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Fertilizer best management practices by SSNM and customized fertilizers for elephant foot yam (*Amorphophallus paeoniifolius)* cultivation in India

G BYJU[1], M NEDUNCHEZHIYAN[2], JAMES GEORGE[3], S SUNITHA[4], R KAMALKUMARAN[5], P P SINGH[6], K MAMATHA[7], SURAJIT MITRA[8], JAYANTA TARAFDAR[9], KETAN DESAI[10], V RAVI[11], M VANI[12], SABITHA SOMAN[13] and K R REMYA REMESH[14]

ICAR-Central Tuber Crops Research Institute, Sreekariyam PO, Thiruvananthapuram, Kerala 695 017

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ABSTRACT

Elephant foot yam [*Amorphophallus paeoniifolius* (Dennst.) Nicolson] is an important tuber crop grown in many parts of India for its starchy corm and the average yield of this crop is far below the potential productivity of 100 tonnes/ha. One of the reasons attributed to the lower yield is the imbalanced application of essential plant nutrients. Site specific nutrient management (SSNM) is the application of plant nutrients based on the soil and crop need, yield target and developed with the aid of models such as QUEFTS. This paper gives the result of four year study conducted to calibrate and validate the QUEFTS model for elephant foot yam cultivation and the development of SSNM zonation maps and secondary and micronutrient fortified customised fertilizers for the crop in major growing environments of India. Data collected from different field experiments conducted in major elephant foot yam-production regions of India during 1968 to 2011 were used to calibrate the model. The derived parameters of minimum and maximum accumulation of N (130 and 460), P (900 and 2100) and K (100 and 170) are proposed as standard borderline values in the QUEFTS model for elephant foot yam. A linear increase in corm yield was suggested by the model with N, P and K uptakes of 3.97, 0.71, and 7.05 kg N, P and K/1 000 kg corm. The average NPK ratio in total plant dry matter was 5.56:1:9.88. Based on these results, the model was calibrated using historical data as well as by conducting field experiments. It can be observed that fertilizer best management practices by SSNM resulted in an average actual corm yield of 33.45 tonnes/ha, whereas, the model predicted a yield of 35 tonnes/ha. The results of the study showed good agreement between predicted and measured corm yields during the four years, which indicated that the calibrated model can be used to improve NPK fertilizer recommendations for elephant foot yam in India. Based on the results and using soil fertility maps and agro ecological unit maps, SSNM zonation maps and secondary and micronutrient fortified customised fertilizers were developed for major elephant foot yam growing environments of India.

Key words: Customised fertilizers, Elephant foot yam, QUEFTS, SSNM

The current nutrient recommendation for elephant foot yam [*Amorphophallus paeoniifolius* (Dennst.) Nicolson] in India is based on differential rate trials conducted at experimental stations (blanket recommendation) and adjusted with soil test data (Muhr *et al*. 1965, Biswas *et al*. 1985), the popularly known soil test based fertilizer recommendation. Many studies are available which developed such blanket fertilizer recommendations for elephant foot yam for different situations (Mandal and Saraswat 1968, Asokan *et al*. 1984, Mukhopadhyay and Sen 1986, Nair *et al*. 1990, Nair and Mohankumar 1991, Nair *et al*. 1991, Verma *et al*. 1995, Sen *et al*. 1996, Mukhopadhyay and Sen 1999, Kundu *et al*. 1998, Geetha 2001). The blanket NPK recommendation developed by ICAR-CTCRI for elephant foot yam is 100:50:150 kg/ha of N: P_2O_5:K_2O (Nair *et al*. 1990). The major limitation of the soil test based, blanket fertilizer recommendation is that it is not a soil and crop based approach; moreover, we are not able to find out the nutrient rates for specific yield targets. All the blanket recommendations referred above were developed before the release of the high yielding varieties of elephant foot yam in India and hence yield-response functions developed earlier for local cultivars may not hold good for these high yielding varieties. In order to overcome these limitations of the soil test based, blanket fertilizer recommendation, Witt *et al*. (1999) introduced the concept of site specific nutrient management (SSNM) which is specific to soils and crops,

[1]Principal Scientist (Soil Science) (e mail: byju_g@yahoo.com), ICAR-Central Tuber Crops Research Institute, Sreekariyam P O, Thiruvananthapuram 695 017, Kerala; [2]Regional Centre of ICAR-Central Tuber Crops Research Institute, Bhubaneswar 751 019, Odisha; [5]Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu; [6]Rajendra Agricultural University, Muzaffarpur, Dholi 848 121, Bihar; [7]Horticultural Research Station, Kovvur 534 350, Andhra Pradesh; [8,9]Bidhan Chandra Krishi Viswa Vidyalaya, Kalyani 741 235, West Bengal; [10]Aspee College of Horticulture and Forestry, Navsari Agricultural University 396 450, Gujarat

yield oriented and also takes into account nutrient interactions with the aid of models such as Quantitative Evaluation of Fertility of Tropical Soils (QUEFTS).

