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Spatializing the Coffee Yield Model SAFERNAC with Soil Fertility Data Across Tanzania

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Abstract — **The aim of this work was to explore the behavior and usability of the new model SAFERNAC over coffee growing areas throughout Tanzania. Soil fertility data from 1,131 georeferenced points in three zones were fed into the model under four distinct approaches – baseline (no input), organic (manure), inorganic (NPK) and combination of manure and mineral fertilizer. The simulated yields were descriptively compared per zone. They were loaded into QGIS 3.2, interpolated using the Inverse Distance Weighting (IDW) algorithm and the resultant raster maps clipped on basis of digitized boundary shapefiles. Baseline yields were effectively computed from 99.2% of the surveyed sites. The model showed high sensitivity to pH, which has a greater influence on P than N or K. Calculated yields decreased in the order Zone 2 > Zone 1 > Zone 3. The difference in yield between NPK 160:80:80 alone and a combination of NPK 80:40:40 (half dose) plus 5 tons manure was neither quantitatively nor spatially significant. SAFERNAC has proved its usability across the Tanzanian coffee soils, in simulating yield of parchment coffee. The combination approach (organic materials and mineral fertilizers) is most appropriate, as it can reduce the fertilizer cost by about 50% without seriously compromising the expected yields.**

***Index Terms*— Coffee yields, soil fertility data, spatialization, SAFERNAC, Tanzania**

I. Introduction

A new model called SAFERNAC (Soil Analysis for Fertility Evaluation and Recommendation on Nutrient Application to Coffee) was recently developed by scientists from Tanzania Coffee Research Institute, Sokoine University of Agriculture and Wageningen University, the Netherlands [1]. The model was built by calibration of an earlier generic model QUEFTS [2]-[3] using the results of two field experiments at Lyamungu. The calibration was done in a process of fitting the coffee data stepwise and regressing the simulated yields against actuals to get the best fit at each step and the overall best fit. It has three components: SOIL (OC, total N, available P, exchangeable K and pH water), PLANT (physiological nutrient use efficiency, plant density and maximum yields per tree) and INPUT (organic and inorganic nutrients). It calculates baseline (no-input) parchment yield for quantitative soil fertility evaluation, and yield with inputs for fertilizer recommendation and economically optimum rates. The model was initially tested with soils of Hai and Lushoto Districts in Northern Tanzania and found to work well. According to [4]-[5], there are many incentives for applying such a model on a regional scale, i.e. over an area larger than that for which it has been developed. This is termed "model spatialization". The objective of this follow-up work was therefore to spatialize SAFERNAC by exploring its behavior and usability across the coffee soils in Tanzania.

II. Materials And Methods

Soil fertility data from 1,131 georeferenced sites were used for this study, as derived from an earlier study by [6]. For purposes of this work, the coffee growing zones were regrouped into three. Zone 1 included Arusha, Kilimanjaro, Manyara, Mara and Tanga regions, while Zone 2 covered Morogoro, Iringa, Njombe, Ruvuma, Mbeya and Songwe regions; and Zone 3 covered Kagera, Mwanza, Geita, Kigoma and Katavi regions as shown in Figure 1. In each zone, districts had been selected on merit of growing coffee and/or having history with coffee. The data involved in this particular study are the ones that constitute the SOIL component of the model [1]. The PLANT component was left as default: D = 1300 trees ha-1; fD =0.5486; PhE as 7 and 21 kg parchment per kg N, 40 and 120 kg parchment per kg P, 8 and 24 kg parchment per kg K at accumulation (a) and dilution (d) respectively.

