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Soil-based, field-specific fertilizer recommendations are a pipe-dream☆

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ABSTRACT

Fertilizer recommendations are key for farmers: the investment is relatively large for smallholders and risky with unknown yield responses and variable fertilizer prices. Are agronomists able to provide useful site-specific fertilizer recommendations that reduce these uncertainties? We evaluated the influence of errors introduced due to soil sampling and chemical analysis procedures both within- and among laboratories on fertilizer recommendations. Using what we consider to be conservative estimates of the uncertainty in estimating soil supply of N, P and K in a single composite soil sample, the resulting 90% confidence interval of fertilizer recommendations ranged from 86 to 186, 0–58 and 38–114 kg N, P and K ha^{-1} respectively. The numerous laboratory services and digital applications providing field-specific recommendations appear to promise more accuracy than soil analysis can realistically deliver. We conclude that a field-specific fertilizer recommendation based on a single composite soil sample is indeed a pipe-dream.

1. Introduction

Economic and environmental sustainability is key for future food systems. One of the most important aspects of sustainability of farming systems is the efficient use of nutrients. Ensuring efficient recovery of applied nutrients by crops makes optimal use of scarce resources, while preventing losses from the soil and damage to the environment. Maximum recovery efficiency can be achieved by optimizing amounts of inputs and timing of nutrient applications to plant demand, taking into account nutrient supply from the soil: the ultimate goal of the agronomist. Guidance for fertilizer management is often given according to the '4R' principles of the right type, right amount, right time and at the right place (Johnston and Bruulsema, 2014). Applying N in split applications is a well-known strategy, also in dry smallholder environments (Piha, 1993). Placement of P close to the roots is effective in enhancing crop recovery using precision planters (Aune et al., 2017). In many smallholder farming systems soil P and K supply is limited, causing large spatial variability in crop yields (Njoroge et al., 2017, 2019). Soil fertility is strongly affected by past management of crop residue and application of animal manure (Giller et al., 2011), often preferentially applied on more intensively managed homefields or gardens (Tittonell et al., 2007).

Tools such as Quantitative Evaluation of the Fertility of Tropical Soils QUEFTS (Janssen et al., 1990; Smaling and Janssen, 1993) were developed specifically to harness information on soil chemical properties to predict how nutrient uptake and yield of crops respond to applied fertilizer and nutrient availability in tropical soils. QUEFTS can be used for situations where NPK is limited, but assumes that water or other nutrients are not limiting. QUEFTS has been used both to predict yields and to derive fertilizer recommendations. An adapted version of QUEFTS has been used successfully for site-specific nutrient management (SSNM) of rice where soil nutrient supply was derived from omission plots (Dobermann et al., 2002). This SSNM system was further developed using large numbers of site-based nutrient omission trials and has evolved into a yield-gain approach for N combined with a balance approach for P and K for a determined target yield (Buresh et al., 2010; Sharma et al., 2019). Sattari et al. (2014) concluded that the basic structure of QUEFTS was sound and could be used to predict yields for both temperate and tropical regions, giving confidence in the QUEFTS model. However, the observed variability in between soil characteristics and crop nutrient uptake across locations is large (Njoroge, 2019). Local conditions (Sattari et al., 2014), variable plant stands and differences in crop management are among the causes of these noisy relationships (Tittonell et al., 2008). The influence of errors in soil sampling and laboratory analysis remains unquantified.

Is the concept of site-specific nutrient recommendations based on chemical analysis of soil samples a realistic prospect, or simply a pipe-dream? Here we evaluate the effects of errors and uncertainty in soil

☆ A pipe dream is "an unattainable or fanciful hope or scheme" (Apple Dictionary); "a fantastic, impracticable plan or desire" (Roget's II The New Thesaurus, 3rd Edition); "a fantastic notion likened to a dream produced by opium-smoking" (Shorter Oxford English Dictionary)

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sampling and analysis on predictions of crop yields using QUEFTS and on estimates of required N, P and K fertilizer to reach a target yield. We subsequently analyse how these errors in the amounts of fertilizer to be advised influence expected yields and agronomic efficiencies.