Better fertilizer recommendations are now made by using simulation models. The QUEFTS model originally developed for maize by Janssen *et al*. (1990), takes into account the interactions of N, P and K. Witt *et al*. (1999) validated the model for rice by conducting experiments in six Asian countries and Pathak *et al*. (2003) used the model for wheat in India. Byju *et al*. (2012) calibrated and validated the model for cassava in India. If we can develop the basic relationships between corm yield and nutrient uptake of elephant foot yam, the modified QUEFTS model can be used for prescribing site specific NPK recommendations.

With this concept in mind, a study was conducted to quantify the variation in soil nutrient supply in elephant foot yam fields in major growing environments of India, where the crop is cultivated on a large scale, to develop a new approach for fertilizer best management practices by SSNM using a modified QUEFTS model and to develop customised fertilizers based on the SSNM approach. The main objectives of the present study were to (1) derive model input parameter values that enable NPK fertilizer recommendations (2) establish maximum and minimum nutrient uptake efficiencies, (3) calibrate and validate QUEFTS model for elephant foot yam cultivation and (4) develop fertilizer best management practices by developing SSNM zonation maps and customised fertilizers for major growing environments of India.

MATERIALS AND METHODS

The theoretical framework of the QUEFTS model for making fertilizer recommendations has been explained in detail by Witt *et al*. (1999), Liu *et al*. (2006) and Byju *et al*. (2012). The maximum yield of elephant foot yam obtained under experimental conditions in each of the major growing environments was fixed as the climatic yield potentials and the values ranged from 60–100 tonnes/ha. Yield goals were fixed at 70-80% of the climatic yield potential because beyond that level, internal nutrient efficiencies in the plant decline (Fageria and Baligar 1981). Moreover, Cassman and Harwood (1995) reported that about 80% of the climatic yield potential seems to be the maximum possible yield that can be obtained by most farmers under field conditions.

The QUEFTS model was first calibrated by the following four steps. (a) The borderlines describing the maximum and minimum accumulation of N, P and K in total plant dry matter were fixed and their sensitivity to different criteria of data selection was studied. (b) The optimum uptake requirements of N, P and K (YN, YP, YK) at different potential yields (Y_{max}) were calculated. (c) The indigenous nutrient supplying capacity and fertilizer nutrient recovery efficiencies were estimated. (d) The simulated optimal internal efficiencies of NPK were compared with historical data.

Data from several field experiments on elephant foot yam with N, P and K applications conducted in India during the years 1968-2011 were collected for the purpose. These experiments included wide range of environments in India where elephant foot yam is grown and hence they cover varied soil, climatic conditions and agrotechniques. Data from published literature were collected from the field experiments which included a control plot (unfertilized) and plots with different rates of NPK (fertilized) which varied between the regions and years. Table 1 shows the descriptive statistics of the data set used for developing empirical models describing the relationship between corm yield and NPK contents in elephant foot yam. The data

Table 1 Descriptive statistics of the data set used for developing empirical models describing the relationship between fresh corm yield and nutrient content in elephant foot yam

Parameters	Unit	No. of observations	Mean	SD[1]	Minimum	Maximum
Corm yield	t/ha	82	42.50	8.15	8.65	102.27
Total dry matter	t/ha	82	8.50	7.62	1.79	18.75
N in total DM[2]	kg/ha	82	159.65	54.12	35.55	458.25
P in total DM	kg/ha	71	24.50	9.22	6.25	83.84
K in total DM	kg/ha	71	298.75	55.61	62.75	786.58
N fertilizer application	kg/ha	82	95.00	20.33	25.00	250.00
P fertilizer application	kg/ha	71	55.00	17.77	20.00	100.00
K fertilizer application	kg/ha	71	130.00	16.84	25.00	300.00
IE[3], Nitrogen	kg corm/kg N removed	82	251.54	27.17	116.52	385.67
IE, Phosphorus	kg corm/kg P removed	71	1364.38	65.61	675.25	2236.71
IE, Potassium	kg corm/kg K removed	71	135.82	24.51	67.72	211.65
RIE[4], Nitrogen	kg N removed/t corm	82	3.88	2.31	2.25	5.88
RIE, Phosphorus	kg P removed/t corm	71	0.71	0.13	0.34	1.19
RIE, Potassium	kg K removed/t corm	71	7.17	1.13	3.66	11.55
REn, N recovery efficiency	%	82	32.35	15.21	15.25	72.13
REp, P recovery efficiency	%	71	15.20	11.05	10.22	43.66
REk, K recovery efficiency	%	71	34.42	21.65	12.26	77.82

