***RESEARCH PAPER***

# Developing a quantitative system for coffee yield prediction and ISFM recommendation calibrated for Northern Tanzania

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## ABSTRACT

The aim of this study was to develop a simple and quantitative system for coffee yield estimation and nutrient input advice, so as to address the problem of declining annual coffee production in Tanzania (particularly in its Northern coffee zone), which is related to declining soil fertility. The study was conducted between 2010 and 2013 at TaCRI Lyamungu, with source data taken from Hai and Lushoto districts, Northern Tanzania. An earlier model QUEFTS, developed for maize but under similar conditions as those of Arabica coffee in the study areas, was used as a benchmark. Secondary fertilizer trial data were used in model calibration for coffee, while adding two more steps related to balanced nutrition and the economics of integrated soil fertility management (ISFM). Primary soil analytical data and calculated yields on basis of tree number were used for model testing. The result was a new model which we hereby call SAFERNAC (Soil Analysis for Fertility Evaluation and Recommendation on Nutrient Application to Coffee). The model consists of three modules: SOIL (the soil properties of interest), PLANT (all the crop and crop management parameters such as physiological nutrient use efficiency, plant density, maximum possible yields per tree) and INPUT (nutrient inputs – organic and inorganic). It consists of two subsequent parts – a baseline approach (no input) for coffee land evaluation; and an integrated soil fertility management (ISFM) approach that involves application of nutrient inputs, for ISFM planning and design of fertilizer experiments. The model was checked for accuracy of the adjusted equations, and found to be capable of reproducing the actual yields by 80-100%. The new model is a useful tool for use in coffee farms.


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*Key words: Coffee yield model, soil fertility evaluation, nutrient equivalent, nutrient inputs*


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## 1. INTRODUCTION

The importance of coffee in the Tanzanian economy is well documented by [1], [2] and [3], among others. Coffee prefers very deep (more than 1.5 m), well drained friable loam and clay soils. Soils with high available water holding capacity, a pH in the range of 5-7 and a high nutrient holding capacity are most suitable [4]. Its average nutrient removal from a 1 ha soil per growing cycle is 135 kg of N, 35 kg of $P_2O_5$ and 145 kg of $K_2O$ [5]. With a substantial part also getting lost through leaching and downstream flow in the soil, it is essential to

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In Tanzania, coffee is grown in a wide variety of agro-ecological zones. Mlingano Agricultural Research Institute (MARI) [7], following the system developed by De Pauw in 1984 and adopted by [8], described the coffee zones as Eastern Plateaus (E12-E15), High plateaus and plains (H1, H2, H3, H5), Volcanoes and rift depressions (N4, N10), Central plateaus (P6) and Western Highlands (W1-W4). These include an altitudinal range of 500 – 3500 metres above mean sea level, and rainfall range of 500 – 3500 mm (mostly over 1000 mm). According to the fundamental growth conditions for coffee [4], [9], [10], water availability in these zones does not pose a serious limitation to coffee, and neither does irradiance or temperature in this tropical Tanzanian situation. This statement, however, does not take into account the imminent threat of climate change. Following [11], this leaves soil condition as a major factor of coffee productivity in the Tanzanian coffee growing zones. In the Northern coffee zone, which fits into agro-ecological zones E, H and N, and is dedicated exclusively to the production of mild Arabica coffee, annual production is on a decline [12] and soil fertility degradation has been pointed out as an important limiting factor.

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Soil fertility is not a distinct property of the soil as such, since many soil properties influence fertility and also influence each other. In its part, soil fertility affects, and is also affected by, the choices that farmers make regarding agricultural production, fertilization, and soil and water conservation regimes, a study of which needs a method for measuring soil fertility. Unfortunately, there is no unique technique [13]. Ultimately, farmers are not interested in the soil properties themselves, but how they affect agricultural production. Crop models, such as QUEFTS [14], become useful in explaining the effects on yields of individual soil properties that are measured by soil sampling. The predicted yield can then be used as an integrative indicator of soil fertility.

QUEFTS is one of the series called the Wageningen Crop Models. It uses calculated yields of unfertilized maize as a yardstick, and soil fertility is interpreted as the capacity of a soil to provide plants with the primary macronutrients. Four successive steps are involved: a calculation of the potential supplies of N, P and K, actual uptake of each nutrient, yield ranges as depending on the actual uptakes, and lastly, pairwise combination of yield ranges, and the yields estimated for pairs of nutrients are averaged to obtain an ultimate yield estimate. QUEFFS was described [14] as a useful tool in quantitative land evaluation, whose principles may be applied to other crops, soils, nutrients and agro-ecological regions. The framework on which the model was built is in synchrony with the physiographic requirements of Arabica coffee.

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One of the important thrusts of Tanzania Coffee Research Institute (TaCRI) is in the area of integrated soil fertility management (ISFM). Considering the diverse environments under which coffee is grown, crop yield and fertilizer modelling becomes of great importance. With many coffee yield modelling attempts so far based on the crop and its physiological processes [15], this work focused on the land and its capacity to support coffee. Its objective was to make a coffee ISFM decision support tool on basis of soil properties, organic and inorganic nutrient inputs; calibrated for the northern coffee zone of Tanzania, with a prospect of scaling up and out.

