Simulation of fertilizer requirement for irrigated wheat in eastern India using the QUEFTS model

(Simulation des Düngebedarfs für Bewässerungsreis in Ost-Indien mit dem Modell QUEFTS)

DEBTANU MAITI¹, DILIP K. DAS¹, & HIMANSHU PATHAK²

¹Department of Agricultural Chemistry and Soil Science, Faculty of Agriculture, Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, West Bengal, India, and ²Unit of Simulation and Informatics, Division of Environmental Science, Indian Agricultural Research Institute, New Delhi, India

(Received 26 May 2005; accepted 25 April 2006)

Abstract
Crop modelling can provide us with a vast amount of real-time information about fertilizer dose to achieve the target yield, crop conditions, etc. Nutrient-use efficiency in wheat is low because of conventional blanket and imbalanced fertilizer use. Estimation of fertilizer requirements based on quantitative approaches can assist in improving yields and nutrient-use efficiency. Field experiments were conducted in 20 sites in eastern India to assess the soil supply, requirement and internal efficiency of nitrogen (N), phosphorous (P), potassium (K) and zinc (Zn) in wheat. The data were used to calibrate the QUEFTS (QUantitative Evaluation of the Fertility of Tropical Soils) model for site-specific, balanced fertilizer recommendations. The parameters of maximum accumulation (a) and maximum dilution (d) in wheat were calculated for N (35 and 100 kg), P (129 and 738 kg), K (17 and 56 kg), and Zn (21502 and 140244 mg). Grain yield of wheat showed good correlation with N ($R^2 = 0.937^{**}$), P ($R^2 = 0.901^{**}$) and K uptake ($R^2 = 0.801^{**}$). The NPK ratio to produce 1 ton grain yield of wheat was derived to be 4.9:1.0:8.9. The relationships between chemical properties and nutrient supplying capacity of soils were also established. The model was validated using the data of four other experiments. Observed yields with different amounts of N, P, K and Zn were in good agreement with the predicted values suggesting that the validated QUEFTS model can be used for site-specific nutrient management in wheat.

Keywords: Fertilizer requirements, target yield, QUEFTS, SSNM, wheat

Introduction
Nutrient-use efficiency in wheat is low because of conventional blanket and imbalanced fertilizer use. The site-specific nutrient management (SSNM) strategies that include crop nutrient requirements, indigenous nutrient supply and recovery efficiency of applied fertilizer should be used to increase yield and nutrient efficiency of wheat. Estimates of indigenous
nutrient supply, nutrient requirements, internal efficiency, recovery efficiency of nutrients and subsequent fertilizer recommendations for wheat (*Triticum aestivum* L.) have been made through field experiments at several researcher-managed sites. However, these estimates can only partly be extrapolated to farmers’ fields, because of the much broader range of soil, climatic and management conditions. Therefore, estimates of fertilizer requirements should be based on more generic, quantitative approaches, such as simulation modelling. However, most existing models only address a single nutrient, and interaction of the nutrients is largely ignored.

The crop removal of nutrients per unit area of cultivated land has also increased considerably (Ladha et al. 2000). There are uncertainties about nitrogen (N), phosphorous (P) and potassium (K) requirements of wheat, because the internal nutrient efficiencies (IE) vary greatly depending on nutrient supply, crop-management practices and climatic conditions (Van Duivenbooden et al. 1996). The new technologies like computer-based crop modelling can provide us with a vast amount of real-time information about fertilizer doses to achieve the target yield, crop conditions, weather, etc. The models can be easily used by the farmers enabling them to make more precise application of inputs.

The QUEFTS (QUantitative Evaluation of the Fertility of Tropical Soils) model, originally developed by Janssen et al. (1990), and first applied in Kenya and further evaluated by others (Smaling & Janssen 1993; Witt et al. 1999) considered interactions of N, P and K. The QUEFTS model is used to process the user’s data and the exterior data into personalized information or decision support system (DSS). The QUEFTS also enhances understanding of data taken under certain conditions and helps extrapolate their applications to other conditions and locations. This model facilitates better understanding of the interrelationship between soil or crop-management and various components in a system and can integrate numerous experimental results from different conditions. Integration of this simulation model with agricultural field research may be the best way to bring about further improvements. The QUEFTS model can also be used in different crops and different nutrients. Keeping this in view, the present investigation was undertaken for fertilizer requirements of wheat with the following objectives: (i) to estimate N, P, K and Zn requirements, (ii) to estimate indigenous nutrient supplying capacity of soil, (iii) to determine recovery efficiency of nutrients, and (iv) to evaluate site-specific nutrient management in wheat.