2. Materials and methods

The QUEFTS model (Janssen et al., 1990; Smaling and Janssen, 1993) was used. The model has two major components, with each a set of parameters. The first component describes the relationship between soil- and fertilizer supply and plant uptake for N, P and K. The parameters required by QUEFTS for this component are measured values for soil pH, soil organic carbon (SOC), available P based on Olsen (0.5 M $NaHCO_3$, pH 8.5) extraction and exchangeable K based on a 1 M ammonium acetate extraction. Further, parameters are needed to quantify the recovery of applied fertilizer. The second component of the model relates nutrient uptake to yield. Here, internal use efficiency and minimum and maximum dilution are required parameters. The uncertainty in the uptake-yield relationship is much smaller than the uncertainty in the supply-uptake relationships that depend on parameter values derived from soil sample analysis (Njoroge, 2019). Both soil sampling and the chemical analysis procedures involve error, and these errors are additive.

Sampling error due to field variability can be large on a sub-metre scale with reported sampling standard deviations of up to 40% (Ferrari and Vermeulen, 1955). Within-field variability can be large even in fields with a long history of uniform management: a 30% coefficient of variation was reported for 8 bulked subsamples taken within 20 m quadrats (Singh et al., 2012). In smallholder fields, known for their heterogeneity, a similar variability may be assumed. Here, a conservative approach was taken and we assumed a field sampling error of only 10%, small in comparison to variability found within transects (Morton et al., 2000). Further, errors in measurements of different soil fertility parameters were assumed to be independent, although strong co-variation can be expected, especially for unfertilized fields.

To address the errors in chemical analysis, we used data from the Wageningen Evaluation Programs for Analytical Laboratories (WEPAL, www.wepal.nl). WEPAL runs a well-established proficiency testing procedure for laboratories conducting soil and plant analysis. Sets of well-mixed samples are dispatched to many laboratories for comparison as part of a so-called 'ring-test'. The variability in analytical results obtained among and within accredited laboratories was quantified for key soil characteristics including soil organic carbon and N contents, pH-$H_2$0, plant available contents of P (Olsen extract) and P, K and S (Mehlich-3 extract). For each sample, the mean, standard deviation and the coefficient of variation (CV) were computed for each soil characteristic. The errors due to within-laboratory variability, were quantified with repeated analysis of a single sample (*Sample* 993) in 7 to 11 participating laboratories.

The QUEFTS model was used to compute maize grain yields for nine "soil" scenarios using a standard parameter set (Njoroge, 2019). In each scenario, average soil pH was 5.2 with a soil organic C content of 20 mg kg^{-1}. The scenarios included combinations of average Olsen P values of 5, 10 or 15 mg kg^{-1} and an average of 1, 2 or 5 mmol kg^{-1} exchangeable K. These scenarios are combinations of below-, at- and above-yield response thresholds of 10 mg kg^{-1} for Olsen P and 2 mmol kg^{-1} exchangeable K. Firstly, for the soil parameters pH, SOC, Olsen P and exchangeable K, 5000 values were drawn from a normal distribution. These distributions were based on the reported among-laboratory CVs (Table 1) combined with a fairly modest 10% CV to account for within-field variability. For each soil scenario a set of 2000 input combinations were randomly selected from these distributions and used to compute the soil nutrient supply (see Fig. A.1 for an example) and the advised amounts of fertilizer for a target maize grain yield of 5 t ha^{-1}. The advised amounts of N, P, K fertilizer for a specific set of input combinations where then applied to a another randomly selected set. The agronomic efficiency (AE) for N, P and K (ANE, APE and AKE respectively), for e.g. ANE calculated as ($yield_{NPK}$ - $yield_{PK}$)/N applied, using yields for omission treatments with only NP, NK or PK applied. Calculated yields, agronomic efficiencies and recommended fertilizer applications were sorted, and displayed as cumulative frequencies.