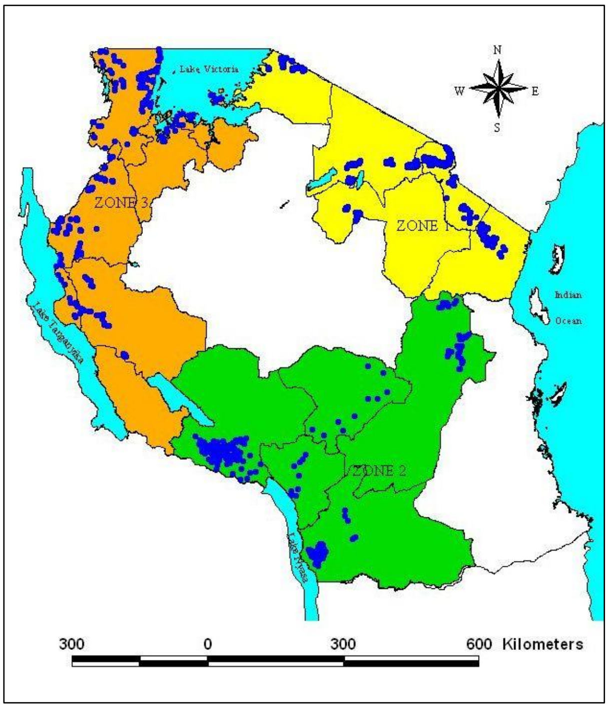

Fig. 1: Tanzania coffee zones (study sites in blue)

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Soil pH was used to establish the correction factors for available N, P and K (fN, fP and fK) as in Equations 1-3.

$$fN = 0.25(pH - 3) \quad (1)$$

$$fP = 1 - 0.5(pH - 6)^2 \quad (2)$$

$$fK = 2 - 0.2pH \quad (3)$$

Then relationships were empirically worked out between the correction factors, OC and the amount of total N, available P and exchangeable K to get the total available forms of each in kg ha^{-1} as in Equations 4-6.

$$SN = fN \times 5 \times OC \quad (4)$$

$$SP = fP \times 0.25 \times OC + 0.5 \times P_{Bray} \quad (5)$$

$$SK = fK \times 400 \times \frac{K_{exch}}{OC} \quad (6)$$

Available nutrients from inorganic fertilizers were calculated from their total application and recovery fraction (RF) which, for coffee, was set at 0.7, 0.1 and 0.7 for N, P and K respectively [7]. Those from organic materials had an additional factor called substitution value (SV), which, for cattle manure, was set at 0.6, 0.87 and 1.0 for N, P and K respectively, as derived from [8]-[9]. Total available nutrients (TX) was expressed as SX for baseline, SX+(IXi x RFx) for inorganic and SX+(IXo x SVo x RFx) for organic, where X stands for single nutrient N, P or K. Then pairwise nutrient uptake was calculated as in Equation 7.

$$U1(2) = \frac{TA1 - 0.25\left(TA1 - TA2 \times \frac{a2}{d1}\right)^2}{TA2\left(\frac{d2}{a1} - \frac{a2}{d1}\right)} \quad (7)$$

Where U1(2) is the uptake of nutrient 1 under ample supply of both nutrients 1 and 2, while TA1 and TA2 are total available nutrients 1 and 2. Corresponding yield estimates at maximum accumulation YXA and at maximum dilution YXD were calculated as in Equations 8 and 9.

$$YXA = aX \times UX \quad (8)$$

$$YXD = dX \times UX \quad (9)$$

Pairwise yields $Y_{1,2}$ were calculated as in Equation 10.

$$Y_{1,2} = Y_2A + \left(\frac{2(Y_2D - Y_2A)(U_1 - \frac{Y_2A}{d1})}{\frac{Y_2D}{a1} - \frac{Y_2A}{d1}}\right) - \left(\frac{(Y_2D - Y_2A)(U_1 - \frac{Y_2A}{d1})}{\frac{Y_2D}{a1} - \frac{Y_2A}{d1}}\right)^2 \quad (10)$$

Where Y1,2 represents the yield response to nutrients 1 and 2 within limits of the availability of nutrient 3. Such nutrients, according to the model, are N, P and K. Y represents yield, D the limit of dilution and A the limit of accumulation. U stands for the maximum possible uptake of a given nutrient. ‘a’ and ‘d’ stand for the physiological efficiencies in kg parchment coffee per kg nutrient taken up, at accumulation and dilution levels respectively.

Six yield estimates YNP, YNK, YPN, YPK, YKN and YKP were derived as above and their average taken as the final estimated yields. Further elaboration is given in [10].

SAFERNAC was run four times in each location – the baseline approach, organics alone (in this case, cattle manure at 5 tons ha^{-1}), inorganics alone (NPK 160:80:80) and organics with half dose of inorganics (NPK 80:40:40). Estimated mean yields per zone (including standard deviation and coefficient of variation) under the four different approaches were descriptively compared.