**Materials and methods**

*Determinations of use efficiencies*

The following procedures were used to describe nutrient use efficiencies:

\[
\text{RE}_\text{Nu} = \frac{(\text{UN}_\text{Nu} - \text{UN}_0)}{\text{FN}_\text{Nu}}
\]

where: RE is apparent recovery efficiency of applied fertilizer nutrient (kg nutrient in plant dry matter per kg nutrient applied); Nu is the nutrient of concern; UNu is plant nutrient accumulation in total above-ground plant dry matter at maturity (kg ha\(^{-1}\)) in plots receiving the respective fertilizer nutrient at the rate of FNu (kg ha\(^{-1}\)); and UNu0 is the total nutrient accumulation without nutrient addition (Cassman et al. 1996).

\[
\text{IE}_\text{Ex} = \frac{\text{Y}}{\text{UN}_\text{Nu}}
\]

(2)
where: IEx is internal nutrient efficiency (kg grain/kg nutrient in plant dry matter), and Y is grain yield (kg ha\(^{-1}\)) (Witt et al. 1999).

**Trial details**

Two trials were conducted in this experiment. The first one was conducted for determination of maximum accumulation (a) and maximum dilution (d) values for QUEFTS. The second trial was conducted for site-specific nutrient management to compare observed and simulated values of yield and nutrient uptake where the fertilizer requirement of different nutrients were fixed based on the QUEFTS model to achieve the target yields of 5 and 6 t ha\(^{-1}\). The first and second trials comprised of 20 and 4 sites (farmers’ fields), respectively.

**Model background**

Wheat yields in some places are showing a declining trend. This may be due to the imbalanced use of fertilizers which not only reduce the fertilizer-use efficiency but also enhance soil nutrient depletion resulting in net decrease in the yield of crops (Dawe et al. 2000; Regmi et al. 2002). Estimation of fertilizer requirements based on quantitative approaches can assist in improving wheat yields and increasing nutrient-use efficiency. We used the QUEFTS (QUantitative Evaluation of the Fertility of Tropical soils) model for estimation of N, P, K and Zn requirements and their recommendations for a target yield (5 and 6 t ha\(^{-1}\)) of wheat. Although the original version of QUEFTS was written for maize it was reprogrammed by C. Witt at the International Rice Research Institute, Philippines, for rice. The same programme (modified by C. Witt) of QUEFTS was used in this investigation. The model considers the interactions of N, P, K and Zn and climate-adjusted potential yield of the concerned areas or regions.

A field-tested model (QUEFTS) can be used to transfer the results of experimental research to other soils, climate and management conditions outside the experimental sites. QUEFTS assumes that yield is a function of N, P and K supply from soil and fertilizer. In the model, a distinction is made between potential supply of a nutrient (maximum quantity that is supplied from soil and fertilizer) and its actual uptake by the crop. Actual uptake of a nutrient equals potential supply only, if all other growth conditions are optimal. The essence of QUEFTS is the relation between nutrient uptake and yield. The model is also used for nutrients other than N, P and K.

**Steps of QUEFTS**

QUEFTS involves four steps:

- **Step I.** Assessment of potential indigenous nutrient supply. Nutrient uptake in fertilizer omission plots was used as a measure of soil nutrient supply and relationships with soil chemical tests were established.
- **Step II.** Estimation of uptake of N (UN), P (UP) and K (UK) as fractions of potential supply of N (SN), P (SP) and K (SK), i.e. supply from soil plus fertilizer, taking recovery efficiency of applied nutrient into account.
- **Step III.** Designation of yield ranges as functions of actual uptakes of N, P and K when they are maximally accumulated and maximally diluted.
Step IV. Calculation of the final yield estimate by combining the yield ranges for nutrients by accounting of their interactions.