## 2. METHODOLOGY

### 2.1 Background

Efforts to collect and collate the available soil data for purposes of gauging the TaCRI recommendations on soil fertility management started in 2005. Soil data from various places in Kilimanjaro, and results from NPK reference trials at TaCRI Usagara C farm, and fertilizer x tree density trial, Lyamungu were collected. These data were used between 2007 and 2010 in calibrating an earlier developed fertilizer advice model QUEFTS (Quantitative Evaluation of the Fertility of Tropical Soils) [14], [16], [17], [18] and [19], to coffee.

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#### 2.1.1 Estimation of physiological nutrient use efficiency (PhE) by coffee

Because in the trials whose data are used in this work crops had not been analyzed, the uptake of nutrients was estimated by dividing the yield by the physiological nutrient use efficiency (PhE), which relates agronomic yield with nutrient uptake in all crop components [17]. Unfortunately there has been no real data on PhE by coffee in Tanzania. They were therefore derived from literature ([20], [21], [22], and [23]), and tuned to the results of TaCRI fertilizer trials (see Table 1). It was assumed that they represent average values. The medium physiological nutrient use efficiency (PhEM) is then found by dividing dry matter production of parchment coffee by gross uptake of nutrients. (Note: In the table, dry matter production of pulp and vegetative growth refers to the annual production going together with an annual dry parchment coffee production of one ton.) This results in 1000/70 (=14), 1000/12.5 (=80), 1000/63 (=16) for N, P and K.

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Table 1: Rounded indicative values of dry matter production and average nutrient contents in various components of the coffee tree.

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| Component | Dry matter (DM) | N | P | K |
|---|---|---|---|---|
| Parchment coffee | 1000 | 20 | 2.3 | 18 |
| Pulp | 875 | 16 | 6.0 | 17 |
| Vegetative growth | 2000 | 34 | 4.2 | 28 |
| Total DM; Gross uptake | 3875 | 70 | 12.5 | 63 |

Nitrogen, = N; phosphorus = P; potassium = K.

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#### 2.1.2 Experimental data for model calibration

In the calibration of QUEFTS, we used coffee-based data from two TaCRI's on-station field trials (NPK reference trial; fertilizer x tree density trial) to establish relationships between soil fertility indices and nutrient uptake by coffee. The NPK reference trial had been superimposed on established coffee in 1983. The design was $3^2$ factorial with N and K both applied at rates of 80, 160 and 240 kg per ha per year while all units received 60 kg P per ha per year. N and K were applied in three rounds and P in two rounds. Three extra experimental treatments were included as well: N0P0K0, N2P0K2, N2P2K2, where N2 and K2 stand for 160, and $P_2$ for 120, kg ha$^{-1}$ year$^{-1}$. The fertilizer x tree density trial was started at Lyamungu in 1994. It had a split-plot design with tree density (1330, 2660, 3200 and 5000 trees ha$^{-1}$) as the main treatment, and N application as a sub-treatment (0, 90, 180 and 270 kg N ha$^{-1}$ year$^{-1}$, split-applied in three rounds). Only yields of the best year were used in order to minimize the risk that other factors than soil fertility and NPK had influenced yields. Some soil analytical data of both trials were available (Table 2). Starting with the parameter values of the original QUEFTS model, a trial-and-error procedure was followed until the fit could not be improved further.

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Table 2: Soil analytical data for the two on-station trials

| Location | SOC* g/kg | SON* g/kg | P-Bray 1 mg/kg | Exch K mmol/kg | pH water |
|---|---|---|---|---|---|
| | | | *NPK reference trial* | | |
| Usagara C | 18 | 2.8 | 67 | 19 | 5.7 |
| | | | *Fertilizer x tree density trial* | | |
| Trees per ha | | | | | |
| 1330 | 22 | 2.2 | 86 | 22.1 | 5.7 |
| 2660 | 24 | 2.4 | 109 | 21.1 | 5.8 |
| 3200 | 21 | 2.1 | 65 | 17.3 | 5.6 |
| 5000 | 18 | 1.8 | 119 | 18.2 | 5.3 |

*SOC.......,

## 2.2 Adaptation of QUEFTS to coffee

The first task in adapting QUEFTS to coffee was to review, with the coffee crop in mind, its various steps. These steps deal with the assessment of available nutrients from soil and inputs (A), the calculation of actual uptake (U) of nutrients as a function of the amounts of available nutrients (A), and the estimation of yield (Y) as a function of the nutrients taken up (U). While QUEFTS assessed available nutrients in unfertilized soils [15] and in chemical fertilizers [16], there was a need to consider in Step 1 also organic nutrient inputs as ISFM components.

The calculation of actual uptake of nutrients (Step 2) was adopted as in QUEFTS, as it mainly involved theoretical concepts. The actual uptake of Nutrient 1 ($U_1$) is calculated twice: $U_{1,2}$ is a function of $A_1$ and $A_2$ being the available amounts of Nutrients 1 and 2, $U_{1,3}$ is  a function of $A_1$ and $A_3$. The lower of $U_{1,2}$ and $U_{1,3}$ is assumed to be the more realistic one in accordance with Liebig's Law of the Minimum.