The organized and georeferenced Excel data sheets were converted to GIS-workable shapefiles using ArcView GIS Version 3.2 [11]. The vector base map used was the Census Map of Tanzania at a scale of 1:2,000,000 [12]. The shapefiles were exported to QGIS 3.2 for further processing. To facilitate interpolation and reduce noise from the non-coffee regions, boundary shapefiles for the three study zones were digitized. The point shapefiles were interpolated using the Inverse Distance Weighting (IDW) algorithm as in [13], and the resultant raster images were clipped on basis of the boundary shapefiles. The simulated yields at baseline (Y_{base}), organics (Y_{org}), inorganics (Y_{inorg}) and organics with half dose inorganic (Y_{combi}) were interpolated.

III. Results

A. Model behavior in different soils

The SAFERNAC model was able to estimate baseline (no-input) yields in 1,122 out of 1,131 locations surveyed, which is 99.2%. The rest, for which the model failed to calculate yields, were discounted from further analyses. Zone 1 had three sites Maji ya Chai in Arumeru (pH 7.81); Malindi and Mlalo in Lushoto (pH 7.82 and 4.51 respectively). Zone 3 had a total of six sites Heru Juu in Kasulu (pH 8.19), Ugaraba in Uvinza (pH 4.55 with another complication of low K), Lugonesi, Ilangu, Mazwe and Ifumbula in Mpanda with respective pH values of 3.87, 3.53, 4.03 and 4.26. These pH values are well beyond the limitations set for the model to work optimally (pH 4.5 to 7.0). The model appears overly sensitive to pH, which has a greater influence on soil-available P than N or K. Whereas Equations 1 and 3 are linear, Equation 2 for fP is asymptotic with a curve of peak 1.0 at pH 6.0 and touching the x-axis at pH 4.58 (lower end) and 7.42 (upper end). Above or below those figures, the model gets “confused” in computing the soil-available P, giving negative values for both fP and SP. In Zone 2, no site was discounted because they all fell within the desirable pH range and baseline yields were estimated. Of the nine discounted sites, 3 were affected in both baseline and organic approaches while the rest were affected in the baseline approach only. In the other approaches, especially those involving inorganic fertilizers, SAFERNAC was generally successful in computing the estimated yields; and this is an indication that the model sensitivity to pH is more to do with P availability and tends to diminish as fertilizer P is added.

B. Descriptive comparison per zone

After discounting the nine locations for which it was impossible to calculate baseline yields, a total of 494, 257 and 371 locations remained in Zones 1, 2 and 3 respectively. Zone

1 had the widest range of 7.83-1268.59 kg ha^{-1}, while other ranges for Zone 2 and 3 were 29.75-963.28 and 10.51-741.32 kg ha^{-1} respectively. A generally high standard deviation (>100 kg ha^{-1}) was noted across the approaches, indicating that the data are more spread out in space relative to the means. In all the approaches, calculated yields decreased in the order Zone 2 > Zone 1 > Zone 3. The difference in yield between NPK 160:80:80 alone and a combination of NPK 80:40:40 (half dose) plus 5 tons manure was not significant, implying that use of organic matter can reduce the fertilizer cost by about 50% without seriously compromising the expected yields.

The coefficients of variation (CV) for Zone 1 were 42.97%, 30.79%, 31.13% and 25.67% for baseline, organic, inorganic and combination respectively. Similar trend was noted in the other zones with respective CVs of 42.09%, 28.99%, 23.42% and 23.04% for Zone 2; and 54.47%, 27.42%, 24.23% and 21.24% for Zone 3. These trends imply that the variability of the estimated yields is high at baseline level (no input), decreasing to a minimum at combination level (organics and inorganics).

C. *Interpolation results for Zone 1*

Figure 2a (baseline) shows that about 85% of total land area is moderately fertile and capable of producing over 400 kg ha^{-1}, the bulk of which falling between 400-600 kg ha^{-1}. The rest, including parts of Mara, Tanga and Babati, can produce 200-400 kg ha^{-1}. Over 600 kg ha-1 are found in Karatu, with scattered patches around Mt. Meru and Kilimanjaro. Figure 2b (organic) shows substantial improvement with category 200-400 kg ha^{-1} diminishing. 400-600 kg ha^{-1} is maintained in many places except in the volcanic areas of Kilimanjaro and large parts of Arusha Region, where estimated yields were in the range 600-800 kg ha^{-1}. Figures 2 c and d (inorganic and combination) were apparently alike in many respects, with yields generally well over 600 kg ha^{-1}. The only notable difference is the slight decrease in the area around Karatu, capable of producing over 800 kg per ha with the application of manure and half dose of inorganic fertilizers.