**Determination of ‘a’ and ‘d’ values for QUEFTS (Experiment I)**

Maximum accumulation (a) and maximum dilution (d) values of N, P, K and Zn on the basis of internal efficiencies were determined for wheat (cv. UP-262) growing in Inceptisol, based on the experiments conducted in 20 sites [pH, 6.80 – 7.65; organic C (%), 0.41 – 0.56; available N (kg ha\(^{-1}\)), 469.36 – 542.25; available P (kg ha\(^{-1}\)), 9.50 – 18.75; available K (kg ha\(^{-1}\)), 59.00 – 102.50 and available Zn (mg kg\(^{-1}\)), 0.44 – 0.67] of Nadia district in West Bengal, India, during the year 2001–2002 and 2002–2003 in a randomized block design with 20 replications. There were seven treatments such as: T\(_1\), –N; T\(_2\), –P; T\(_3\), –K; T\(_4\), –Zn; T\(_5\), +NPKZn; T\(_6\), FYM only and T\(_7\), control. The recommended dose of N, P, K, Zn and FYM for wheat were 100, 50, 50, 0.5 kg ha\(^{-1}\) and 6 Mg ha\(^{-1}\), respectively. The yield and uptake data were recorded in these entire treated plots including the nutrient omission plot of N, P, K and Zn. In the QUEFTS model, ‘a’ and ‘d’ values were calculated by slope of envelope function grain yield vs. nutrient uptake. The envelope lines of nutrient accumulation and dilution were determined on the basis of internal efficiency of different nutrients which were further used as inputs in QUEFTS. Three sets of constants of ‘a’ and ‘d’ were estimated by excluding the upper and lower 10 percentile (Set I), 15 percentile (Set II) and 20 percentile (Set III) of calculated internal nutrient efficiencies. The 20 percentile as outlier means exclusion of 20% of total data, where 10% of total data has been excluded from the upper part and rest 10% of total data from the lower part. Thus only 20% of total data were excluded and the rest (80%) was retained. Those derived three sets of ‘a’ and ‘d’ values of the QUEFTS model were used in wheat for fertilizer recommendations and simulation of nutrient uptake.

**Interpretation of data**

The following relationships were developed:

1. The relationship between the supply of nutrients (nutrient uptake in omission plot) and available nutrients of N, P, K and Zn in post-harvest soils of wheat were established by developing equations.
2. The yield of wheat in relation to plant nutrients of N, P and K at 5, 6, 7 and 8 t ha\(^{-1}\) potential yields were estimated through the use of the QUEFTS model.
3. A comparison of observed and simulated (using QUEFTS) nutrient uptake of N, P and K by wheat.

**Preliminary QUEFTS model validation**

The data from five field studies previously conducted at different locations of India were chosen to validate the calibrated model: (i) three villages around Delhi (28.35°N, 77.12°E) (Bajaj 1982); (ii) Indian Agricultural Research Institute, New Delhi (28.55°N, 77.52°E) (Sachdev et al. 1990); (iii) Hisar, Haryana (29.10°N, 75.46°E) (Singh 1984); (iv) Udaipur, Rajasthan (24.35°N, 73.42°E) (Jain & Jain 1993) and (v) Pantnagar, Uttaranchal (29.00°N, 79.30°E) (Anurag et al. 1992). Observed yields were in good agreement with the predicted values (Figure 1), indicating that the model can be used to improve fertilizer recommendations of wheat in India.
Application of the model for Site-Specific Nutrient Management in wheat (Experiment II)

Field experiments on wheat (*Triticum aestivum* L.) cv. UP-262 were conducted in the *Rabi* season of 2002–2003 in farmer’s field, block area of Ranaghat II, district of Nadia, West Bengal (22°57'N latitude and 88°20'E longitude, average altitude of 7.8 m above mean sea level) by taking four replications (sites) in a randomized block design. The physico-chemical properties of the four sites were pH, 7.15–7.33; organic carbon (C) (%), 0.42–0.46; available N (kg ha$^{-1}$), 441.20–508.08; available P (kg ha$^{-1}$), 8.40–14.25; available K (kg ha$^{-1}$), 77.00–92.80 and available Zn (mg kg$^{-1}$), 0.39–0.55. Seeds were sown at 100 kg ha$^{-1}$. The recommended levels of N, P, K, Zn and FYM for wheat were 100, 50, 50 kg ha$^{-1}$, 0.5 kg ha$^{-1}$ with suitable carrier and 6 t ha$^{-1}$, respectively. Each field was divided into six subplots using following treatments: T$_1$: set I, target yield of 5 t ha$^{-1}$; T$_2$: set I, target yield of 6 t ha$^{-1}$; T$_3$: set II, target yield of 5 t ha$^{-1}$; T$_4$: set II, target yield of 6 t ha$^{-1}$; T$_5$: set III, target yield of 5 t ha$^{-1}$ and T$_6$: set III, target yield of 6 t ha$^{-1}$. Fertilizer dose of N, P and K were fixed on the basis of the QUEFTS model by putting various ‘a’ and ‘d’ values of N, P and K of Set I, set II and Set III for achieving the target yield of 5 and 6 t ha$^{-1}$ in wheat. Observed yield and uptake by wheat were compared with target yields and predicted or simulated (using QUEFTS) nutrient uptake. The best set of ‘a’ and ‘d’ values of QUEFTS were selected based on potential yield and validation.