[1]SD – Standard deviation, [2] DM – dry matter, [3] IE – internal efficiency, [4] RIE – reciprocal internal efficiency.

collected included (1) soil properties – pH, organic carbon, available N, P and K; (2) crop data – corm yield, above ground biomass yield and (3) rates of NPK applied.

After the initial calibration of the model was done as described above, it was further fine tuned, validated and tested by conducting a field experiment at ICAR-CTCRI farm for four consecutive years during 2011 to 2014. The experiment was laid out in randomized complete block design (RCBD) with five treatments and four replications per treatment. The treatment details are given below.

In N omission plot, only P and K at 150% recommended rate (Nair *et al*. 1990) were applied to ensure that macronutrients other than N did not limit plant N uptake from indigenous sources. This treatment was sampled at harvest of the crop for each of the four years to estimate indigenous N supply (INS), defined as total plant N accumulation at maturity in a 0-N plot. These measurements were used to estimate: (a) N use efficiencies using the difference method and (b) INS used as an input parameter for SSNM.

In P omission plot, only N and K at 150% of the recommended rate (Nair *et al*. 1990) were applied to ensure that macronutrients other than P did not limit plant P uptake from indigenous sources. This treatment was sampled at harvest of the crop for each of the four years to estimate indigenous P supply (IPS), defined as total plant P accumulation at maturity in a 0-P plot. These measurements were used to estimate: (a) P use efficiencies using the difference method and (b) IPS used as an input parameter for SSNM.

In K omission plot, only N and P at 150% of the recommended rate (Nair *et al*. 1990) were applied to ensure that macronutrients other than K did not limit plant K uptake from indigenous sources. This treatment was sampled at harvest of the crop for each of the four years to estimate indigenous K supply (IKS) defined as total plant K accumulation at maturity in a 0-K plot. These measurements were used to estimate: (a) K use efficiencies using the difference method and (b) IKS used as an input parameter for SSNM.

In SSNM plot, nutrient recommendations were made following the SSNM approach using the calibrated QUEFTS model. Specific optimal NPK fertilizer rates were predicted using indigenous nutrient supplies and yield in nutrient omission plots. The calibrated QUEFTS model was used to work out NPK recommendations at the beginning of each growing season. A linear optimization procedure was used in Microsoft Excel Solver module to find the best combination of N, P and K fertilizer rates to achieve the yield goal under the constraint of optimizing the internal N, P and K efficiencies in the plant. The model was constrained to arrive at a solution close to the situation of most balanced nutrition, that is, where the ratio between accumulation and potential supply of each macronutrient was close to 0.95 (Janssen *et al*. 1990). In order to meet the principles of fertilizer best management practices (FBMP) (http://www.nutrientstewardship.com/what-are-4rs), based on the soil test data and crop need (Kabeerathumma *et al*. 1987), magnesium, zinc and boron fortified customised fertilizer formulation was prepared and used as SSNM treatment. The SSNM treatment was sampled at harvest of the crop for each of the four years to estimate the corm and above ground biomass yields and plant nutrient (N, P and K) accumulation. This treatment was used for comparison with the present recommendation treatment for yield, nutrient accumulation, fertilizer use, nutrient use efficiency, total fertilizer cost and gross return above fertilizer cost.

In present recommendation (PR) plot, nutrient recommendations were made following standard package of practices (Nair *et al*. 1990). The PR treatment was sampled at harvest of the crop for each of the four years to estimate the corm and above ground biomass yields and plant nutrient (N, P and K) accumulation. This treatment was used for comparison with the SSNM treatment for yield, nutrient accumulation, fertilizer use and nutrient use efficiency.

Before the beginning of field experiments, soil samples were collected for characterisation of the soil physico-chemical parameters. The soil samples were air dried and sieved through a 2 mm sieve and analysed for pH (Byju 2001), organic carbon (Walkley and Black 1934), available N (Page *et al*. 1982), available P (Bray and Kurtz 1945) and exchangeable K (Knudsen *et al*. 1982).