Table 1
Variation in soil analysis results among laboratories for Olsen (Olsen P) or Mehlich-3 (P, K, S) extractions for a large number of samples. Overall means of the average analysis value, standard deviations and coefficient of variation among *n* laboratories. Sample 993 was repeatedly sent to the same laboratories. Data were kindly provided by WEPAL.

		Analysis of many samples by different laboratories				Analysis of Sample 993ǂ		
Element	Unit	*n**	Mean	SD	CV%	*n*	Range CV%	Average CV%
Soil org. C	g/kg	83	26.1	2.22	**9.9**	10	2.2–12.0	**6.2**
pH-H_2O	–	207	6.5	0.24	**3.7**	11	0.5–3.6	**1.9**
Olsen P	mg/kg	82	58.4	14.1	**30.3**	11	2.5–38.5	**18.8**
K	mg/kg	59	7797	403	**7.9**	9	1.3–9.8	**9.2**
N	g/kg	106	2.1	0.17	**10.7**	9	3.3–22.8	**8.6**
P	mg/kg	53	635.1	55	**15.2**	8	5.3–26.0	**13.3**
S	mg/kg	47	876.0	152	**21.9**	7	2.1–25.8	**11.3**

*The number of laboratories that analysed a specific sample differed per test-sample in the ring-test, *n** indicates the total number of analyses per soil characteristic, *n* represents the average number of laboratories per soil characteristic. ǂSample 993 contained 25.2 ± 2.0 g soil organic C kg^{-1} soil, pH of 5.59 ± 0.13, 62.4 ± 23.9 mg P (Olsen) kg^{-1} soil, 55.0 ± 7.3 mg K (Mehlich) kg^{-1} soil, 2.45 ± 0.22 g N kg^{-1} soil, and total amounts of 1097 ± 265 mg P kg^{-1} soil, 7834 ± 472 mg K kg^{-1} soil, 1677.7 ± 669.5 mg S kg^{-1} soil.

3. Results

The overall average CV values for all samples were smallest for pH-$H_2$0 and largest for Olsen P (Table 1).

Samples included both very low and very high contents, where CV% for Olsen P was much larger when soil mass fractions were smaller, typically > 30% for values < 20 mg/kg. This was not the case for soil organic carbon. Surprisingly, the average CV% for sample 993 was only slightly smaller when compared to the among-laboratory CV% for most characteristics (Table 1). The results are anonymous, so we do not know if the smaller CV values were from the same laboratories. However, these results in indicate that errors within certified laboratories can be substantial.

Uncertainty in soil parameters results in a wide range of QUEFTS-estimated soil N, P and K supply and consequently maize grain yield estimates, with larger ranges for scenarios with a larger average soil P and K supply (Fig. A.2). The largest ranges within the 0.1–0.9 probabilities are 28–78, 9–18 and 57–129 kg N, P and K ha^{-1}. For P, the cumulative frequencies of fields either well-below or well-above the critical threshold of 10 mg kg^{-1} actually overlapped. For example, the scenario with a soil containing Olsen P of 5 mg kg^{-1} resulted in a 10% chance of finding a value above the threshold of 10 mg kg^{-1} simply due to the errors in estimation while the 15 mg kg^{-1} scenario gave a 20% chance of finding a value below this threshold (Fig. A.2). For K, differences among scenarios were larger. With no fertilizer applied, the possible yield ranges within the 0.1–0.9 probabilities are also large: ranging from 1600 to 3400 kg ha^{-1} for the control to 5763–6987 kg ha^{-1} for the NPK treatment (Fig. A.3). Such wide ranges in estimated soil N, P and K supply result in a wide range of possible fertilizer recommendations (Fig. 1). The 90% confidence intervals (CI) for fertilizer recommendations are 86–186 kg N ha^{-1} for all scenarios. Scenarios strongly differed for P and K: for soils at critical thresholds (with an Olsen P of 10 mg kg^{-1} and exchangeable K of 2 mmol kg^{-1})