In Step 3, yield ranges between maximum and minimum limits are derived on basis of the actual nutrient uptakes. Yields at maximum accumulation of N, P and K in the crop (YNA, YPA, YKA) and at maximum dilution (YND, YPD, YKD) are calculated as the product of actual uptake (U) and physiological nutrient use efficiency (PhE) at accumulation and dilution (PhEA and PhED), respectively. PhE in this study is expressed in kg parchment coffee per kg of nutrient taken up.

Step 4 mainly followed the QUEFTS principles. Yield ranges are combined in pairs (YNP, YNK, YPN, YPK, YKN, and YKP) taking nutrient interactions into account. The average value of those six yields is considered the final yield estimate (YE). Some restrictions are imposed to ensure that calculated YE does not surpass the maximum dilution of N, P or K (YND, YPD YKD) or the maximum yield that can be obtained in view of climate and crop properties (YMAX). For coffee, the concepts of $Y_{tree}$MAX and YMAX were introduced as maximum yield limits per tree and per ha, respectively.

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Two additional steps were introduced to facilitate the assessment of the nutrient inputs required for a certain target yield [24]. Step 5 deals with the calculation of physiologically optimum nutrient proportions and the correspondingly required nutrient inputs for balanced crop nutrition. In Step 6 the economically optimum combinations of nutrient inputs are assessed as a function of target yield, soil available nutrients, and prices of input nutrients and yield.

### 2.3 Application of the model for coffee land evaluation

In its baseline approach, the new model was used to perform quantitative land evaluation for coffee by estimating yields on basis of spatial soil data from Hai and Lushoto districts. Data for OC, Total N, Bray 1 P, exchangeable K and pH were used. Those parameters whose units were percentage (OC and total N) and $cmol_c\ kg^{-1}$ (exchangeable K) had to be multiplied by ten to convert to $g\ kg^{-1}$ and $mmol_c\ kg^{-1}$ respectively. Plant density was set at 2000 trees per ha (spacing of 2.0 x 2.5 $m^2$). Other model parameters were left as default.

Data on baseline yield for the two districts were converted to shapefiles under ArcView GIS 3.2 (ESRI, 1996) and then interpolated under ArcGIS 9.3. The inverse distance weighting (IDW) interpolator was used with number of nearest neighbours set to 12 and the power set to 2. Baseline yield data for the two districts [25] was used as a yardstick to test various human intervention strategies; farmyard manure used alone, at 5 tons per ha (about 2.5 kg per tree); inorganic fertilizer N, P and K at the dosage of 160, 60 and 160 kg $ha^{-1}$; and a combination of the two. Scatter diagrams were used to show the effects of farmer ISFM practices in areas of low, medium and high natural fertility.

## 3. RESULTS AND DISCUSSION

### 3.1 The new model SAFERNAC

The calibration of QUEFTS for coffee gave rise to a new model SAFERNAC (Soil Analysis for Fertility Evaluation and Recommendation on Nutrient Application to Coffee). The model is built on Excel spreadsheet which allows for flexibility. Depending on the use to which it is put, it can follow one of the two separate approaches –baseline and ISFM. The parameters that differentiate the two approaches are based on Step 1. Figure 1 is a schematic representation of the model. The module PLANT comprises all indices related to the coffee crop (plant density, maximum yields per tree and per ha, PhEA and PhED). The module SOIL comprises five soil fertility indices (pH, organic carbon, total nitrogen, available phosphorus and exchangeable potassium), and the module INPUT comprises addition of organic and/or inorganic nutrient sources, which is the purpose of ISFM. In the spreadsheet the baseline approach is pursued by assigning zero values to all nutrient input columns. This approach simulates coffee yields under natural fertility, and is meant for use in coffee land evaluation. The ISFM approach assigns non-zero values to the nutrient input columns on spreadsheet, whereby the nutrients can be inorganic, organic or a combination of the two.

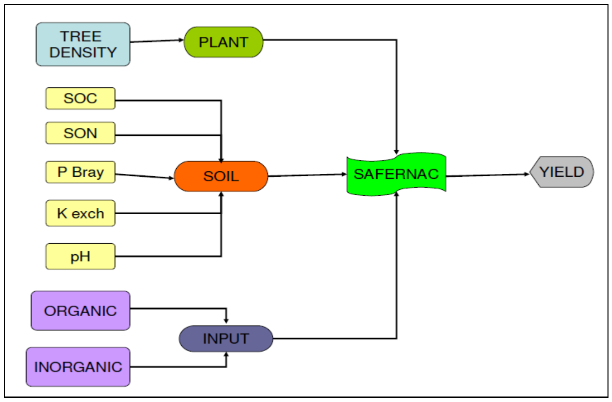


*Figure 5.1: Complete structure of SAFERNAC. Baseline and ISFM approaches are separated by assigning zero and non-zero to the "input" columns on spreadsheet.*

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### 3.2 Model assumptions and prerequisites

The system operates under the following conditions, most of which affect Step 1 equations, with the other steps more generic:

- Soil fertility is conceived as the capacity of a soil to provide plants with nitrogen, phosphorus and potassium as primary macronutrients. The system assumes therefore that other nutrients are far less limiting than those three.
- Irradiance and moisture availability are optimum,
- Soil is well drained (minimum of drainage class 3 – [26]),
- Soil is deep enough (90 cm and more),
- pH($H_2$0) is in the range 4.5-7.0,
- Values for SOC, P-Bray 1 and exch K for the topsoil (0-20 cm) are below 70 g $kg^{-1}$, 30 mg $kg^{-1}$ and 30 mmol $kg^{-1}$, respectively.

