We thank Bouma (2020) and Ros et al. (2020) for their thoughtful comments on our paper. Both letters express a concern that our conclusion, “Soil-based, field-specific fertilizer recommendations are a pipe-dream” is harsh. They further express doubts as to whether our analysis supports such a conclusion. Bouma expresses a concern that our paper directs a hundred years of research in the dustbin. The key issues they raise are as follows: 1) Both letters provide a short description of how critical thresholds are typically identified where crops will respond to a specific nutrient addition within a specific setting, i.e. thresholds are calibrated to crop types and regional conditions. 2) Authors of both letters strongly doubt that a regional and model-based approach combined with farmer experience will result in more reliable and sustainable recommendations than traditional recommendation systems. 3) Bouma highlights that we ignored differences in soil types and find this a weakness of the study. 4) Ros et al. are of the opinion that using the error propagation was based on QUEFTS, a model that was originally developed for tropical soils (Janssen et al., 1990) but has also been used for countries in other climate zones, e.g. China (Jiang et al., 2017; Liu et al., 2006). Our approach provides a quantitative error analysis. Poor accuracy of soil tests in, e.g., the Dutch fertilizer recommendation system appear to be accurate, yet this is a false accuracy as the variability between trials is large and a differentiation up to 20 kg K₂O per hectare is certainly not substantiated by the evidence provided (Ehlert et al., 1998).

Further, our analysis is based on the idea that soil analysis is used for fertilizer recommendations for a single crop, not for recommendations for a rotation or for a soil. Fertilizer recommendation systems can be focused on either fertilizing the soil or fertilizing the crop. Fertilizing the soil aims at building and maintaining soil P and K pools that are large enough to feed the crop. Fertilizing the crop focuses on crop growth and yield responses where building soil pools is a welcome side-effect but not the primary objective. In many smallholder systems, soil nutrient pools are strongly depleted and will not approach sufficiency levels in the near future. Especially building plant-available soil P pools to satisfactory levels requires large investments over many years, which is beyond the reach of many smallholders, and is nigh-on impossible in strongly weathered tropical soils with a very large P sorption capacity. In such systems, strategies should aim to fertilize the crop rather than the soil, combining a corrective application with banded or placed P applications (Sanchez, 2019). One of the key findings of our work is that application of balanced fertilizers including N, P and K in ratios of about 1:0.41:0.67 strongly reduces the influence of the size of soil nutrient pools on yield responses to applied fertilizers and reduces between-field variability. This reduction in between-field variability is also observed in on-farm experiments: Njoroge et al. (2019) found that variation between fields that were fertilized with NPK was about 50% less that fields that received NP, NK or PK.

1. Our analysis highlights that a single analysis of a pooled soil sample results in outcomes with a large uncertainty. Fertilizer recommendations are based on a single soil analysis in most commonly-used systems. The uncertainty from laboratory analysis will therefore also propagate into the recommendations made. We agree with Ros et al. that a calibration of relative measures to system-specific conditions is a key component of any recommendation system. For example, the 10 mg kg⁻¹ threshold for Olsen P that we used may vary between soil types and crops, due to differences in mycorrhizal

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* Corresponding author.
E-mail address: tom.schut@wur.nl (A.G.T. Schut).

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symbiosis and/or extent of rooting systems and length of cropping seasons. But this does not address the uncertainty in assessment as to whether a particular field is at or below the threshold and the amount of nutrients a soil can supply. Therefore, field specific recommendations are, also in these recommendation systems, probably acceptable on average but not accurate for any individual field.

2. The influence of error is present in all recommendation systems. The use of QUEFTS allowed to quantify the influence of uncertainty on the prediction of soil N, P and K supply and therefore on site-specific N, P and K fertilizer recommendations. The error of prediction is unknown in most traditional fertilizer recommendation systems, i.e. the recommendation is based on a prediction of soil nutrient supply, nutrient recovery from fertilizers and expected crop demand. All three components vary from year to year, which makes it difficult to evaluate the accuracy of field specific recommendations. In one of the few analysis of errors in fertilizer recommendations based on soil tests, Fryer et al. (2019b) concluded that “…Mehlich-3 extractable P and K in Arkansas accurately predicted the correct crop response to fertilization at 38–50% of the site-years for P and 60–78% of the site-years for K”. The most common error was a false-negative result: the lowest accuracy occurred at site-years where P, K, or P and K were recommended, while fewest errors were observed when P and K fertilizer was not recommended. The results from Fryer et al. (2019b) suggest that Mehlich-3 extractable K from oven-dried soil can predict with reasonable accuracy where K fertilizer is needed to maximize agronomic yield, but is a poor predictor of the optimal fertilizer-K rate that is needed. Response predictions for flooded rice were even poorer and only accurate for 40% for soil test P and K (Fryer et al., 2019a).