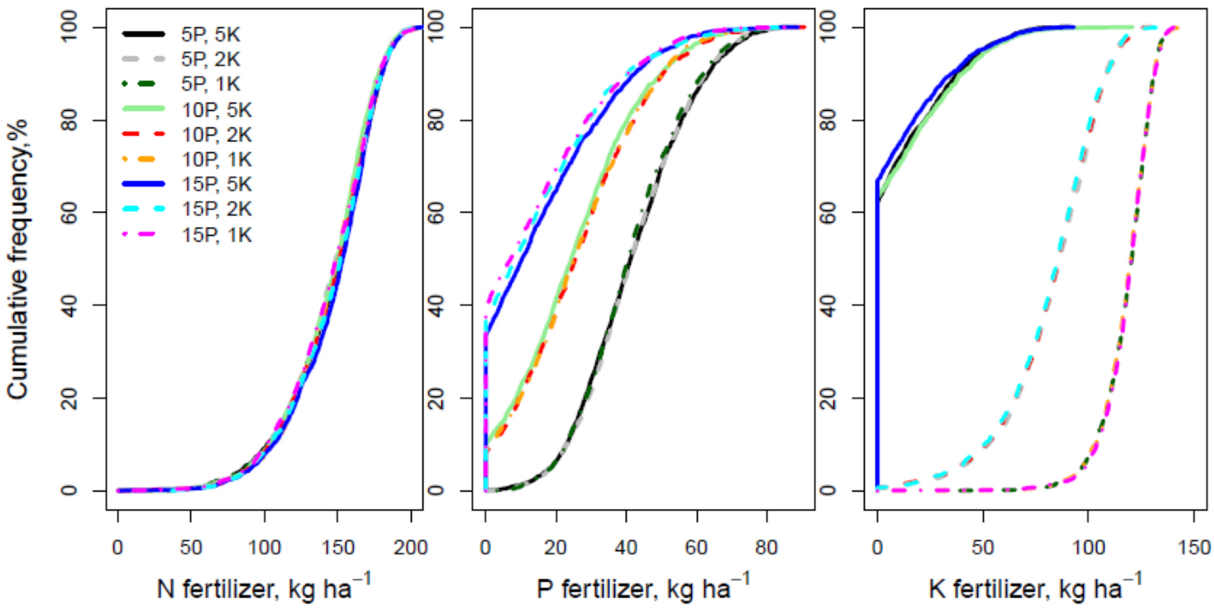

Fig. 1. Cumulative frequencies of the advised amounts of N, P and K fertilizer to reach a target yield of 5000 kg maize grain ha^{-1}. Each line reflects a scenario based on a soil sample with a pH of 5.2, 20 mg C kg^{-1} and 5, 10 and 15 mg Olsen P kg^{-1} combined with 1, 2 or 5 mmol K kg^{-1}, these latter concentrations are shown in the legend. For each scenario, actual parameter values for the model were drawn from a normal distributed range due to combined errors due to soil sampling in the field and to analysis in the laboratory.

these CIs were 0–58 kg P ha^{-1} and 38–114 kg K ha^{-1} and recommendations were more variable than for the least or most fertile soils. For the least fertile soils, the average fertilizer recommendation resulting from QUEFTS is 40 kg P ha^{-1}, but there is also a 10% chance that $<$ 22.5 or $>$ 57.5 kg P ha^{-1} is recommended. On the most fertile soil with 15 mg P kg^{-1}, there is a 50% chance of a recommendation $<$ 10 kg P ha^{-1}, while 20% of farmers will be recommended to apply $>$ 22 kg P ha^{-1}. For soils well above the critical threshold for crop response of 2 mmol kg^{-1} K, where no yield response can be expected, more than 30% of farmers will be advised to apply some K, and about 20% advised to apply more than 20 kg ha^{-1}. The differences in N fertilizer recommendations between scenarios were small as soil N supply depends only on SOC and pH and limitations in soil P and K supply are compensated by P and K fertilizer.

