soil physico-chemical properties, especially pH, which affected the availability of nutrients [60]. This was interpreted well for the low available phosphorus in alkaline soil (Table 2) [61]. Meanwhile, the results also indicated the applicability and feasibility of bio-fertilization additionally with conventional fertilizing in watermelon production. Therefore, considering these factors, we have improved the NE system for watermelon plantations based on a balanced nutrient uptake (see http://china-zh.ipni.net/library/nutrient-expert). We could thus cut down 48.7% N, 27.5% P_2O_5, and 29.5% K_2O of the currently inorganic fertilization rate, with a combination of organic fertilizer applications, to achieve robust production and economic returns in the future, according to these balanced nutrient requirements for watermelon production.

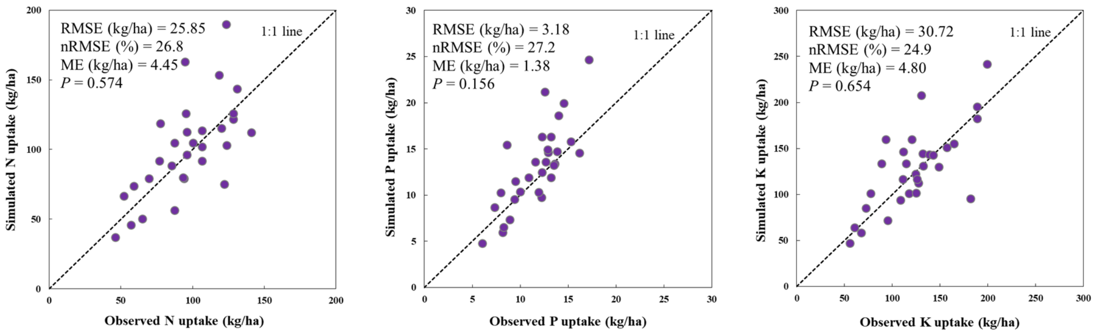

Figure 5. Relationships between observed and simulated N, P, and K uptake in the shoot dry matter for watermelons in Hebei province, China. The observed data were obtained from field experimental plots where the Nutrient Expert (NE) decision support system was applied. The simulated nutrient uptake data were estimated using the QUEFTS model. The dotted line represented the 1:1 line.

4. Conclusions

The nutrient uptake requirements for watermelon were simulated by the QUEFTS model under 30–90 t/ha potential yields to evaluate the balanced nutrient requirements. Regardless of yield potential, the model predicted a linear increase in yield if nutrients were taken up in balanced amounts of 2.11 kg N, 0.27 kg P, and 2.69 kg K per 1000 kg of fruit production until yield reached about 60–70% of the yield potential, with an N:P:K ratio of 7.81:1.00:9.96. The corresponding IEs for N, P, and K were 475, 3682, and 372 for balanced nutrition. The optimal N, P and K removals in 1000 kg fruit were 1.1, 0.2, and 1.8 kg, respectively, accounting for 50.9%, 58.2%, and 66.4% of the N, P, and K in shoots, respectively. Field validation demonstrated that the QUEFTS model could be used to simulate balanced nutrient uptake, which is useful for realizing a rational nutrient management practice for watermelon plantations.

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