3. We agree with Bouma that soil types strongly differ in a wide range of properties that affect yields and the influence of soil type on water-limited yields is strong. However, under good agronomic practices, which include placement of basal fertilizers and top-dressing with N in split applications, the differences between soil types in agronomic efficiency (AE) are minor when moderate amounts of fertilizer are applied and target yields are well below the yield potential in a given field. The differences in AE between fields in a region are therefore not strongly influenced by soil type, and soil tests for a particular nutrient are not related to responses to that nutrient (Maman et al., 2018). Further, Njoroge et al. (2019) observed that past management was more important than soil texture in explaining differences in yield among fields. These somewhat surprising results can be understood when considering that yields are, in general, limited by N and P and occasionally K in many smallholder systems. Under good agronomic management, the N input is adapted to crop demand. AE is, therefore, largely determined by the supply of P and K in the soil: high AEs for N are only possible when P and K are abundantly available. Differences in P recovery among soils are strongly reduced by P fertilizer placement close to the crop roots. Placed fertilizer eliminates the strong pH influence on P availability and circumvents strong soil P retention by sesquioxides in the soil, by creating local pockets of P-saturated soils where P is available for plant uptake (van der Eijk et al., 2006). Soils with strong P retention create a smaller volume of P saturated soil but with higher concentrations and “apparently these opposing tendencies caused that the crop response to incorporated P was not affected by the soil’s P retention capacity.” (Van der Eijk et al., 2006). However, the differences in uptake from soil P and K stocks remain when P is applied in moderate amounts, as plant demand is not fully met.

4. We acknowledge that within-laboratory variability is smaller than between-laboratory variability. We have tested a situation where a sample was sent to any certified laboratory that is part of the Wageningen Evaluation Programs for Analytical Laboratories (WEPAL, www.wepal.nl) ring test. In our view, this is the most honest test as internal quality standards of laboratories are unknown to users. A user is therefore unaware whether a particular laboratory is better than others: there is no comparable certificate or objective quality standard available. Many laboratories have a national or ISO certification that indicate if proper procedures are followed for e.g. sample preparation, yet they do not evaluate the accuracy or reproducibility of results (Hartmann and Suvannag, 2018). This requires proficiency tests or ring-tests. Outcomes of the WEPAL ring tests are anonymous and only known by the laboratory. Further, a high repeatability of analytic procedures alone is not sufficient, also the bias and differences between a specific laboratory and the laboratory that was used to determine the critical thresholds used are important. In our analysis, we assumed that the threshold value is known precisely while also this value has a range due to variability in the underlying field experiments, soil sampling procedures, and laboratory errors.
5. Spectral analysis or proximal soil sensing (Molin and Tavares, 2019) provide ample opportunities to reduce costs of analytical procedures and can also be used to repeatedly measure in the field, substantially reducing the field sampling error. A lower cost for analyses provides options to change the standard sampling procedure where a single sub-sample of a pooled sample is analysed, to one where multiple samples from each field are taken and analysed. Further proximal sensing is most promising in reduction of field sampling errors. We increasingly see promises being made of proximal soil sensors that can scan the soil and be used to provide a fertilizer recommendation (van Beek, 2019). While this may be a good marketing strategy for consultants and companies selling advisory services, these promises are not supported by the peer-reviewed literature (Holmes et al., 2019; Fatzold et al., 2020). The spectral reflectance or transmission signature is specific for organic matter content, clay mineral content, metal-OH bonds or first-second or third overtones of OH, SO₄ or CO₃ groups and CO₂ and H₂O bonds in molecules (Stenberg et al., 2010). The good accuracy of predictions of soil texture, pH, organic matter and N contents with soil spectra can be fully understood. But it is often overlooked that the spectral reflectance or transmission signal is not specific for soil P or K content: estimates rely on autocorrelations, e.g. between P and K and organic matter and clay content, amongst others (Molin and Tavares, 2019). Organic material in plants or soil, but also in animal manures, have a rather narrow range of macronutrient content with rather stable N:P:K ratios. However, when fertilizer is applied, these ratios are no longer in tune with soil nutrients and autocorrelations are broken. Predictability of Olsen P and exchangeable K contents of soils using spectral methods is poor and includes a large prediction error (Towett et al., 2015). These two soil chemical parameters are most important for fine-tuning fertilizer recommendations, as N fertilizer is nearly always needed. Other techniques that are specific for P and K atoms, such X-ray fluorescence or laser induced breakdown spectroscopy (Lu et al., 2013), are not yet sensitive enough or limited to bench-top applications (Molin and Tavares, 2019) and measure only total, not available concentrations. Further, soil N supply strongly varies with seasonal conditions and soil N supply cannot be predicted from soil analysis, even in regions with a long history of synthetic fertilizer use. So despite the promises of soil proximal sensing and its ability to provide cheap in situ soil measurements, in our opinion the currently available in situ sensors will not improve P and K fertilizer recommendations.

Our findings highlight the need to acknowledge and report on the influence of error in laboratory procedures for analysis of nutrient contents, especially under nutrient-limiting concentrations that frequently occur in smallholder environments. Rigorous ring-testing procedures with transparent outcomes are key, such as those developed by WEPAL, aligning with current Global Soil Laboratory Network initiatives (Hartmann and Svunnang, 2018). Further, strict protocols for calibration and testing of novel scanners and sensors that are used in the field need to be developed. In our opinion, tests must include fields with and without N, P and K fertilizers in various ratios to test the validity of predictions, especially where strong autocorrelations between soil characteristics and nutrient concentrations can be expected. We urge laboratories to report on the accuracy of soil nutrient content predictions on independent sites, including predictions of plant nutrient uptake for unfertilized fields and nutrient omission plots.

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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