From individual treatment plots, soil samples were collected at the active growth stage of elephant foot yam (3 months after planting). The soil samples were air dried and sieved through a 2 mm sieve and analysed for pH, organic carbon, available N and P and exchangeable K following the procedures referred above. Leaf samples were also collected at 3 months after planting to assess the crop nutritional status for different treatments based on critical nutrient concentrations. Leaf samples were dried in a hot air oven at 65^0C for 48 hrs until constant weight was attained. Then the dried samples were ground in a stainless steel Wiley Mill. Plant N, P and K contents were estimated using dried and ground samples of the leaves. The total N content was determined by digesting the samples in sulfuric acid (H_2SO_4) followed by analysis of total N by Kjeldahl method (Bremner and Mulvaney 1982). Tissue P was determined after digestion with triple acid (HNO_3 : $HClO_4$: H_2SO_4 10:4:1) by the vanado–molybdo phosphoric yellow colour method and tissue K by using a flame photometer (Jackson 1972).

From individual treatment plots, soil samples were collected at the time of harvest of elephant foot yam at 9 months after planting. The soil samples were air dried and sieved through a 2 mm sieve and analysed for pH, organic carbon, available N and P and exchangeable K following the procedures referred earlier. At physiological maturity, total weights of leaf, pseudostem and corm were measured from three plants of each plot and leaf, pseudostem and corm samples (50 g each) were also collected separately. Total weights of corm were taken from all the plants in each plot excluding the border row for estimation of corm yield at the time of final harvest.

Leaf, pseudostem and corm samples were dried in a hot air oven at 65⁰C for 48 hr until constant weight was attained and the dry weight of the samples was recorded. Then the dried samples were ground in a stainless steel Wiley Mill. Plant N, P and K contents were estimated using dried and ground samples of leaf, stem and corm following the procedures referred earlier.

Based on dry weights of leaf, pseudostem and corm and N, P and K contents of leaf, pseudostem and corm (per cent), total N, P and K uptake at harvest was estimated in kg/ha.

Nutrient use efficiencies were estimated using the differences between N, P or K fertilized treatments and the nutrient omission plots (Cassman *et al*. 1996). Terms used are agronomic efficiency (AE; kg corm yield increase per kg N, P or K applied), recovery efficiency (RE; kg N, P or K removed from fertilizer per kg N, P or K applied) and physiological efficiency (PE; kg corm yield increase per kg N, P or K removed).

Agronomic efficiency = (Y–Y0)/F

Recovery efficiency = (U–U0)/F

Physiological efficiency = (Y–Y0)/(U–U0)

where, Y – corm yield (kg/ha) in fertilized field; Y0 - corm yield (kg/ha) in unfertilized field; U – total plant uptake of N/P/K (kg/ha) in fertilized field; U0 - total plant uptake of N/P/K (kg/ha) in unfertilized field; F – rate of application of N/P/K fertilizer (kg/ha).

The statistical analysis of data consisted of analysis of variance (ANOVA) for different soil and plant parameters, yield, NPK uptake, nutrient use efficiency and economic parameters using SAS statistical software (SAS Institute Inc. 2002). Least significant difference (LSD) test was used at 0.05 level of probability to test differences between treatment means.

The calibrated QUEFTS model was validated for other major elephant foot yam growing areas of India. A part of the historical data of the locations were used to validate the model for other areas. Based on all the above results and based on soil fertility maps of these states (http://www.iiss.nic.in/STCR.html), major growing environments of elephant foot yam were classified into different management zones and SSNM zonation maps were prepared using ArcGIS 10.0. The NPK recommendations of each zone and published information on the secondary and micronutrient status and requirement of major elephant foot yam growing environments of India were used and secondary and micronutrient fortified customized fertilizer formulations were developed for major growing environments of India.

RESULTS AND DISCUSSION

Selection of data set for adjusting QUEFTS to elephant foot yam

Internal nutrient efficiency, fertilizer nutrient-recovery efficiency and soil indigenous supply for cassava were estimated using the data set given in Table 1. From the original data set, 2.5% of the lowest and greatest values of the data set were removed to get 2.5^{th} and 7.5^{th} percentiles of the whole data set. This was done to get a data set where elephant foot yam growth is not limited by factors other than N, P, and K because calibration of QUEFTS needs a set of data that is not influenced by any limitation other than N, P, and K supply (Witt *et al*. 1999). The constants of 'a' and'd' showing the internal efficiencies at maximum accumulation and dilution of the nutrients are given in Table 2. The sensitivity of the developed relationships between corm yield and N, P, and K uptake was studied by two other sets of constants by deleting 5% and 7.5% of the highest and lowest data respectively (sets 2 and 3, Table 2). The model parameter values recommended for use in QUEFTS for elephant foot yam are shown as set 4, Table 2.