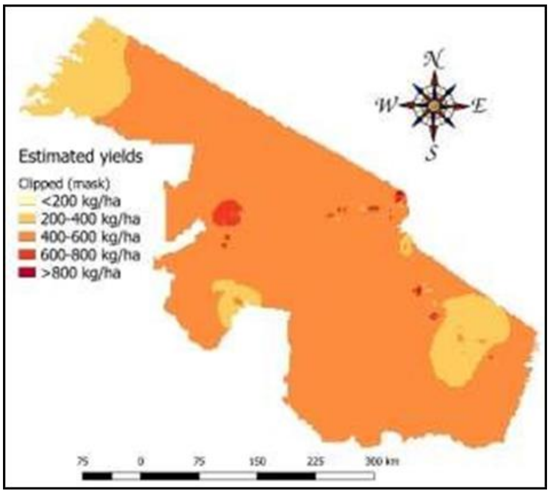

Fig. 2a. Estimated yield Zone 1 baseline.

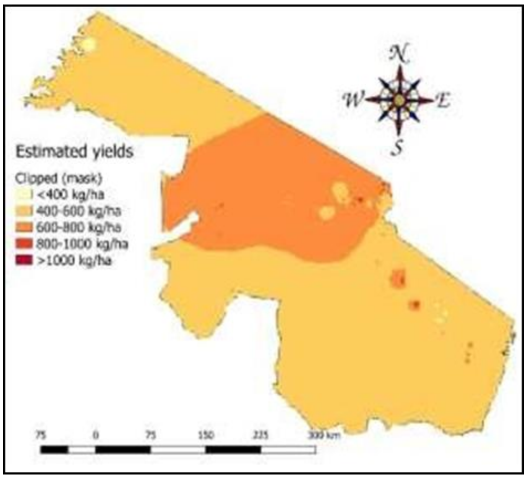

Fig. 2b. Estimated yield Zone 1 organic

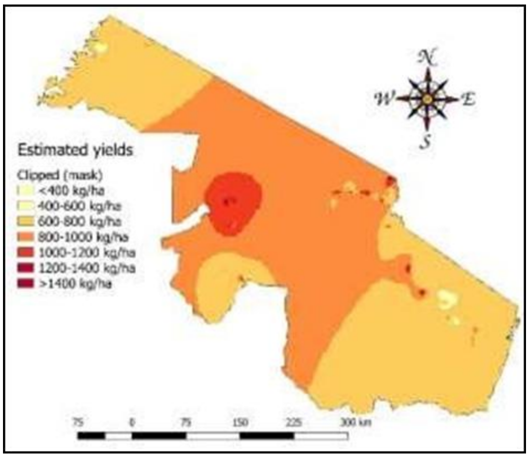

Fig 2c. Estimated yield Zone 1 inorganic

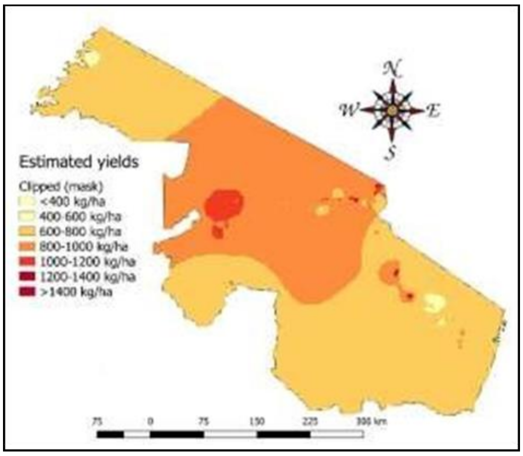

Fig 2d. Estimated yield Zone 1 combination

D. *Interpolation results for Zone 2*

Figure 3a (baseline) shows, as in Zone 1, that about 90% of total land area is moderately fertile and capable of producing 400-600 kg of parchment coffee per ha. Pockets of land in Ludewa (Njombe) and Rungwe (Mbeya), and smaller ones in Songea, Mufindi and Kilolo can produce over 600 kg ha^{-1}. The rest, including parts of Northern Morogoro, Iringa, Njombe and Songwe can produce 200-400 kg ha^{-1}. Figure 3b (organic) shows substantial improvement with about 80% of the land now falling under category 600-800 kg ha^{-1}. The rest, mostly in the 400-600 kg ha^{-1} category, includes most of Northern Morogoro with small patches in Mufindi and Songwe. The last two maps (Figures 3c and d) are visually alike, with the bulk of the land well over 800 kg ha^{-1}. The only difference is a slight increase in extent of higher categories (>1000 kg ha^{-1}) in the combination map.