When these recommendations are implemented, maize grain yields vary strongly around the yield target of 5000 kg ha^{-1} with a standard deviation of 622 to 733 kg ha^{-1} for the scenarios with 10 mg P kg^{-1} and 2 mmol K kg^{-1} and 15 mg P kg^{-1} and 5 mmol K kg^{-1} respectively (Fig. 2). Consequently, the expected AEs vary strongly. The ANE for the slightly acidic soil with a pH of 5.2 is around 23–24 kg kg^{-1} (Table A.2) For example, the ANE will be below this expected ANE for more than 90% of fields, with median values around 15 kg kg^{-1}. The lowest values of ANE are found on fields with a very small soil supply of P and K, reflecting an unbalanced N, P and K availability for the crop. The lower than expected median ANE can be understood when considering the chances that P and/or K are limiting. The odds that both P and K are oversupplied in relation to N is only 0.25, the odds that both P and K are limiting are 0.25, while chances are 0.5 that either P or K are limiting. This indicates that P and K should be always be supplied to ensure than ANE is at the desired level. Rather than considering this as a shortage of P and/or K, this can also be seen as oversupply of N on more than 90–97% of the fields. The median of advised N application was

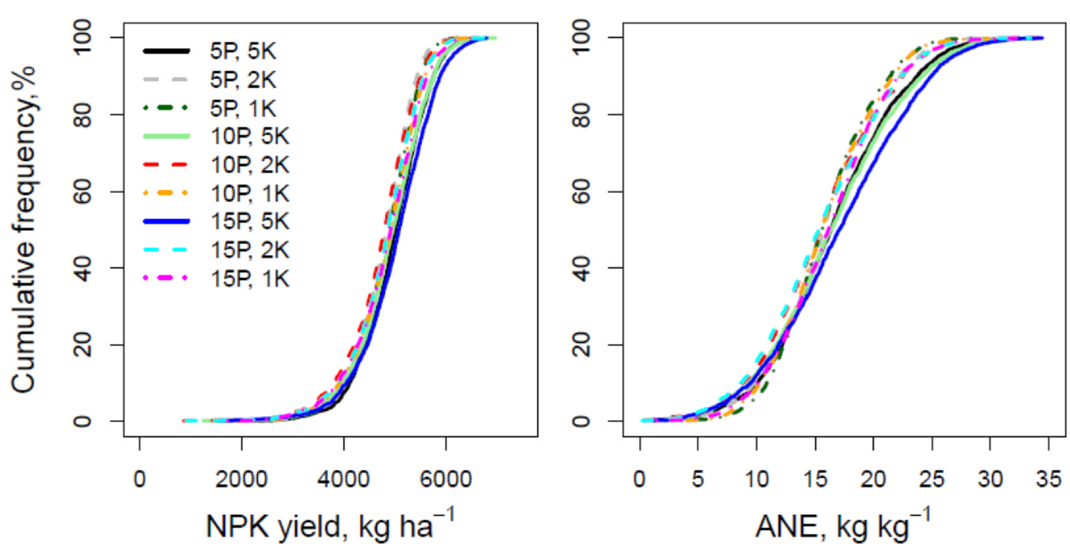

Fig. 2. Cumulative frequencies of the expected yields and agronomic N efficiency when applying site-specific recommendations based on a single soil sample. The differences in AE within a scenario result from errors in soil sampling and soil analysis. See the caption of Fig. 1 for an explanation of the legend.