Internal nutrient efficiency

The descriptive statistics of internal nutrient efficiencies for elephant foot yam is shown in Table 1. The mean values of internal efficiency of N, P and K are 251.54, 1 364.38 and 135.82 kg fresh corm yield/kg. The mean reciprocal internal efficiency (RIE), the amount in kg of N, P, or K removed to produce 1 000 kg corm yield, values are 3.88, 0.71, and 7.17 for elephant foot yam. When the internal efficiency values of N, P, and K were analyzed from unfertilized and fertilized plots separately, it could be observed that the values were greater in unfertilized plots for N and K and the values were greater in fertilized plots

Table 2 Constants of borderline functions showing the relationship of fresh corm yield of elephant foot yam to maximum accumulation (a) and dilution (d) of N, P and K in total plant dry matter

Nutrient	Set 1		Set 2		Set 3		Set 4[a]	
	a (2.5^{th})	d (97.5^{th})	a (5^{th})	d (95^{th})	a (7.5^{th})	d (92.5^{th})	a	d
N	129.5	459.6	134.6	454.2	138.2	449.4	130	460
P	900.1	2099.8	910.5	2094.3	917.2	2089.1	900	2100
K	99.6	169.9	104.2	164.5	109.6	161.4	100	170

Note: Constants 'a' and 'd' of set 1, 2 and 3 were determined after eliminating the lowest and highest 2.5, 5 or 7.5 percentiles respectively of all internal efficiency (IE) data presented in Table 1.

[a] Recommended standard parameters of the 'a' and 'd' values for elephant foot yam. The r-values, the minimum uptake of N, P and K needed to produce any measurable corm yield in step-2 of QUEFTS model were fixed as zero due to the lack of required data (Witt *et al*. 1999).

for P. This is a clear indication that both N and K were the limiting nutrients in those major elephant foot yam-production regions, whereas P was not a limiting nutrient for elephant foot yam growth and production.

To test the sensitivity of the model to boundary values of NPK uptake, the model was run with three different sets of parameters (sets 1–3, Table 2), keeping the potential yield at 100 tonnes/ha of fresh corm. When the data were deleted from 2.5 to 5.0 to 7.5 percentiles, a lot of difference could be observed in the slope of the boundary lines (Table 3). However, the balanced NPK uptake requirements were similar for all three sets of data. The differences were found to be maximum when the yield targets were close to yield potential. Similar findings have been reported by Witt *et al*. (1999) for rice, Pathak *et al*. (2003) for wheat, Liu *et al*. (2005) for wheat and maize and Byju et al. (2012) for cassava. Because there is large variability of internal efficiencies in farmers' fields, we propose that set 4 (Table 2) could be used as standard parameter set in QUEFTS for elephant foot yam as these include the maximum range of variability.

Potential yield and nutrient requirements

There is great variation in the potential yield (Y_{max}) of elephant foot yam among the major production regions of India. The potential yield values range from 60 to 100 t/ha fresh corm. The NPK uptake requirements at different yield potentials of elephant foot yam showed that the relation between yield and nutrient (N, P, or K) uptake is linear at lower yield targets, indicating that plant growth is mainly limited by NPK uptake. At greater yield targets that are closer to yield potential, there was great reduction in the internal efficiency values (Table 4), and similar observations were earlier made by Witt *et al*. (1999) for rice, Pathak *et al*. (2003) for wheat and Byju *et al*. (2012) for cassava. When the yield target approaches the yield potential, the IE values decreased drastically from the linear level and reached minimum values. The results indicate that maximizing the nutrient efficiencies by balanced NPK application will give more profit to farmers than aiming for greater yield targets closer to potential yield. Irrespective of the yield potential, the calculated NPK uptake ratios in the total plant dry matter of elephant foot yam were 5.56:1:9.88 in the linear part of the relationship. The NPK uptake requirements in total plant dry matter for 1 000 kg corm in the linear part of the relation were 3.97, 0.71, and 7.05 kg N, P, and K irrespective of the yield potential. The corresponding IE values for N, P, and K were 252, 1 400.9, and 142 kg/kg. It can be observed that both the NPK uptake and IE values of elephant foot yam were similar to the values from the data set used for developing the model (Table 1). The IEs of all nutrients were found to be lower in the data set, which could be due to nutrient imbalances or differences in potential yields at various experimental locations (Pathak *et al*. 2003). It can also be seen that the linear part of the relationship is always 75 to 80% of the whole yield range. These observations are consistent with the results reported in cassava (Byju *et al*. 2012).