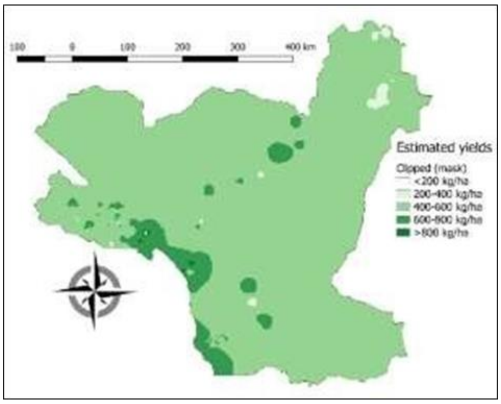

Fig 3a. Estimated yield Zone 2, baseline

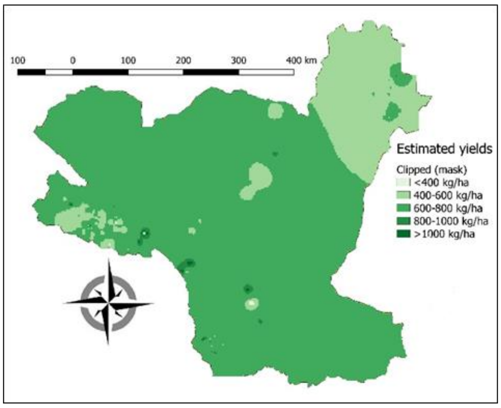

Fig 3b. Estimated yield Zone 2, organic

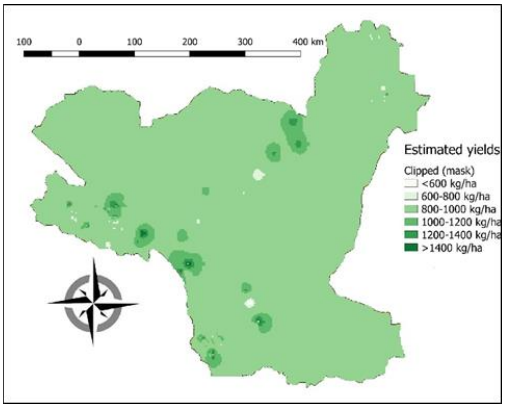

Fig 3c. Estimated yield Zone 2, inorganic.

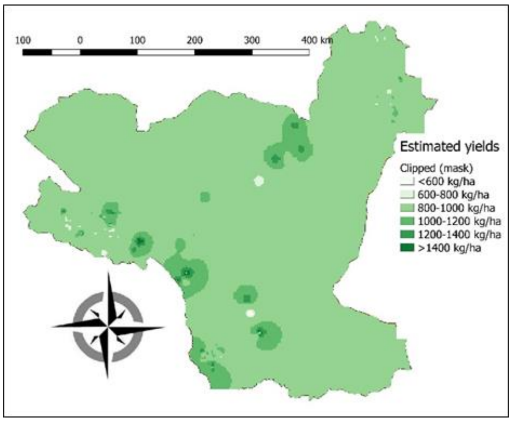

Fig 3d. Estimated yield Zone 2, combination

E. Interpolation results for Zone 3

This zone showed to be the least fertile of the three, capable of producing in the range 100-600 kg ha^{-1} without adding any input (Figure 4a). About 85% of the total land area can produce 200-300 kg ha^{-1}. The north-western end of the country (Bukoba, Missenyi, Muleba and Karagwe) is a little better, producing 300-400 kg ha^{-1}. Some pockets at Kigoma, Uvinza and large part of Mpanda could hardly reach 200 kg ha^{-1}. Upon addition of manure (Figure 4b), substantial improvement is witnessed from a maximum of 600 to 800 kg ha^{-1}, and the minimum from 100 to 200 kg ha^{-1}. Remarkable improvement is shown in Geita, Sengerema and the whole of Kagera river basin (about 30%, producing above 600 kg ha^{-1}). The approximately 70% remaining can produce in the range 400-600 kg ha^{-1}. The last two maps (Figures 4c and d) are visually alike. The only difference is a slight decrease in extent for the higher categories (>800 kg ha^{-1}) for the combination map, especially around Ngara and Biharamulo.