Climatic conditions

The research station is situated about 130 km north of the Bay of Bengal and experiences a humid subtropical climatic condition. During wheat growing season of 2001–2002 and 2002–2003, the total rainfall and average maximum and minimum temperature were 954.90 and 840.10 mm; 32.55 and 32.94°C; 25.48°C and 24.75°C respectively. Similarly, during the wheat-growing season of 2001–2002 and 2002–2003 the corresponding figures were 39.2
and 142.41 mm; 29.32 and 28.24°C; 15.85 and 16.43°C respectively. The data was collected from nearest Meteorological Department of Bidhan Chandra Krishi Viswavidyalaya in the Nadia district of West Bengal. It is valid for all experimental sites since the 20 sites of all experiments were situated closely which were within about 1–2 km distance with uniform land situation.

**Soil analysis**

1. Soil pH was determined in 1:2 soil-water suspension ratio (Jackson 1973).
2. EC was done in the supernatant liquids of the 1:2 soil water suspension using Conductivity meter (Jackson 1973).
3. Organic C was determined by the Walkley and Black method (Jackson 1973).
4. Available N was determined by the Kjeldahl method (Jackson 1973).
5. Available P was determined by the Olsen method (Olsen et al. 1954).
6. Available K was extracted by the neutral normal ammonium acetate method (Jackson 1973).
7. DTPA-extractable Zn was extracted by following the procedure of Lindsay and Norvell (1978) and determined with the help of Atomic Absorption Spectrophotometer (AAS), Perkin Elmer, Model-AAnalyst 100.

**Plant analysis**

Plant samples were determined for N by Kjeldahl distillation as outlined by Jackson (1973) after digesting the samples with diacid mixture (H₂SO₄:HClO₄ :: 9:1); and P and K by Vanado molybdate blue colour and flame photometrically, respectively as described by Jackson (1973) after digesting the samples with ternary acid mixture (HNO₃:HClO₄:H₂SO₄ :: 10:4:1). Zinc was determined as described by Jackson (1973) with the help of Atomic Absorption Spectrophotometer (AAS), Perkin Elmer, Model-AAnalyst 100 after digesting the samples with ternary acid mixture (HNO₃:HClO₄:H₂SO₄ :: 10:4:1).

**Statistical analysis**

All the data of wheat of two years were pooled statistically and then the relevant data were statistically analysed for Duncan’s Multiple Range Test (DMRT), correlation and multiple regression etc. following the procedures as outlined by Cochran and Cox (1955), Panse and Sukhatme (1967) and Gomez and Gomez (1976).

**Results and discussion**

*Indigenous supply, internal efficiency, N requirement and recovery efficiency*

The following relationship between soil organic carbon (OC) and N uptake by wheat in N-omission plots (Figure 1) was established for estimation of soil N supply (SN):

\[
SN (\text{kg ha}^{-1}) = 103.07 \text{ OC} (\%) + 5.46 \quad (R^2 = 0.91^{**})
\]  

An alternative to estimate indigenous N supply could be the grain yield obtained in a no-N plot as grain yield has a good correlation \(Y = 0.006 + 35.5, R^2 = 0.51^{**}\) with N uptake in wheat (Figure 2). Similar views have also reported for wheat by Pathak et al. (2003).
Grain yield ranged from 1.50 – 5.50 t ha\(^{-1}\), with N application rates varying from 0 – 100 kg ha\(^{-1}\) across the sites (Table I). Total above-ground N accumulation ranged from 21.0 – 119.5 kg ha\(^{-1}\), and an internal efficiency of 32 – 102 kg grain kg\(^{-1}\) N, with an average of 62.3 kg grain kg\(^{-1}\) N.

Since the experiments were conducted under irrigated conditions, the variation in internal efficiency was possibly due to variations in the supply of N. Data presented in Table II show that to produce 1 t of grain, the N requirement varied between 8.3 and 29.6 kg with an average of 17.1 kg.

Recovery efficiency of N (REn) varied between 34.5 – 51.2% (Table I) with an average of 41.3%. Recovery of applied N varied considerably with the amount of N applied. A close relationship between recovery efficiency and level of N (Fn) in kg was observed, as depicted by the equation:

\[
\text{REn} \, (\%) = \left( 0.55 \, \text{Fn} + 7.10 \right) / \text{Fn} \, (R^2 = 0.64^{**})
\]

Figure 2. Relationship between indigenous N, P, K and Zn with organic C, Olsen P, exchangeable K and DTPA-Zn, respectively. Data are based on wheat experiments conducted in 20 sites of Nadia district of West Bengal during the year 2001 – 2002 and 2002 – 2003.
This suggested that instead of using a fixed value for recovery efficiency, the above equation can be used for wheat in eastern India where soils are generally low in organic C (<0.5%).