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### 3.3 Calibration of model parameters of SAFERNAC

Results of model calibration are summarized in Appendix 1. These include a simplification of constants (as in fK, SAN, SAP and SAK), introduction of INPUT parameters IAi and IAo and an important PLANT parameter fD in Step 1. Another major adjustment is in Step 3, where the PhE values were recalibrated and expressed as kg parchment coffee per kg of nutrient taken up at accumulation "a" and dilution "d" as shown in Table 3. On the other hand, the factors rN, rP and rK subtracted from UN, UP and UK respectively for maize was removed – they do not apply in areas growing coffee in Tanzania. Step 4 follows QUEFTS principles. Additionally, limitations have been set to the model such that YE ≤ max (YND, YPD, YKD, YMAX) by using two PLANT parameters $Y_{tree}$MAX and YMAX.

Table 3: Physiological efficiency at maximum, medium and minimum availability of N, P and K (in kg parchment coffee)

| | PhE* | Symbol | N | P | K |
|---|---|---|---|---|---|
| Maximum | PhED | D | 21 | 120 | 24 |
| Medium | PhEM | M | 14 | 80 | 16 |
| Minimum | PhEA | A | 7 | 40 | 8 |

* Physiological nutrient use efficiency at dilution (d), medium (m) and accumulation (a)

### 3.4 Balanced NPK Nutrition and crop nutrient equivalents

Some principles of balanced NPK nutrition and crop nutrient equivalents as explained by [27] and applied in Rwanda [28] are adopted in this work. It is assumed that the values of uptake efficiency (UE = U/A) and those of physiological efficiency (PhE = Y/U), averaged for all three nutrients N, P and K, are maximum when the available amounts and the uptakes of N, P and K have optimum proportions. In case the ratio PhED/PhEA is the same for N, P and K, the optimum proportions are equal to the ratios of the reciprocals of the medium physiological efficiencies (PhEM). This implies that in a situation of balanced nutrition, 1 kg of available N has the same effect on coffee yield as 0.175 kg of available P, or 0.875 kg of available K, and similarly does the uptake of 1 kg N have the same effect on coffee yield as the uptake of 0.175 kg P or 0.875 kg K. These values are used to define the unit of nutrient equivalents, referred to as kE.

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Once "target yield" or TY and PhEM are known, the relationship Y = U * PhEM can be used in determining the target uptake (TU) and target availability (TA), the latter being the sum of SA (available nutrients from the soil) and IA (available nutrients from input). When SA is known we can estimate the amount of nutrients needed to be added to the soil (both organic and inorganic) to attain the target yield: IA = TA-SA. For balanced crop nutrition, TAN = TAP = TAK, TAi being expressed in kE.

Balanced nutrition is the best possible situation from the environmental point of view, as it ensures maximum uptake of the available nutrients and minimum loss to the environment. Expressing quantities of nutrients in (k)E, and substituting $A_1 = A_2 = A_3$, $d_1 = d_2 = d_3$, $a_1 = a_2 = a_3$ and d/a = 3 in Step 3, it follows from that U/A = 0.9583. The average value of the uptake efficiencies is then maximum (being 0.96), and hence the average portion of non-utilized available nutrients is at minimum, being only 4%.

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Because soil available nutrients are usually not in optimum proportions, nutrient inputs should be managed in such a way that the sums of (SA + IA) get balanced. This implies that inputs should start with the most limiting nutrient. It should be applied till the available amounts of the most and the one but most limiting nutrients are in balance. Further application should be with these two nutrients according to their optimum proportions till the supplies of all three nutrients are balanced. From there onwards, all three nutrients are applied according their optimum proportions. An example is given in Figure 2 representing an imaginary soil having organic C 26 g $kg^{-1}$, organic N 2.6 g $kg^{-1}$, $P_{Bray\ I}$ 52 mg $kg^{-1}$, exchangeable K 20 mmol $kg^{-1}$, and pH($H_2O$) 5.2. The amounts of soil available N, P and K are then 71.5, 30.4 and 295.4 if expressed in kg $ha^{-1}$, and 71.5, 173.8 and 337.6 if expressed in kE ha$^{-1}$. The sum of soil available nutrients is 583 kE ha$^{-1}$. Tree density is set at 2000 and hence fD is 0.76. The calculated yield without fertilizer application is 1086 kg ha $^{-1}$. Because SAN is smaller than SAP and SAK (expressed in kE), inputs should start with N, followed by N+P, and finally with N+P+K. The maximum possible yield is 3800 kg ha $^{-1}$. That is why in Figure 2 the yield curve levels off at high quantities of available nutrients.