144 ± 30 kg N ha^{-1} (Fig. 1), with the realised median ANEs of 15.4–16.9 kg kg^{-1} (Fig. 2) this resulted in an average yield gain of 2290 to 2433 kg ha^{-1} when compared to the control without fertilizer. The same average yield gain could have been achieved with 97 to 104 kg N ha^{-1}, if P and K were applied in required amounts and ANEs were 23.5 kg ha^{-1}.

Recommending fertilizer with an optimum N:P:K ratio strongly reduces the error in recommendations to 10–20 kg N ha^{-1} (Table A.2). The ANE of these balanced NPK fertilizer applications predicted using QUEFTS were 23–24 kg kg^{-1} (Table A.2), close to the expected value of 25 kg kg^{-1}.

4. Discussion

The QUEFTS model was developed and evaluated for maize (Smaling and Janssen, 1993) and is a strong tool that captures the major patterns of crop yield response to fertilizer and interactions between N, P and K dependent on inherent soil fertility (Njoroge, 2019; Shehu et al., 2019). The concepts on which QUEFTS is based have been further developed and applied for a wide range of crops including rice (Xu et al., 2015), potato (Kumar et al., 2018), cassava (Ezui et al., 2016) and soybean (Yang et al., 2017). Modern crops have a tightly conserved relationship between yield and nitrogen accumulation (Cassman and Harwood, 1995), even more for P than for N and K (Ciampitti et al., 2013). The functions to convert crop uptake to grain yield used in QUEFTS are well-established for a wide range of crops and provide good insights into interactions among the major nutrients: N, P and K (Jiang et al., 2017). This is further illustrated by an increase in the proportion of explained variation in observed yields from 45 to 87%, when QUEFTS yield predictions were based on measured uptakes in neighbouring plots rather than on estimated uptakes (Njoroge, 2019). The parameters used for these functions are based on many measurements of crop yields and nutrient concentrations, minimising the influence of sampling and analysis errors. By contrast, site-specific fertilizer recommendations are based on a single analysis of a typically-bulked soil sample.

We observed that the variability in results from soil analysis was large, especially for Olsen P with a coefficient of variation of around 30%. Most of this uncertainty was due to differences between repeated analysis at different times in the same laboratory for all characteristics tested, except Olsen P with 19% within- and 30% between-laboratory CV. This variability in soil nutrient analysis results, combined with sampling errors due to within-field variability, translated into a wide range of soil supply estimates when using QUEFTS, which in turn translates to wide ranges in predicted soil supply of N, P and K and therefore in wide ranges in fertilizer recommendations for a specific target yield. When these recommendations are used in the field, a wide range of ANE, APE and AKE can be expected. These agronomic efficiencies are on average much smaller than the values reported for a balanced nutrient supply.

QUEFTS is most sensitive to pH and soil N supply (Smaling and Janssen, 1993). Njoroge et al. (2019) identified that the uncertainty in soil N supply is a major weakness in the QUEFTS approach and suggested to use estimates based on N uptake in control plots, similar to the approach suggested earlier for SSNM with rice (Dobermann et al., 2002; Pasuquin et al., 2014). Deriving soil N supply from soil parameters is particularly difficult as the mineralisation of N from soil organic matter is poorly understood in quantitative terms (Cassman and Harwood, 1995). In QUEFTS, an implicit assumption is made that nutrients are derived from a 0.2 m deep topsoil, with a typical bulk density of 1.35 t m^{-3} (B.H. Janssen, 2014. Personal communication). When P and K are available in abundance in the soil and other factors such as water are not limiting the maximum soil N supply is revealed: control yields can double when PK was applied over a number of seasons (Njoroge, 2019) aligning with observations from long-term experiments (Jate, 2010). Fertilization had a minor effect on N mineralization from soil organic matter in controlled experiments (Cadisch et al., 1994), suggesting that soil stoichiometry is not very important for short-term decomposition, in contrast to sequestration of SOC (Kirkby et al., 2013). This indicates that increased N uptake due to P and K fertilization should be attributed to a larger root length and a larger volume of explored soil (Cadisch et al., 1994; Pasley et al., 2019). Estimates of N mineralization may improve when accounting for fresh organic matter inputs with much higher mineralization rates (Janssen, 2011; Van Dijk, 1982). Yet efforts to predict N mineralization based on laboratory-based isolation of active SOC fractions have yielded disappointing results (Magid et al., 1996). This uncertainty in soil N availability and poorly quantified interactions between plants and soil calls for a plant-based assessment of nutrient availability (Briat et al., 2020).