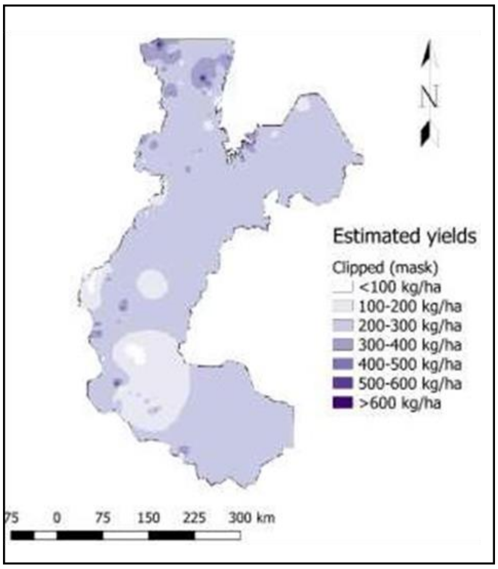

Fig 4a. Estimated yield Zone 3, baseline

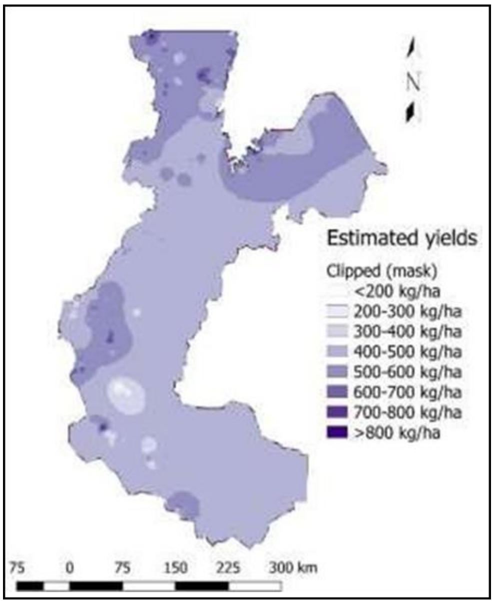

Fig. 4b. Estimated yield Zone 3, organic

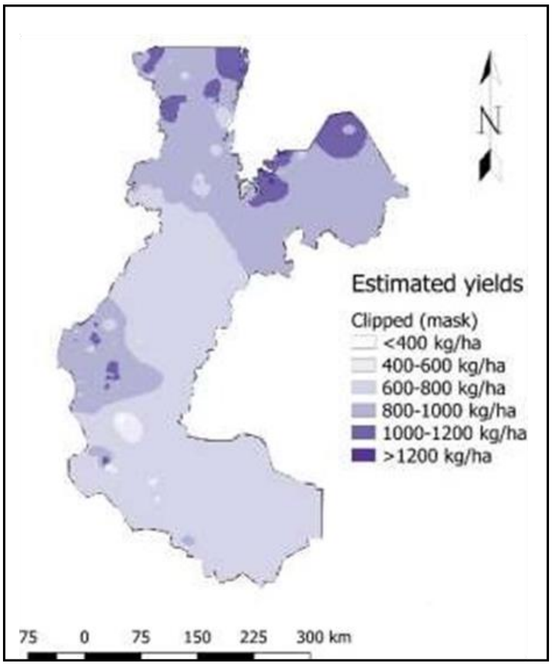

Fig 4c. Estimated yield Zone 3, inorganic

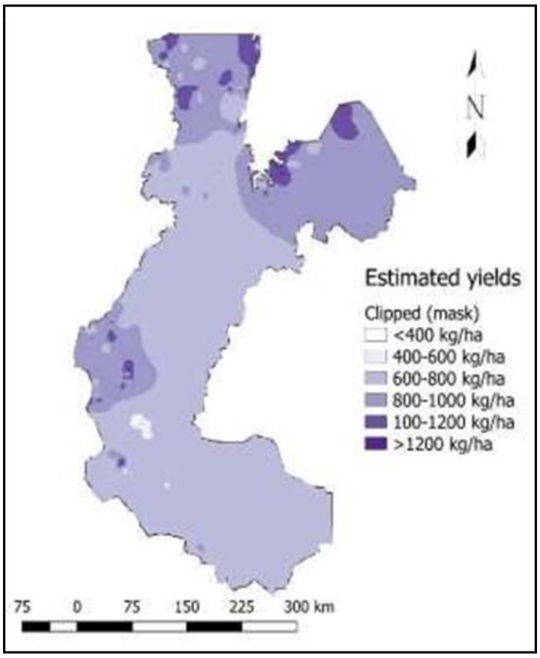

Fig 4d. Estimated yield Zone 3, combination

IV. Discussion

A. Choice of methodology

In Tanzania, coffee is grown in diverse geographical locations (see Figure 1), varying in soil types [14], climatic trends [15] and even management practices. SAFERNAC was developed on basis of plot data from Lyamungu, and then initially tested with a total of 116 georeferenced point data representing two districts in Zone 1 where the model was developed. From [4], the extension of scope to cover a total of 1,131 point data from 44 districts throughout Tanzania, termed spatialization or regionalization, is justified. Another spatialization approach, widely used by agronomists and meteorologists is remote sensing [16]-[17].

The prime purpose of SAFERNAC is to evaluate soil fertility and as such, the consideration of climate and management practices, reflecting what [18] did with GLAM model, and what [19] did with Spatial- EPIC model, was deemed unnecessary in this case.

Estimated parchment yields, in kg ha^{-1}, were descriptively and spatially assessed. The purpose of descriptive assessment was to compare zones in terms of natural soil fertility and response to the application of various inputs. Spatial interpolation, as well described by [20]-[21], was used for purposes of yield trend analysis for the four approaches. The latter uses the sampled points to predict the values at locations where no samples were taken, according to Tobler's Law of Geography. It has been used successfully in many areas such as geology, hydrology [22], environment [23], mining, climatology and meteorology [24]-[25], biology [26], forestry, agriculture [27]-[28], etc. Spatial interpolation uses a variety of methods, and in this case [29] noted that to-date there is no rule of thumb on the most appropriate interpolation technique for certain situations though general suggestions have been published. In this study inverse distance weighting (IDW), one of the most widely used interpolation technique [13] was selected. It was also recommended by [24] as