**Indigenous supply, internal efficiency, P requirement and recovery efficiency**

In Indian conditions, the Olsen method is generally used to estimate available P supply of soils with a pH ranging from 6 – 8.5 (Gupta et al. 1992). The following relationship was established between Olsen P in soil and plant P (Figure 2) to calculate indigenous P supply (SP):

\[
SP (\text{kg ha}^{-1}) = 1.28 \text{ Olsen P (kg ha}^{-1}) + 2.05 (R^2 = 0.84^{**})
\]  

(5)

Alternatively, grain yield in P-omission plots can also be used as an index of soil P supply since there was a good correlation and co-efficient of determination of variability \( (Y = 0.009X - 8.73, R^2 = 0.53^{**}) \) between grain yield and P uptake (Figure 3).
Grain yield of wheat in the experiments with P ranged from 1.40 – 5.30 t ha\(^{-1}\), with the application of P varying between 0 and 50 kg ha\(^{-1}\) (Table I). Above-ground P accumulation ranged from 2.7 – 37.5 kg ha\(^{-1}\). Internal efficiency of P ranged from 125 – 740 kg kg\(^{-1}\), with a mean of 290.4 kg. To produce 1 t of wheat grain 2.1 – 5.2 kg P was needed with a mean of 3.8 kg P. Recovery efficiency of P varied from 14.2 – 29.8%, with a mean of 21.2% (Table I).

The following relationship was established between recovery efficiency of P and P fertilizer levels in kg (Fp):

\[
\text{REp} \, (\% ) = \frac{1.58 + 0.33 \text{Fp} - 0.004 (\text{Fp})^2}{\text{Fp}} \, (R^2 = 0.71^{**})
\] (6)

Indigenous supply, internal efficiency, K requirement and recovery efficiency

Ammonium acetate-extractable K (Ex. K) is widely used as a parameter of available K for wheat also. A relationship (Figure 1) between K uptake in no-K plots, a measure of soil K supply (SK) and exchangeable soil K (kg ha\(^{-1}\)) was established:

\[
\text{SK} \, (\text{kg ha}^{-1}) = 1.03 \text{Ex. K} \, (\text{kg ha}^{-1}) + 6.11 \, (R^2 = 0.95^{**})
\] (7)

Figure 3. Relationship between grain yield of wheat and plant nutrients of N, P, K and Zn. The upper and lower lines indicate yields with maximum dilution and maximum accumulation, respectively by taking upper and lower 10 percentile as outliers. Although 10% of the total data lied outside the lines, but they were not shown in the figure as they are of less importance. Data are based on experiments conducted in 20 sites in Nadia district of West Bengal during the year 2001 – 2002 and 2002 – 2003.
Alternatively, soil K supply can also be obtained from the grain yield of K-omission plots, as grain yield has a good correlation \((Y = 0.024X + 18.69, \quad R^2 = 0.55^{**})\) with K uptake (Figure 3).

Grain yield of wheat in the experiments with K ranged from 1.75 – 5.50 t ha\(^{-1}\) and K uptake ranged from 43.0 – 216.0 kg ha\(^{-1}\) (Table I). Internal efficiency of K ranged from 14 – 59 with a mean of 33.4 kg grain kg\(^{-1}\) K. To produce 1 tonne of grain, 13.7 – 40.1 kg K was needed (mean 29.7 kg t\(^{-1}\)). Recovery of K varied between 41.1 and 61.4 with a mean of 51.2% (Table I). The following equation was developed which can be used for the recovery efficiency of K (REk) in soils containing medium to higher exchangeable K content with the help of K fertilizer levels in kg (Fk):

\[
REk (\%) = \left[ -5.22 + 0.78 \frac{Fk}{C0} - 0.003 \left( \frac{Fk}{C0} \right)^2 \right] / Fk \quad (R^2 = 0.55^{**})
\]

**Indigenous supply and internal efficiency of Zn**

The diethylene triamine pentacetic acid-extractable Zn (DTPA-Zn) is widely used as an index for available Zn content in soil. A relationship (Figure 1) between Zn uptake in no-Zn plots, a measure of soil Zn supply (SZn) and DTPA-extractable Zn in soil (kg ha\(^{-1}\)) was established:

\[
SZn (g/ha) = 73.04 \times DTPA-Zn (kg ha\(^{-1}\)) - 25.97 \quad (R^2 = 0.94^{**})
\]

An alternative to estimate indigenous Zn supply could be the grain yield obtained in a no-Zn plot as grain yield has a good correlation \((Y = 0.05X + 0.01, \quad R^2 = 0.56^{**})\) with Zn uptake in wheat (Figure 3).