Many laboratories offer a service based on spectral analysis of soil samples. However, spectral methods are very poor in assessing soil P, K and S availability (Towett et al., 2015), adding even more uncertainty to estimates of soil nutrient supply. Based on wet chemistry, estimates of soil nutrient supply with a probability of 0.1–0.9 ranged from 28 to 78, 9–18 to 57–129 kg ha^{-1} for N, P and K. These ranges are already very wide in relation to the amounts applied on smallholder fields: standard recommendations are about typically 56 kg N ha^{-1} and 25 kg P ha^{-1} increasing nutrient availability for plant uptake with about 28 kg N ha^{-1} and 2.5 kg P ha^{-1}. This provides strong support for the Cate-Nelson approach (Cate Jr. and Nelson, 1971) which recognized that soil analysis can, at best, be used to provide an indication of an increased probability of a yield response to fertilizer application.

The debate around the assessment of plant available soil nutrients has raged for more than a century (Dyer, 1894). Soil tests often fail to accurately quantify the amount of nutrients that are available to plants due to uncertainty resulting from sampling and analytical procedures as shown above, in addition to uncertainty in the bulk density and rooted volume of soil that the roots explore, and the inability of soil tests to accurately mimic the bioavailable fraction of nutrients that a plant takes up as discussed in e.g. Marschner and Rengel (2012). Soil tests do have value in assessing the probability of a response to applied nutrients (Cate Jr. and Nelson, 1971; Sanchez, 2019). The soil pH, SOC and available P and K contents are useful indicators and general proxies of soil health. In particular settings (e.g. soils with homogeneous and consistent management practices, i.e. including a longer history of fertilization with synthetic fertilisers and organic manures, and a well-mixed ploughed layer of e.g. 25–30 cm depth), measures of nutrient intensity may correlate well to nutrient availability for plant uptake and soil tests can be calibrated to predict nutrient uptake, although many caveats exist (Marschner and Rengel, 2012). However, in smallholder settings, nutrient management, soil depth and soil bulk density vary strongly and interpretation of soil tests needs to account for this variability. In such environments, soil tests are useful to determine the desired fertilizer composition for crops within a given region, though recognising the need to tailor balanced nutrition to specific management, for example, fertile homefields that received animal manure in the past and infertile outfields that were not manured (Njoroge et al., 2019; Zingore et al., 2007b).

Future nutrient management may benefit from the assessment of the amount of biomass that a field supports, primarily as a proxy of soil fertility. This is most useful in strongly variable landscapes where field fertility strongly varies on short distances (Njoroge et al., 2017). Unfortunately, despite the current focus of soil research on digital soil mapping, spectroscopic methods for measuring soil nutrient status suffer from many of the same problems as wet chemistry. A recent ring test of pH and SOC contents of a standard sample revealed a huge variation in analytical results among laboratories using spectroscopic methods, which appeared to be due to differences in equipment used and a lack of standardization of calibration procedures (Steering Committee on Soil Spectroscopy, 2020). This is particularly worrying given that pH and SOC are among the soil fertility indicators best predicted using spectrometry (Towett et al., 2015).