the best algorithm in representing rainfall variability in Annaba, Algeria; and by [26] in showing spatial variability of habitat-forming sessile organisms in the marine ecosystems of Mexico. It was also used successfully by [27] to create maps of potential sugarcane yield distribution within TPC Sugar Estate boundaries using the FAO semi-quantitative land evaluation model [30]-[31].

The interpolated rasters were clipped on basis of administrative boundary shapefiles (regional boundaries) in which the sampled points were not evenly distributed. Sampling had focused on areas currently growing coffee or have any history with coffee, so the unsampled areas either have no history with coffee or were just skipped due to time and budget constraint. According to [21], the number and distribution of sample points can greatly influence the accuracy of spatial interpolation. This provides a point of caution on the use of the above maps, whereby users need to bear in mind that they give only the soil's point of view and do not attempt to answer the question why currently there is coffee here and no coffee there. Places may have suitable soils but because of other limitations such as climate (which was not part of SAFERNAC), they would not be able to support the intended crop.

B. Implication of the results

SAFERNAC has demonstrated its capability to simulate parchment coffee yields in 99.2% of the surveyed sites. This is the fraction that satisfied the model assumptions and pre-conditions. The estimated baseline yield variation per zone is an indication that soil fertility differs as well, following a decreasing trend Zone 2 > Zone 1 > Zone 3. This trend was rather unexpected because Zone 1 is supposed to be more fertile than Zone 2 from the lithological point of view. While Zone 2 is an intersection of the Usagaran-Ubendian systems of the Proterozoic eon with high grade metamorphic rocks (amphibolites and gneisses), most of Zone 1 is composed of more recent volcanic rocks of the Miocene age [32]-[33]. Because the data for Zone 2 were adapted from another project [34] whose objective was not land evaluation per se, some bias in the distribution of survey locations is suspected, and we plan to re-do it in a more holistic manner that will include currently non-coffee areas with potential for new coffee establishment.