Grain yield ranged from 1.75 – 5.50 t ha\(^{-1}\), with Zn application rates varying from 0 – 0.5 kg ha\(^{-1}\) with suitable carrier across the sites (Table I). Total above-ground Zn accumulation ranged from 0.02 – 0.15 kg ha\(^{-1}\), and an internal efficiency of 20805 – 145230 kg grain kg\(^{-1}\) Zn with a mean value of 70322.1 kg grain kg\(^{-1}\) Zn.

The estimates of N, P, K and Zn requirements refer to current crop and fertilizer management practices, but may not reflect the optimum nutritional balance where N, P, K and Zn are neither limiting nor in surplus. The observed variation in internal efficiencies and nutrient requirements was due to nutritional imbalances. Therefore, a modelling approach is advocated as in QUEFTS, to estimate the optimum nutrient requirements as a basis for an appropriate and improved fertilizer recommendation. Results of a preliminary evaluation are discussed in the following sections.

**Evaluation of ‘a’ and ‘d’ values**

Three sets (Set I, II and III) of constants of envelope functions relating grain yield to the maximum accumulation (a) and maximum dilution (d) of QUEFTS in irrigated wheat were developed by treating the upper and lower 10, 15 and 20 percentiles of the internal efficiencies as outliers. In order to determine the fertilizer recommendations of N, P, K and Zn to achieve the target yield these constants were developed. Three sets of values for ‘a’ and ‘d’ were for N (35, 100; 37, 96 and 39, 92), for P (129, 738; 144, 652 and 150, 605), for K (17, 56; 21, 52 and 24, 49) and for Zn (21502, 140244; 24831, 129630 and 27778, 118750 respectively. With an increase in percentiles from 10 – 20, the value of ‘a’ increased while that of ‘d’ value decreased markedly. The same trend was observed for all nutrients (Pathak et al. 2003).
Evaluation of model QUEFTS for wheat in eastern India

The QUEFTS model was evaluated for wheat using the relations as discussed earlier. The relationships between yield and plant N, P, K and Zn used were:

\[
\begin{align*}
Y_{NA} &= 35 \text{ Un} \\
Y_{ND} &= 100 \text{ Un} \\
Y_{PA} &= 129 \text{ Up} \\
Y_{PD} &= 738 \text{ Up} \\
Y_{KA} &= 17 \text{ Uk} \\
Y_{KD} &= 56 \text{ Uk} \\
Y_{ZnA} &= 21502 \text{ Uzn} \\
Y_{ZnD} &= 140244 \text{ Uzn}
\end{align*}
\]

where: \(Y_{NA}\) and \(Y_{ND}\) (\(Y_{PA}\) and \(Y_{PD}\), \(Y_{KA}\) and \(Y_{KD}\), \(Y_{ZnA}\) and \(Y_{ZnD}\)) are yields obtained when N (P, K and Zn) in the wheat crop was maximally accumulated and diluted, respectively; \(\text{Un}, \text{Up}, \text{Uk}\) and \(\text{Uzn}\) were uptake of N, P, K and Zn respectively. From these equations, yield ranges corresponding with the actual uptake of N, P, K and Zn are calculated. The relationships between yield and plant N, P, K and Zn (Figure 3) were presented.

Sensitivity of QUEFTS to ‘a’ and ‘d’ values

The sensitivity of the model to ‘a’ and ‘d’ values was tested using three sets of constants by treating the upper 10, 15 and 20 percentiles of the internal efficiencies as outliers. In order to determine the N, P and K requirements to achieve a target grain yield (Figure 4), the potential supply of N, P and K was set as non-limiting and the yield potential was set to 7 t ha\(^{-1}\).

Nutrient requirements calculated by the model were similar for all three sets of constants (Figure 4), except at yield targets that were close to the yield potential. Such yield targets rarely occur in farmers’ fields. Thus, we propose to use the QUEFTS model parameters of Set I for a standard version of QUEFTS focusing on decision-making on fertilizer requirements of wheat, as these include the maximum range of variability.

Nutrient requirement vs. potential yield

The model QUEFTS calculates nutrient requirements to achieve a certain yield target depending on the potential yield. Depending on season and site, the potential yield of currently grown wheat in eastern India ranges from 5–8 t ha\(^{-1}\). The relationship between grain yield and nutrient accumulation of N, P and K as predicted by QUEFTS was linear at lower yield levels, reflecting a situation where plant growth was mainly limited by nutrient supply (Figure 5). The model also calculates a decrease in internal efficiencies when target yields are close to yield potential. Thus, it may be more profitable for farmers to maximize
Figure 4. Yield of wheat in relation to plant nutrients at different sets of constants ‘a’ and ‘d’, calculated by excluding the upper and lower 10 (Set I), 15 (Set II) and 20 percentiles (Set III) of all internal efficiency data. The upper and lower lines indicate yields with maximum dilution and maximum nutrient accumulation, respectively accumulation, respectively.
Figure 5. Yield of wheat in relation to plant nutrients at 5, 6, 7 and 8 t ha$^{-1}$ potential yields. The upper and lower lines indicate yields with maximum dilution and maximum nutrient accumulation, respectively.
nutrient efficiencies by a more balanced nutrition than to aim for higher yield targets with yield levels approaching maximum yields.