Indigenous nutrient supply and fertilizer nutrient recovery efficiency

The INS, IPS and IKS were determined from plots that did not receive N, P and K fertilizers respectively and there were wide variation in INS, IPS, and IKS values, the mean values being 94.16, 17.52, and 154.66 kg/ha, respectively. The average values of recovery efficiencies of N, P, and K were 32.35, 15.20, and 34.42%, respectively elephant foot yam(Table 1).

Model validation

The calibrated QUEFTS model for elephant foot yam was validated by on-station validation experiment conducted for four years from 2011 to 2014. The relationship between corm yield and maximum accumulation and dilution of N, P, and K in total plant dry matter was developed using data set shown as set 4, Table 2. Indigenous nutrient supplies of

Table 3 Relationship between corm yield and NPK uptake in total plant dry matter of elephant foot yam using sets 1, 2 and 3 from Table 2.

Corm yield	N uptake (kg/ha)			P uptake (kg/ha)			K uptake (kg/ha)		
(t/ha)	Set 1	Set 2	Set 3	Set 1	Set 2	Set 3	Set 1	Set 2	Set 3
10.00	40	36	36	7	6	7	70	72	71
15.00	59	54	54	11	10	10	106	108	106
20.00	79	72	72	14	14	14	141	144	142
25.00	99	91	90	18	17	17	176	180	177
30.00	119	109	108	21	21	21	212	215	213
35.00	139	127	126	25	24	24	247	251	248
40.00	159	145	144	28	28	28	283	287	283
45.00	179	163	162	31	31	31	318	323	319
50.00	198	181	180	35	35	35	353	359	354
55.00	218	199	198	39	38	38	389	395	390
60.00	241	220	219	43	42	42	428	436	429
65.00	264	258	258	47	47	47	469	467	461
70.00	300	290	283	53	52	51	534	522	507

Table 4 NPK uptake requirements, internal efficiencies (kg corm/kg nutrient) and reciprocal internal efficiency (kg nutrient/1000 kg corm) for elephant foot yam as calculated by QUEFTS for certain yield targets.

Corm yield	Nutrient uptake			Internal efficiency			Reciprocal internal efficiency		
(t/ha)	N	P	K	N	P	K	N	P	K
	kg/ha			kg/kg			kg/1000 kg		
10.00	40	7	70	250	1429	143	4.00	0.70	7.00
15.00	59	11	106	254	1364	142	3.93	0.73	7.07
20.00	79	14	141	253	1429	142	3.95	0.70	7.05
25.00	99	18	176	253	1389	142	3.96	0.72	7.04
30.00	119	21	212	252	1429	142	3.97	0.70	7.07
35.00	139	25	247	252	1400	142	3.97	0.71	7.06
40.00	159	28	283	252	1429	141	3.98	0.70	7.08
45.00	179	31	318	251	1452	142	3.98	0.69	7.07
50.00	198	35	353	253	1429	142	3.96	0.70	7.06
55.00	218	39	389	252	1410	141	3.96	0.71	7.07
60.00	241	43	428	249	1395	140	4.02	0.72	7.13
65.00	264	47	469	246	1383	139	4.06	0.72	7.22
70.00	300	53	534	233	1321	131	4.29	0.76	7.63

The model was run using constants of set 4 (Table 2). The potential yield was set to 100.0 t/ha fresh corm yield.

N, P, and K during 2011 were calculated using the relationship developed by Byju *et al*. (2012) and in subsequent years they were calculated based on the nutrient uptake in nutrient omission plots of experiment conducted during the previous year. The NPK fertilizer requirements were estimated using the Microsoft Excel spreadsheet version of QUEFTS in combination with a solver module.

The selected location represented Ultisols where elephant foot yam cultivation is concentrated in Kerala state. Table 5 gives the details of the model validation. It can be observed that fertilizer best management practices by SSNM resulted in an average actual corm yield of 33.45 t/ha, whereas the model predicted a yield of 35 t/ha. The results of the study showed good agreement between predicted and measured corm yields during the four years, which indicated that the calibrated model can be used to improve NPK fertilizer recommendations for elephant foot yam in India. The results of validation of SSNM of elephant foot yam conducted in the states of Tamil Nadu (Coimbatore), Andhra Pradesh (Kovvur), Bihar (Dholi), West Bengal (Kalyani) and Gujarat (Navsari) showed better performance of the treatment compared to present recommendation (Anon. 2013, 2014).