The CV trends imply that the variability is high at baseline level (no input), corroborating the heterogeneity observed by [4], [14] as one of the bottlenecks of model spatialization. On the other hand, according to [35], CVs of up to 50% or more are common for many elements in soils when sampling is completely random. The CVs were decreasing variously from the maximum at baseline to the minimum at combination. This trend implies that the variation in soil fertility tends to smoothen up as external inputs are added by way of fertilizers and/or ameliorants. It also suggests a more stable situation with the ISFM combinations. Organic and inorganic nutrient sources are in complementarity. Whereas organic matter improves physical, chemical and biological processes in the soil [36], thereby enhancing root activity, application of inorganic fertilizers supplies energy required by microorganisms for organic matter mineralization [37]. The impact of this complementarity is higher yields, as noted by [38] for maize in Kenya.

C. Comparison with other similar studies

Model spatialization has been attempted by many researchers. Maize yield simulation was successfully done in various agricultural zones of Colombia using the AquaCrop model [39]. A GIS-based Spatial-EPIC model was used by [19] to predict yield variability of maize, wheat and rice at provincial and state level in India, whereby it was demonstrated that all levels, from field to country or beyond, can be modelled for any crop productivity. In their part, [18], assessing the GLAM model with groundnuts across India, noted that the simpler the model is, the easier it will be to spatialize or extend over larger areas. SAFERNAC is simple enough, as it only requires soil properties and NPK fertilizer as inputs. For simplicity sake, plant related variables such as nutrient use efficiency, and management related ones such as plant density were worked out and adopted as default, whereas climatic variables were not considered. This simplicity has contributed to model usability in the coffee growing areas countrywide, with baseline yield effectively estimated in 99.2% of the surveyed sites.

D. Perspectives of crop modelling

Crop models are gaining popularity by the day, as decision support tools [40] and also for guiding research. In the latter case, [41] noted that models can contribute to identify gaps in our knowledge, thus enabling more efficient and targeted research planning. Many crop models are in use; some generic and others crop-specific. Examples of generic models (or model suites) are DSSAT [42], APSIM [43] and QUEFTS [2]; whereas examples of the crop-specific ones are PNUTGRO for peanuts [44], SIMBA for bananas [45], CANEGRO for sugarcane [46] and SAFERNAC for coffee [1]. However, as noted by [18] and [47], crop models are a crude representation of the real world. They are imperfect approximations to interactions between biotic and abiotic factors. In some situations, the uncertainties associated with choices in model structure, model inputs and parameters can exceed the spatiotemporal variability of simulated yields, thus limiting predictability. That's why [41] cautioned users not to consider crop models as a panacea to all agricultural production problems. However, they admitted that an intensely calibrated and evaluated model can be used to effectively conduct research that would eventually save time and money; and significantly contribute to developing sustainable agriculture that meets the world's needs for food.

V. Conclusion

In this work we explored the behavior and usability of a new model called SAFERNAC with the coffee soils across Tanzania. Soil fertility data from three defined coffee growing zones were subjected to the model following baseline (no-input), organic, inorganic and combination approaches. The model was able to estimate baseline yields in 99.2% of the survey locations. The rest did not qualify because they have pH values well beyond the prescribed limitations (pH 4.5 to 7.0). The model showed high sensitivity to pH, which has a greater influence on soil-available P than N or K. Three sites failed in both baseline and organic approaches while six failed in the baseline approach only. In the other approaches, especially those involving inorganic fertilizers, SAFERNAC was generally successful in computing the estimated yields; and this is an indication that the model sensitivity to pH is more to do with P availability and tends to diminish as fertilizer P is added.

In all the approaches, calculated yields decreased in the order Zone 2 > Zone 1 > Zone 3. On the other hand, in all the study zones, estimated yields increased in the order Baseline <<< Organic < Inorganic <= Combination. The application of 5 tons of manure alone made a highly significant impact on yields. The difference in yield between NPK 160:80:80 alone and a combination of NPK 80:40:40 (half dose) plus 5 tons manure was not significant, implying that use of organic matter can reduce the fertilizer cost by about 50% without seriously compromising the expected yields. This was also evident with the maps generated, whereby there was not much visual distinction between the inorganic and combination maps.

The model has therefore proved its usability across the Tanzanian coffee soils, in simulating yield of parchment coffee. The baseline (no input) approach is meant for coffee land evaluation which is of interest to potential investors who are looking for suitable land parcels for opening up new coffee farms. The organic approach is of interest to farmers who wish to indulge in organic farming whereas inorganic approach is for conventional farmers. The integrated soil fertility management (ISFM) approach that involves a combination of organic fertilizers (manures, composts and decomposed coffee by-products) and mineral fertilizers is appropriate for restoration and maintenance of soil health..

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