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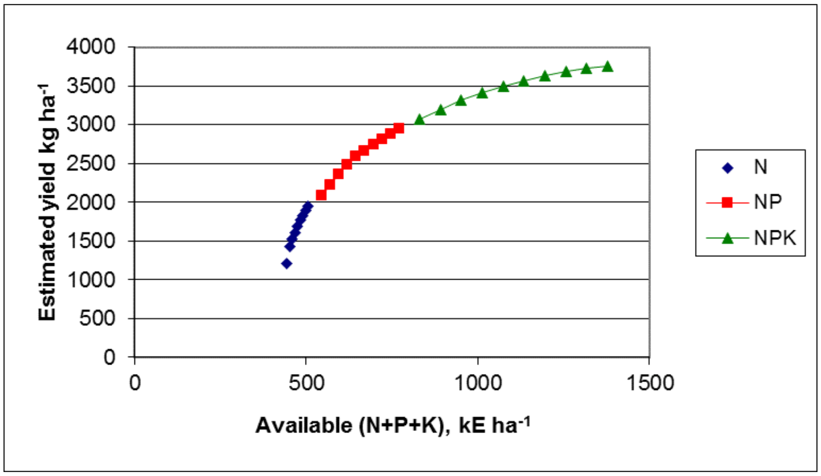


*Figure 2: Relation between calculated coffee yields and the amount of available nutrients expressed in kE ha $^{-1}$, for three ranges of nutrient input.*

### 3.5 Outcomes of model demonstration

In Appendix 2, the outcomes of the successive steps 1-4 in the basic SAFERNAC spreadsheet are shown as a two-treatment example for the on-station experiment of Usagara C: amounts of available nutrients (A), actual uptake (U) of N, P and K, yield ranges ($Y_1A$, $Y_1D$), yields as a function of nutrient pairs ($Y_{1,2}$ and $Y_{2,1}$) and the final yield estimate YE. U1,2 stands for UN(P), UP(K), UK(N); U1,3 for UN(K), UP(N), UK(P). Y1,1 stands for YNP, YPK, YKN; and Y2,1 stands for YPN, YKP, YNK. The model was run using the soil analytical data in Table 2 as starting points.

Figures 3a and 3b compare the yields simulated by SAFERNAC (YE) with actual yields ($Y_{act}$) for the NPK reference trial Usagara C and the fertilizer and tree density trial Lyamungu, of which soil data are given in Table 2. Actual yields were 80-100% of the simulated yields and the lines through the origin showed good $R^2$ values. The calibrated equations have therefore demonstrated their capability to reproduce the yields of the trials that had been used for their calibration to a satisfactory degree.

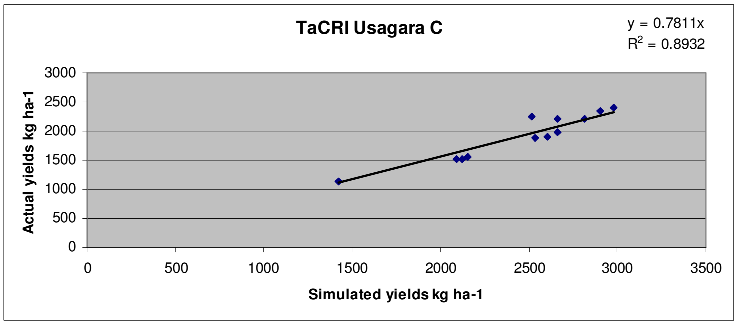


Figure 3a: Simulated and actual parchment yields, TaCRI Usagara C

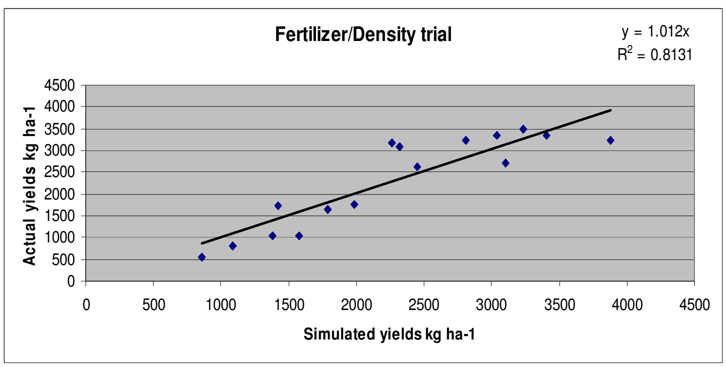


Figure 3b: Simulated and actual parchment yields, TaCRI fertilizer density trial

### 3.6 Estimated baseline yields Hai and Lushoto

Figure 4 shows baseline yield as estimated with SAFERNAC. The baseline yield map for Hai shows high spatial variation, with higher yields (>500 kg ha$^{-1}$) to the east (Lyamungo and Machame) and a pocket at Masama Sawe. The central part (mainly Machame) showed potential of 300 to 500 kg ha$^{-1}$ while the western part (Masama) recorded a low potential of less than 300 kg ha$^{-1}$. The yield map for Lushoto had lower spatial variation, with Lushoto, Soni and pockets of Mlalo recording over 350 kg parchment per ha. Mtae, the rest of Mlalo and parts of Mgwashi showed potential yield between 300 and 350 kg ha$^{-1}$, while lower yields (< 300 kg ha$^{-1}$) are in most of Bumbuli, parts of Soni and northern Mlalo. Bumbuli is a traditional coffee grower with traditional coffee varieties N39 and KP423, and is hereby encouraged to continue with coffee despite the low yield potential shown in this work. On the other hand, the high potential areas of Lushoto and Mlalo have very little coffee if any, and there is enormous potential for coffee establishment despite the likely competition with the temperate fruit trees for which Lushoto district is so famous. Mtae is an upcoming

**Comment [PN22]:** Line 311 to 326 no change letter type coffee area with few farmers who are using the new improved coffee varieties. It is easier for farmers to adopt new varieties because doing so does not require uprooting any existing coffee trees.