Regardless of yield potential the N:P:K ratios for 1 t grain in plants for the linear part of the relationship (up to 80% potential yield) was about 4.9:1:8.9 as calculated by QUEFTS (Figure 4). To produce 1 t grain, 15.8, 3.2 and 28.4 kg N, P and K, respectively would be needed and with this, internal efficiencies (IE) of 63.1, 298.6 and 35.9 kg grain kg\(^{-1}\) N, P and K respectively, would be achieved. The results also supported the findings obtained by Pathak et al. (2003) who suggested that the required N, P and K accumulation in the wheat plant for 1 t grain yield was 23.1, 3.5 and 28.5 kg, respectively, which indicated the NPK ratio in the plant of about 6.6:1:8.1.

Site-specific nutrient management in wheat

Three sets of ‘a’ and ‘d’ values were used to achieve the target yield of approximately 5 and 6 t ha\(^{-1}\) wheat. On the basis of QUEFTS, the simulated N, P and K uptakes were calculated for all sets to achieve the target yield of 5 and 6 t ha\(^{-1}\). The simulated N, P and K uptake (kg ha\(^{-1}\)) was compared with their corresponding observed values (Table II).

The wheat grain yield increased significantly with an increasing level of N, P and K fertilizers. The highest grain yield (5.85 t ha\(^{-1}\)) was observed in treatment T\(_4\) where NPK was applied at 135:42:127 kg ha\(^{-1}\) to achieve the target yield of 6 t ha\(^{-1}\). The highest observed N (101.28 kg ha\(^{-1}\)) and K uptake (199.85 kg ha\(^{-1}\)) were found in treatment T\(_2\) where NPK was applied at 154:52:108 kg ha\(^{-1}\) based on QUEFTS followed by T\(_4\), T\(_6\) and T\(_1\) treatments. The observed N, P and K uptakes were close (80 – 90%) to their corresponding simulated or predicted values. The results suggested that there was a need for revision of recommended fertilizer doses for wheat in eastern India to increase the yield level. Ray et al. (2000) also suggested that the yield targets were attained for wheat (cv. Sonalika) 30 – 35 q ha\(^{-1}\) with ± 10% variation from the desired yield target.

The results (Table III) indicated that the uptake of N, P, K and grain yield have been found to be significantly correlated. The grain yield showed a significant correlation with N uptake (0.937**), P uptake (0.901**) and K uptake (0.801**).

The grain yield of wheat significantly varied with the uptake of N, P and K which, taken together, contributed 95.2% of the variability towards the grain yield of wheat.

Conclusions

The results for the use of the QUEFTS model in 20 sites of new alluvial zones in the Nadia district of West Bengal show that the model might be applicable for estimating nutrient requirements to achieve a yield target of 5 and 6 t ha\(^{-1}\) for wheat. The QUEFTS model takes

| Parameter      | N uptake | P uptake | K uptake | Grain yield |
|----------------|----------|----------|----------|------------|
| N uptake       | 1.000    |          |          |            |
| P uptake       | 0.900**  | 1.000    |          |            |
| K uptake       | 0.947**  | 0.804**  | 1.000    |            |
| Grain yield    | 0.937**  | 0.901**  | 0.801**  | 1.000      |

**Significant at the 0.01 probability level.
into account the soil nutrient supply, relationship of grain yield vs. nutrient uptake and balanced uptake of nutrients. The QUEFTS model can be used for the precision farming and site-specific nutrient management system. The developed parameters of ‘a’ and ‘d’ of N, P, K and Zn in plant can also be used as standard parameters in the model for wheat. To produce a 1 t grain yield wheat the derived NPK ratio was 4.9:1:8.9. The model can also be used in other regions, provided that appropriate equations between soil’s ability to supply and chemical properties are developed. The observed yields of wheat with different amounts of these nutrients were in good agreement with the values predicted by QUEFTS.

Acknowledgements

The authors are grateful to the Indian Council of Agricultural Research (ICAR), New Delhi, for sponsoring this National Agricultural Technology Project (ICAR/NATP/R-W/7B-3, PSR-25) which was successfully completed in collaboration with International Rice Research Institute (IRRI), Philippines and Rice-Wheat Consortium (RWC), New Delhi. It is beyond our grasp of words to acknowledge the farmers of Dhantala and Nokari, District of Nadia, West Bengal, for providing their land for conducting the farmers’ field experiments.