Compared with PR, SSNM significantly increased corm yield, and N, P and K uptake (Table 6). The average yield difference between SSNM and PR for the four crops grown was 5.50 t/ha (20%, P=0.005) and was similar in all the four years studied. Seasonal differences in the performance were not statistically significant (crop year, P = 0.167). There were significant increases in plant N, P and K accumulation in SSNM compared with PR treatment. On average, plant N accumulation increased by 13 kg/ha (8%, P = 0.004), P accumulation by 6.5 kg/ha (34%, P = 0.016), and K accumulation by 40 kg/ha (23%, P = 0.015). Crop-season effects were not significant, i.e. similar increases in nutrient uptakes were achieved during all the years (Table 6).

Table 5 Predicted yield of elephant foot yam by the QUEFTS model at ICAR-CTCRI farm, Thiruvananthapuram, Kerala (average of four years)

Nutrient	Indigenous supply (kg/ha)	NPK fertilizer requirement (kg/ha)	Predicted nutrient uptake (kg/ha)	Predicted yield (t/ha)
N	134.2	100	126	35.00
P	15.7	30	24	
K	123.4	150	248	

The measured yield is 33.45 t/ha. The yield potential was set to 100.0 t/ha.

Significant increases in N use efficiency were achieved through the field- and season specific N management practised in SSNM treatment (Table 6). The AE_N, RE_N and PE_N significantly increased in SSNM treatment compared with PR. Between the two crops grown, the AE_N increased by 22.5 kg/kg (35%, P = 0.007), RE_N by 0.08 kg/kg (20%, P = 0.011) and PE_N by 65 kg/kg (72%, P = 0.014). The AE_P, RE_P and PE_P were significantly increased in SSNM compared with FFP. Between the two crops grown, the AE_P increased by 23.5 kg/kg (17%, P = 0.003), RE_P increased by 0.05 kg/kg (31%, P = 0.006) and PE_P increased by 62 kg/kg (31%, P= 0.015). The K use efficiency parameters also significantly increased in SSNM treatment compared with PR. Between the two crops grown, the AE_K increased by 19.85 kg/kg (23%, P = 0.022), RE_K increased by 0.11 kg/kg (35%, P = 0.027) and PE_K increased by 20.0 kg/kg (38%, P = 0.013). The results of the present study showed that the current NPK management practices for elephant foot yam in India are inconsistent with the physiological NPK requirements of the crop and lead to large nutrient losses.

Table 6 Effect of fertilizer best management practices by SSNM on corm yield, nutrient uptake and nutrient use efficiency (average of four years)

Parameter	Unit	SSNM	Present recommendation	D*	P|T|*
Corm yield	t/ha	33.50	27.00	5.50	0.005
N uptake	kg/ha	181.20	168.20	13.00	0.004
P uptake	kg/ha	25.50	19.00	6.50	0.016
K uptake	kg/ha	215.60	175.60	40.00	0.015
AE_N*	kg/kg	86.70	64.20	22.50	0.007
AE_P*	kg/kg	165.50	142.00	23.50	0.003
AE_K*	kg/kg	105.00	85.15	19.85	0.022
RE_N*	kg/kg	0.48	0.40	0.08	0.011
RE_P*	kg/kg	0.21	0.16	0.05	0.006
RE_K*	kg/kg	0.42	0.31	0.11	0.027
PE_N*	kg/kg	155.50	90.50	65.00	0.014
PE_P*	kg/kg	262.50	200.50	62.00	0.015
PE_K*	kg/kg	72.50	52.50	20.00	0.013

*D, SSNM – FFP; P>|T|, probability of a significant mean difference between SSNM and FFP; AE_N, AE_P and AE_K, agronomic efficiency of N, P and K; RE_N, RE_P and RE_K, recovery efficiency of N, P and K; PE_N, PE_P and PE_K, physiological efficiency of N, P and K.

across India by AICRP on tuber crops were also used for preparation of the zonation maps (Anon. 2013, 2014). Future research is needed to validate and test the customised fertilizer ratios to fine tune the recommendations for specific regions within a district. Figure 1 shows the SSNM zonation maps and secondary and micronutrient fortified customised fertilizer ratios developed using geoinformatics tools for Kerala state using the validated QUEFTS model, agroecological units developed by NBSS&LUP, the soil nutrient status and soil fertility maps (Rajasekharan *et al.* 2013; http://www.iiss.nic.in/STCR.html).