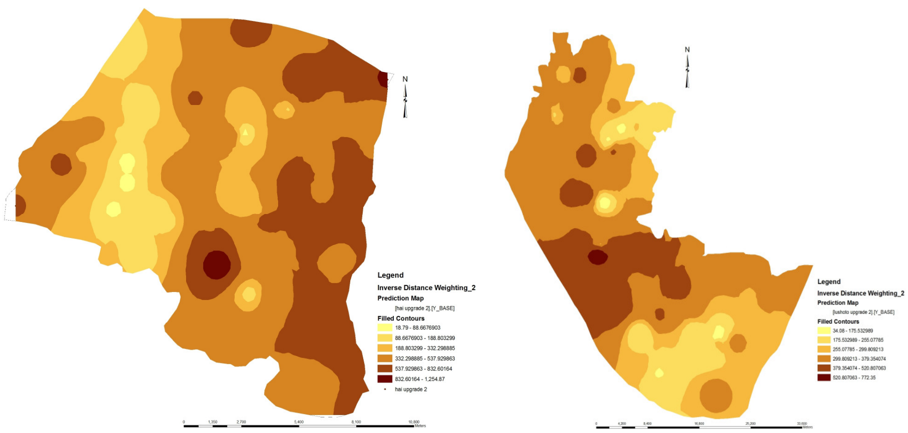


Figure 4: Baseline yield estimated with SAFERNAC, Hai and Lushoto districts

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The high level of variation in coffee production potential within districts, as illustrated in Figure 4, leads to a strong recommendation to the Tanzania Coffee Board (TCB) who are entitled to coffee crop estimation, to collaborate with TaCRI and devise ways to factor in SAFERNAC and soil data, thereby making their estimates more realistic.

### 3.7 Evaluation of ISFM practices

Evaluation results for farmer practices are given in Table 4. The slope represents the rate of change in yield from ISFM interventions with the baseline yield; the latter taken as an indicator of soil fertility. These results are comparable to those of [29] when testing PARJIB model with maize in New Zealand. From the results it is noted that the effect of human intervention (with manure, fertilizer or both) tends to be felt more where baseline yield is low (the increasing Y-intercept), and diminishes progressively as baseline yield increases (the decreasing slope). In other words, response to fertilizer input is greater in soils of lower fertility and vice-versa, and that the uptake of a nutrient is higher in its dilution and lower in its accumulation. The noted variable $R^2$ values are an indication that the soils, even within districts, differ in soil fertility and therefore response to ISFM interventions.

Table 4: Summary of scatter-plot equations comparing ISFM interventions (manure, fertilizer and combination of the two) against baseline yields, both calculated with SAFERNAC.

| **District** | | **Hai** | | | **Lushoto** | |
|---|---|---|---|---|---|---|
| **Parameter** | **Y-int** | **Slope** | **$R^2$** | **Y-int** | **Slope** | **$R^2$** |
| **Manure alone** | **438** | **0.88** | **0.76** | **426** | **0.60** | **0.44** |
| **Fertilizer alone** | **1200** | **0.68** | **0.31** | **988** | **0.35** | **0.05** |
| **Combination** | **1500** | **0.66** | **0.22** | **1240** | **0.25** | **0.02** |

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### 3.8 Description of SAFERNAC in relation to major model categories

A model is a simplified representation of a system. A system is a limited part of reality that contains interrelated elements. The totality of relations within the system is the "system structure". Simulation is the building of mathematical models and the study of their behaviour in reference to those of the systems [30]. Models may be categorized as descriptive or explanatory, empirical or mechanistic, static or dynamic depending on whether a component of time is included, deterministic or stochastic depending on the level of probability allowed; simulating and optimizing depending on intended use [30], [31]. SAFERNAC can be considered partly as a mechanistic model, partly as an empirical model. It is explanatory, but since it does not simulate changes in time it is not a dynamic model.

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The major part of the model which is described in this paper (Steps 1-4), deals with simulation of (nutrient-limited) coffee yields, but as balanced nutrition and economically optimum applications of N, P and K are incorporated (Steps 5 and 6), SAFERNAC has optimizing properties as well. Like QUEFTS, it is meant as a useful tool in quantitative land evaluation and in decisions regarding integrated soil fertility management (ISFM). The yield predicted by SAFERNAC in its baseline module (with no nutrient inputs) can be used as an integrative indicator of soil fertility, which is one of the land qualities used in land evaluation. The principle of balanced NPK nutrition can be applied to arrive at target yields in the most profitable and environmentally friendly way.