References

Anurag T, Singh A, Sharma RD, Singh GR. 1992. Effect of liquid ammonium polyphosphate and some solid phosphatic fertilizers on crop yield and phosphorus availability in Mollisols. J Ind Soc Soil Sci 40:862 – 864. Bajaj JC. 1982. Evaluation of various methods of making fertilizer recommendations for cereal crops in the cultivators’ fields. Trans 12th Internal Congress Soil Sci 6:110. Cassman KG, Gines GC, Dizon MA, Samson MI, Alcantara JM. 1996. Nitrogen-use efficiency in tropical lowland rice systems: Contributions from indigenous and applied nitrogen. Field Crops Res 47:1 – 12. Cochran WG, Cox GM. 1955. Experimental design. New York: John Wiley and Sons. Dawe D, Dobermann A, Moya P, Abdulrachman S, Bijay Singh, Lal P, Li SY, Lin B, Panaullah G, Sariam O, et al. 2000. How widespread are yield declines in long-term rice experiment in Asia? Fields Crop Res 66:175 – 193. Gomez KA, Gomez AA. 1976. Statistical Procedures for Agricultural Research with emphasis on rice. Philippines: IRRI. Gupta AP, Neue HU, Singh VP. 1992. Soil test for phosphorus – a review. Int J Trop Agric 10:1 – 23. Jackson ML. 1973. Soil chemical analysis. New Delhi: Prentice Hall. Jain RC, Jain FM. 1993. Effect of preceding rainy season crops on yield and nutrient uptake by wheat under different levels of nitrogen. Ind J Agronomy 38:643 – 644. Janssen BH, Guikling FCT, Vander Eijik D, Smaling EMA, Wolt J, Reuler H. 1990. A system for quantitative evaluation of the fertility of tropical soils (QUEFTS). Geoderma 46:299 – 318. Ladha JK, Fischer KS, Hossain M, Hobbs PR, Hardy B. 2000. Improving the productivity and sustainability of rice-wheat systems of the Indo-Gangetic plains: A synthesis of NARS-IRRI partnership Research. Discussion paper No. 40. International Rice Research Institute, Philippines. p 31. Lindsay WL, Norvell WA. 1978. Development of a DTPA soil test for zinc, iron, manganese and copper. Soil Sci Soc Am J 42:421 – 428. Olsen SR, Cole CV, Watanabe FS, Dean LA. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. Circular of the United States Department of Agriculture 939. Panse VG, Sukhatme PNC. 1967. Statistical methods for agricultural workers. New Delhi: ICAR. Pathak H, Aggarwal PK, Roeter R, Kalra N, Bandyopadhayya SK, Prasad S, Van Keulen H. 2003. Modelling the quantitative evaluation of soil nutrient supply, nutrient use efficiency and fertilizer requirements of wheat in India. Nutrient Cycling Agro-ecosyst 65:105 – 113. Ray PK, Jana AK, Maitra DN, Saha MN, Chaudhury J, Saha S, Saha AR. 2000. Fertilizer prescriptions on soil test basis for jute, rice and wheat in a Typic Ustochrept. J Ind Soc Soil Sci 48:79 – 84. Regmi AP, Ladha JK, Pathak H, Pasuquin E, Bueno C, Dawe D, Hobbs PR, Joshy D, Maskey SL, Pandey SP. 2002. Yield and soil fertility trends in a 20 year rice-rice-wheat experiment in Nepal. Soil Sci Soc Am J 66:857 – 867. Sachdev MS, Luthra VK, Subbiah BV, Singh CB. 1990. Efficiency of fertilizer N applied to wheat in splits. Fertiliz News 35:11 – 17.
Singh M. 1984. Soil fertility and fertilizer (NPK) use in Haryana. Haryana Agricultural University, Hissar, India. p 177.

Smaling EMA, Janssen BH. 1993. Calibration of QUEFTS, a model predicting nutrient uptake and yields from chemical soil fertility indices. Geoderma 59:21-44.

Van Duivenbooden N, de Witt CT, van Keulen H. 1996. Nitrogen, phosphorus and potassium relations in five major cereals reviewed in respect to fertilizer recommendations using simulation modeling. Fertilizer Res 44:37-49.

Witt C, Dobermann A, Abdulrachman S, Gines HC, Guanghno Wang, Nagarajan R, Satawananont S, Thuc Son Tran, Tan Phamsy, Tiem Le Van, Simbahan GC, Olk DC. 1999. Internal nutrient efficiencies of irrigated lowland rice in tropical and subtropical Asia. Field Crops Res 63:113-138.