The QUEFTS model has been parameterized and calibrated for making NPK fertilizer recommendations for elephant foot yam in India. The fertilizer NPK requirements for a target yield can be calculated using the model. Data collected from different field experiments conducted in major elephant foot yam-production regions of India during 1970 to 2011 were used to calibrate the model. The derived parameters of minimum and maximum accumulation of N (130 and 460), P (900 and 2100), and K (100 and 170) are proposed as standard borderline values in the QUEFTS model for elephant foot yam. A linear increase in corm yield was suggested by the model with N, P, and K uptakes of 3.97, 0.71, and 7.05 kg N, P, and K per 1 000 kg corm yield. The average NPK ratio in total plant dry matter was

Table 7 SSNM recommendation chart for elephant foot yam cultivation in India based on QUEFTS model

OC (%)	Yield target(t/ha) 30	40	50	60	Available P (kg/ha)	Yield target(t/ha) 30	40	50	60	Exchangeable K (kg/ha)	Yield target(t/ha) 30	40	50	60
	N rate (kg/ha)					P_2O_5 rate (kg/ha)					K_2O rate (kg/ha)			
Below 0.5	80	100	120		Below 10	50	75	100		Below 180	120	180	240	
0.5 – 0.8	50	80	100	120	10-20	30	50	75	100	180-280	80	120	180	240
0.8 – 1.2	25	50	80	100	20-30	20	30	50	75	280-360	40	80	120	180
Above 1.2	20	25	50	80	Above 30	10	20	30	50	Above 360	30	40	80	120

The modified QUEFTS model was run several times for different yield targets and for different indigenous nutrient levels and NPK fertilizer requirements were calculated and based on the results, SSNM recommendation chart for elephant foot yam cultivation in India was prepared as given in Table 7.

SSNM zonation maps and customised fertilizers

The results obtained by running the calibrated QUEFTS model were used for preparation of SSNM zonation maps. The soil fertility maps available at the website, http://www.iiss.nic.in/STCR.html were also used to categorise the major elephant foot yam growing environments. The results of validation done both with historical and current on-farm data were used for zonation of the growing environments. The SSNM recommendations and published information on soil status and plant requirement of secondary and micronutrients, secondary and micronutrient fortified customised fertilizer ratios were developed as given in Table 9. The results of SSNM validation experiments conducted

Table 8 SSNM recommendations of elephant foot yam for major growing environments of India (Y_{target} = 40 t/ha (Kerala, Gujarat and Tirunelveli, TN), 50 t/ha (other places))

State	District	N (kg/ha)	P_2O_5 (kg/ha)	K_2O (kg/ha)
Kerala	Ernakulum, Wayanad, Malappuram	80	30	120
West Bengal	South 24 Parganas, North 24 Parganas, Nadia	100	50	80
Andhra Pradesh	West Godavari, Guntur	100	75	80
	Krishna	80	50	100
Tamil Nadu	Tirunelveli	100	50	100
	Erode	80	50	100
Bihar	Samastipur, Vaishali, Begusarai	80	50	100
	Muzaffarpur	80	75	100
Gujarat	Navsari	100	50	80

Table 9 Customised fertilizer ratios for SSNM of elephant foot yam

Customised fertilizer ratio	Elements	Rate of application (kg/ha)	Y_{target} (t/ha)	State	Districts
12:4:18:3:0.4:0.2	N:P:K:Mg:Zn:B	650	40	Kerala	Ernakulam, Wayanad and Malappuram
12:7:15:0.7:0.4:0.4:0.1	N:P:K:Fe:Mn:Zn:B	650	50	AP	Krishna
11:6:14:2.5:0.3:0.1	N:P:K:Mg:Zn:B	700	50, 50	TN, Bihar	Erode, Samastipur, Vaishali and Begusarai
9:8:11:2.5:0.3:0.1	N:P:K:Mg:Zn:B	650	50	Bihar	Muzaffarpur
14:7:12:0.7:0.4:0.4:0.1	N:P:K:Fe:Mn:Zn:B	700	50, 40	WB, Gujarat	South 24 Parganas, North 24 Parganas, Nadia, Navsari
12:9:10:0.6:0.3:0.3:0.1	N:P:K:Fe:Mn:Zn:B	800	50	AP	West Godavari and Guntur
13:6:13:2.5:0.3:0.1	N:P:K:Mg:Zn:B	750	40	TN	Tirunelveli

5.56:1:9.88. Validation of the model using experimental data resulted in good agreement between predicted and measured yields. The study also developed the SSNM zonation maps for fertilizer best management practices of elephant foot yam cultivation in major growing environments of India. Based on the classification of different zones, secondary and micronutrient fortified customised fertilizer ratios were developed and mapped using geoinformatics tools. Further research is needed to validate the customised fertilizers at different agroclimatic and pedogenic environments where elephant foot yam is cultivated in India.

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