### 3.9 Nutrient limited, water limited and potential yields of coffee

In many crop growth models, it is usual principle to distinguish between potential, water limited, nutrient limited and actual yields [11], [32]. SAFERNAC and QUEFTS simulate nutrient-limited yields, with the assumption that soil nutrient supplies in the agro-ecological zones that grow coffee in Tanzania would limit crop growth more severely than water availability (the determinant of water-limited yields –WPP), and certainly more than irradiance or temperature (which, together with the crop characteristics, govern the potential yield – RPP). It may be necessary in the future to include an agro-meteorological component (like the one suggested by [14]) as climate change becomes more and more important for coffee in the country.

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So far SAFERNAC has been developed for a mono-crop of non-shaded coffee. This means that it is more useful in coffee estates (most of which prefer non-shaded coffee) than in smallholder farms. In shaded systems however, irradiance needs to be considered because it is known to be a growth-limiting factor. Integration of various levels of shade (and various intercropping regimes) could enrich the PLANT parameter in SAFERNAC. Once this is achieved, the model will expand its usability to smallholder coffee producers. Another option would be to incorporate (parts of) SAFERNAC into a general coffee growth simulation model in the similar way that QUEFTS was incorporated in TechnoGIN [33].

## 4. CONCLUSION

A new model called SAFERNAC has been developed for yield estimation and fertilizer recommendation in coffee. It can follow two separate approaches, a baseline and an ISFM approach. It uses some chemical soil characteristics (soil organic carbon and/or soil organic nitrogen, available P, exchangeable K and pH in ~~(~~water~~)~~), nutrient inputs (organic and inorganic), and maximum yields per tree and per ha for predicting the parchment coffee yield. When the model is run from soil fertility alone without intervention, it acts as a coffee land evaluation tool. When it is used to guide some crop management decisions such as intensification of coffee production, both natural soil fertility and input of nutrients in form of chemical fertilizer, organic nutrient sources or a combination of the two, play a role. Additional required model inputs are then quantity and quality of added nutrient sources and tree density. It is also possible to ask the model to assess the required nutrient additions for a certain target coffee yield, given tree density and the mentioned soil data. The model then becomes an ISFM decision support tool for coffee.

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**Comment [PN28]:** add in different coffee producing areas of the world

The model was checked using yields of on-station trials of TaCRI and the data for SOC, SON, $P_{Bray\ 1}$, exchangeable K, pH water, tree density and applied fertilizer NPK whereby it was able to reproduce the trial yields by 80-100%. Model usability for coffee land evaluation and ISFM intervention was tested with soils of Hai and Lushoto districts, Northern Tanzania, and proved to be a useful tool in both avenues. The next step will be to pre-test the model among selected smallholder coffee farmers and estates.

## COMPETING INTERESTS

"Authors have declared that no competing interests exist."

## AUTHORS' CONTRIBUTIONS

Author A: Designed this study, managed the analysis of the study, wrote the protocol and wrote the first draft of the manuscript.
Authors B, C and E: Managed the literature searches
Author D: Provided all the ideas of his model QUEFTS, on which this work was based, and also contributed in literature searches.
All authors read and approved the final manuscript.

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## DEFINITIONS, ACRONYMS, ABBREVIATIONS

| **Acronym** | **Description / Long form** |
|---|---|
| A | Availability (of a certain nutrient) for plant uptake |
| a | Short form of PhEA or PhEmin |
| d | Short form of PhED or PhEmax |
| FAO | Food and agricultural organization of the United Nations |
| $I_i$ | Input of nutrients in inorganic nutrient sources |
| $I_o$ | Input of nutrients in organic nutrient sources |
| IA | Available input nutrients |
| INPUT | Model component dealing with application of nutrients |
| ISFM | Integrated soil fertility management |
| K | Potassium (or potash fertilizer) |
| kE | Nutrient equivalent (same effect on yield as 1kg N) |
| MRF | Maximum recovery fraction |
| N | Nitrogen |
| OC (or SOC) | Soil organic carbon |
| P | Phosphorus |
| PhE | Physiological (or internal utilization) efficiency |
| PhEA | Physiological efficiency at accumulation |
| PhED | Physiological efficiency at dilution |
| PhEM | Physiological efficiency at balanced nutrition |
| PLANT | Model component dealing with plant properties like density |

| | |
|---|---|
| QUEFTS | Quantitative evaluation of the fertility of Tropical Soils |
| r | Parameter describing minimum uptake required for yield (not used for coffee in Northern Tanzania) |
| RE | Relative effectiveness of nutrients in organic sources |
| RPP | Radiation-thermal Production Potential |
| SA | Amount of available nutrients from soil alone (natural fertility) |
| SAFERNAC | Soil analysis for fertility evaluation and recommendation on nutrient application to coffee |
| SOIL | Model component dealing with soil properties of interest |
| SV | Substitution value (same as RE) |
| TA | Target amount of available nutrients |
| TaCRI | Tanzania Coffee Research Institute |
| TU | Target uptake (for a target yield) |
| TY | Target yield |
| U | Uptake |
| WPP | Water-limited production potential |
| $Y_{act}$ | Actual yields from experimental sites |
| YE | Yield estimated by the model |
| YKA | Yield associated with the uptake of potassium at accumulation |
| YKD | Yield associated with the uptake of potassium at dilution |
| Ymax | Maximum attainable yield under salient phenological set-up |
| YNA | Yield associated with the uptake of nitrogen at accumulation |
| YND | Yield associated with the uptake of nitrogen at dilution |
| YPA | Yield associated with the uptake of phosphorus at accumulation |
| YPD | Yield associated with the uptake of phosphorus at dilution |