Soil fertility gradients have been described in many smallholder systems (Giller et al., 2006), on a range of soils including poor sands (Zingore et al., 2007a), and clay-rich soils (Tittonell et al., 2013). Many have suggested that these generic patterns of fertility, linked to farmer endowment, need to be accounted for when applying fertilizer (Tittonell et al., 2013, 2010; Vanlauwe et al., 2007). Random soil sampling of SOC across a smallholder village in Zimbabwe failed to reveal soil fertility gradients observed by local farmers (Van Apeldoorn et al., 2014). In recent work, it was found that soil fertility of fertilized fields did not differ among resource endowment groups (Jindo et al., 2020) and did not show a clear relationship with distance to the homestead. Although it is difficult to map relevant fertility gradients and to develop generic rules to differentiate fertile homefields from less fertile outfields, when heterogeneity in soil fertility and crop growth is present, it is readily recognized by the farmers themselves (Giller et al., 2011; Tittonell and Giller, 2013). Adjusting fertilizer amendments to specific fields requires local knowledge of past management and its effects on current soil fertility. Fine-tuning to specific fields is therefore best left to farmers.

5. Conclusions

We conclude that site-specific fertilizer recommendations based on a single soil sample is indeed a holy grail that will remain elusive – a pipe-dream! Errors due from soil sampling and analysis methods result in inaccurate estimates of soil nutrient supply, yet these are needed to tailor fertilizer recommendations to individual fields. Our analysis shows that errors due to soil sampling and soil analysis have a strong effect on the estimated P and K supply, at least as large as the variation found among smallholder fields of poor or good soil fertility status within a given region. The resulting errors in recommendations generate a strongly reduced average agronomic efficiency of N, P and K with large differences between fields. We conclude that soil analysis at best can suggest the increased probability of a yield response to fertilizer applications below a critical threshold - as indicated using the Cate-Nelson approach (Cate Jr. and Nelson, 1971).

Second, although we found that QUEFTS concepts are valid, a large uncertainty exists in estimates of soil N supply when based on SOC and pH measurements. Hence, the best indicator of local soil N supply may indeed be derived from plant uptake (Njoroge, 2019) or from yields in previous seasons, aligning with the SSNM approach of Dobermann et al. (2002) and Buresh et al. (2010). This suggests also that information about past management and observed yields is more informative than soil analysis.

Another important outcome of our analysis is the strong impact of soil P and K availability on the agronomic use efficiency of N. Application of N, P and K in balanced ratios dampens the variability in agronomic use efficiency of N enormously. In absence of reliable and cheap methods to differentiate between sufficient and insufficient soil P and K supply, nutrients are best supplied in reasonable proportions on all fields. These reasonable proportions can be determined at a larger scale, but should be sufficient to compensate P and K offtake. The utility of tools such as QUEFTS is more at (sub-)regional scale to determine the appropriate balanced ratios which should be recommended for a combined application of NPK in composite fertilisers and blends. This can be done with confidence when soil assessments are based on many samples which average out sampling and laboratory errors. For example, in regions with a large native soil K or P pool, or a long history of P and K fertilizer use, NPK fertilizers containing proportionally less P or K should be advised (Pasuquin et al., 2014). Farmers may be able to adjust generic regional recommendations by accounting for long-term historical manure or P fertilizer use that has affected soil nutrient pools (Njoroge et al., 2019). A practical solution is to work with a simple printed table with example NPK(S) fertilization rates needed per ton of required yield increments for the area of interest, based on nutrient offtakes and use of animal manure. To avoid the risk of less-economic or excess application of fertilizers, the quantities of fertilizer to be recommended should target about 50–60% but not exceeding 80% of water limited yield potentials (Lobell et al., 2009) to limit environmental impacts. In practice, the amounts of fertilizer that farmers will apply will depend on their capacity to invest in relation to their (perceived) risk of a profitable crop response. In other words, agronomists can use tools such as QUEFTS to tailor fertilizers at the regional scale while the farmer can use her/his knowledge to best tailor to the individual field.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2020.114680.

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