## APPENDIX 1 SUMMARY RESULTS OF CALIBRATING QUEFTS TO COFFEE.

| **Model steps** | **QUEFTS** | **SAFERNAC** |
|---|---|---|
| 1 | fN= 0.25 (pH-3)<br>fP= 1-0.5 $(pH-6)^2$<br>fK=0.625 (3.4-0.4 pH) | ƒN = 0.25 * (pH – 3)<br>ƒP = 1 - 0.5 * $(pH - 6)^2$<br>ƒK = 2 - 0.2 * pH |
| | SN=fN * 6.8 * SOC or fN*68* SON<br>SP=fP* 0.35 * SOC+0.5 * P-Olsen<br>SK= (fK * 400 * exch.K)/ (2+0.9*SOC) | SAN = ƒN * 5 * SOC or ƒN * 50 * SON<br>SAP = ƒP* 0.25* SOC + 0.5* P-Bray-I<br>SAK = ƒK * 400 * exch.K/SOC |
| | Not considered | $IAN_i$ = MRFN * $IN_i$ = 0.7 * $IN_i$<br>$IAP_i$ = MRFP * $IP_i$ = 0.1 * $IP_i$ |

**Comment [PN42]:** check

**Comment [PN43]:** check

**Comment [PN41]:** check

| | | |
|---|---|---|
| | | $IAK_i$ = MRFK * $IK_i$ = 0.7 * $IK_i$ |
| | Not considered | $IAN_o$ = REN * MRFN * $IN_o$ = 0.42 * $IN_o$<br>$IAP_o$ = REP * MRFP * $IP_o$ = 0.087 * $IP_o$<br>$IAK_o$ = REK * MRFK * $IK_o$ = 0.7 * $IK_o$ |
| | Not considered | $fD = -0.06\,(D/1000)^2 + 0.5\,(D/1000)$<br>where:<br>D = number of trees per ha, and $fD$ = 1 for D = 3333 $ha^{-1}$. |
| 2 | Refer QUEFTS papers | Adopted as in QUEFTS |
| 3 | YND = 70 * (UN-5)<br>YNA = 30 * (UN-5)<br>YPD = 600 * (UP-0.4)<br>YPA = 200 * (UP-0.4)<br>YKD = 120 * (UK-2)<br>YKA = 30 * (UK-2) | $Y_1A = a_1 * U_1$<br>$Y_1D = d_1 * U_1$<br>(a and d referring to PhEA and PhED in kg parchment coffee per kg of nutrient taken up) |
| | Factor "r" subtracted from U in the equations of yields. | The "r" factor removed. Situations that U ≤ r are not applicable in coffee growing areas. |
| 4 | Refer QUEFTS papers | Adopted as in QUEFTS. Concepts of $Y_{tree}MAX$ and YMAX added:<br>$Y_{tree}MAX$ = 2.2 – 0.15 X<br>YMAX = 1000 * X * YtreeMAX<br>where X is 0.001 times number of trees per ha.<br>(YE should not exceed YND, YPD, YKD or YMAX). |
| 5 | Additional step, not in QUEFTS | AN:AP:AK = UN:UP:UK = 1/PhEMN : 1/PhEMP : 1/PhEMK = (1/14): (1/80): (1/16) or **1 : 0.175 : 0.875** |
| | | 1 kEN = 0.175*kEP =0.875*kEK<br>Where kE = kilo nutrient equivalent per ha. |
| 6 | Additional step, not in QUEFTS | An economic loop that considers the quantities and prices of inputs and output for calculating the economic optimum nutrient |

| | | |
|---|---|---|
| | | application |

**APPENDIX 2: OUTCOMES OF MODEL CALIBRATION**

| | | 0:0:0 | | | 240:60:240 | | |
|---|---|---|---|---|---|---|---|
| Step | Quantity | N | P | K | N | P | K |
| 1 | SA | 52 | 21 | 199 | 144 | 24 | 291 |
| | $I_iA$ | 0 | 0 | 0 | 168 | 6 | 168 |
| | $I_oA$ | 0 | 0 | 0 | 0 | 0 | 0 |
| | A | 52 | 21 | 199 | 312 | 30 | 459 |
| 2 | $U_{1,2}$ | 51.7 | 17.5 | 129.2 | 137.4 | 23.1 | 245.1 |
| | $U_{1,3}$ | 51.8 | 20.6 | 174.7 | 143.7 | 24.0 | 242.1 |
| | U | 52 | 17 | 129 | 137 | 23 | 242 |
| 3 | Y.A | 362 | 700 | 1033 | 962 | 925 | 1937 |
| | Y.D | 1086 | 2099 | 3100 | 2886 | 2774 | 5810 |
| 4 | $Y_{1,2}$ | 886 | 1072 | 1084 | 1745 | 2114 | 2465 |
| | $Y_{2.1}$ | 970 | 1085 | 1055 | 1716 | 2464 | 2135 |
| | YE | | | **1420** | | | **2978** |
| | Comp. $Y_{act}$ | | | ***1143*** | | | ***2404*** |

**Comment [PN45]:** insert level fertilizer

**Comment [PN46]:** check