Research Findings

SoilCares mobile lab in action. Photo by SoilCares.

Soil Fertility Status and NPK Blends at Planting for Maize Growing in the Western Kenyan Counties Uasin Gishu and Busia

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Abstract

Crop production on smallholder agricultural land must increase considerably if the growing world population is to be fed. To achieve this, affordable soil testing methods, fertilizer recommendations and the accessibility of optimal fertilizers containing the required nutrients are required. The SoilCares mobile laboratory offers affordable soil testing using infrared spectroscopy and slightly modified Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) for fertilizer recommendations (through the use of blends) to smallholders. SoilCares soil testing results from 2,107 samples from Uasin Gishu and Busia counties in Kenya were analyzed using archetype analysis and QUEFTS to derive: i) more accurate soil fertility classification; and ii) to optimize the formulation of NPK planting blends for maize. The study showed that eight soil archetypes could be distinguished of which four

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were dominant. Additionally, four fertilizer-blend archetypes were distinguishable for all counties which comply reasonably well with the NPK fertilization at planting necessary for 5 t ha^{-1} maize production. These blends are 12:25:0, 6:22:14, 0:40:0, and 13:33:0 (N-P_2O_5-K_2O). Median relative difference between the advised and optimally needed N, P_2O_5 and K_2O application rates at planting were 36, -10 and 0 %, respectively. The method described, including mapping, may be useful in assisting decision-making by the fertilizer industry, traders and policymakers on the production and availability of crop or region specific NPK blends.

Introduction

In order to feed a fast-growing world population ways must be found to increase crop yields, particularly for smallholder farmers in developing countries (FAO, 2009). Many of these smallholders are confronted with an enormous yield gap in crop production, i.e. a difference between potential yield and actual yield. The key factors in determining this potential yield difference are soil nutrient management and soil fertility status (Licker *et al.*, 2010). Nitrogen (N), phosphorus (P) and potassium (K) are macronutrients that play a major role in plant growth and crop yields (Marschner, 2012). In smallholder farming systems, export of N, P and K from fields and farms often exceeds input via e.g. fertilizers. Such negative N, P, K balance sheets lead to a gradual and unsurmountable decrease in N, P and K soil fertility status (Roy, 2003; Smaling, 1993). Restoration of soil fertility status and the provision of crop specific N, P and K recommendations are prerequisites to increase crop yields. Closing the yield gap must therefore begin with precise and affordable soil testing, followed up with the development of fertilizer recommendations, and making such fertilizers accessible to farmers. Shepherd *et al.* (2007) have shown that infrared technology can be used for soil testing. It is an indirect method that requires calibration and validation studies. However, when this is achieved, the method gives precise results and it then becomes a promising and cheap tool for routine soil testing for smallholders.

The QUEFTS fertilization model (Quantitative Evaluation of the Fertility of Tropical Soils, Janssen *et al.*, 1990) has been developed for N, P and K fertilization of maize in Kenya. It calculates the optimal nutrient rates taking into account the measured fertility status of the soil, interactions between soil pH and N-, P-, K-supply, fertilizer nutrient efficiency, and the (desired) yield level. The QUEFTS model has also been applied and tested for the other main staple crops throughout the world (Sattari *et al.*, 2014).

The accessibility of organic and mineral fertilizers to smallholders is often limited even though long-term fertilizer subsidy programmes have been set up in many African countries to promote fertilizer use. Additionally, the repeated use of e.g. urea and (ammonium) N and P containing fertilizers has led to soil acidification, decrease of K status and low use efficiency of N or P, or both of these nutrients. The major reason for these side-effects is that nutrient application is not tuned to the specifically measured soil nutrient status and crop nutrient demand for optimal production.

Negative side effects of blanket fertilizer recommendations are well known, and prescribed blends cannot be applied before: i) the actual and specific soil nutrient status in different regions/countries has been identified; ii) the recommended N, P and K rates for optimal crop production are calculated; and iii) techniques have been established to optimize a limited number of appropriate NPK blends. In this context, 'appropriate' implies that deviations from actual demand are acceptable.

Archetypal analysis is an empirical, data-driven classification algorithm yielding a few typical and representative combinations of the underlying multivariate data set (Cutler and Breiman, 1994). These typical combinations are called archetypes. Once archetypes are established, any new instance represented by the underlying data set can be classified to one archetype. Archetypal analysis has been used in economics (Porzio *et al.*, 2008) and can also be used to classify soil or fertilizer blend archetypes. This is the basis for optimizing appropriate NPK fertilizer blends.

During the first three months of 2014, SoilCares analyzed 2,107 soil samples from agricultural land from the two Western Kenyan counties, Uasin Gishu and Busia (Fig. 1). The goal of the work reported in this paper was to determine for these counties:

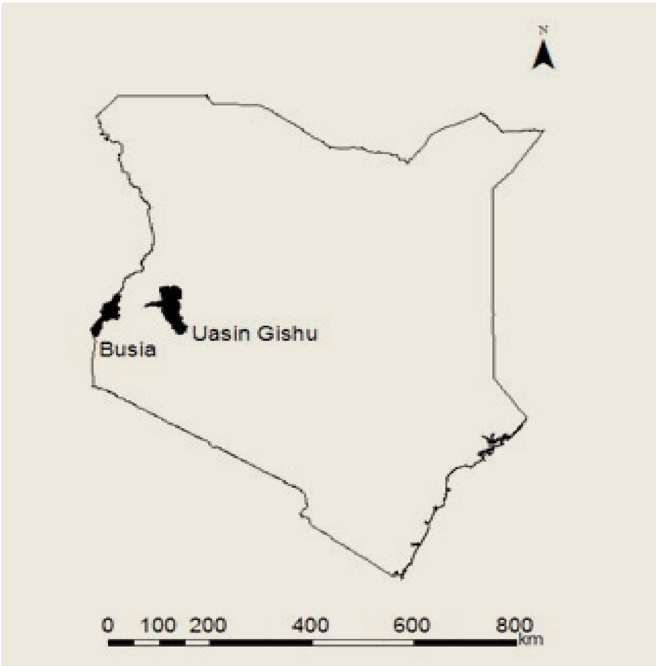

Fig. 1. Location of the two Western Kenyan counties, Uasin Gishu and Busia.

- archetypes of soil fertility status
- archetypes of NPK blends to apply at planting for maize

Materials and methods

The field study was carried out in the two Western Kenyan counties, Uasin Gishu and Busia (Fig. 1).

Soil sampling was carried out by the smallholders themselves. They were provided with an auger, sample bag, registration form, and top soil (0-20 cm) sampling protocol. Mandatory information was inter alia the spatial origin of the soil sample and crop type to be planted. Spatial origin of a sample was defined by sub-location (level 5 of Kenya from the Global Administrative Areas version 2 database). There were 117 sub-locations in total in the Uasin Gishu and Busia counties.

In total, 2,107 soil samples were collected and handed over to the SoilCares Mobile soil testing laboratory (Fig. 2). After receipt, the (moist) soil samples were crushed and sub-sampled using a combined grinder/sub-sampler device. The sub-sample was dried with a forced air flow for about 1 hour at 40^{o}C until dry. Subsequently, the dried samples were crushed, sieved to 2mm, and subdivided to obtain a representative 15 ml sub-sample. This sub-sample was finely ground using a ball-mill followed by determination of the diffuse reflection mid-infrared spectrum. Spectra were analyzed and soil testing data were derived using the SoilCares calibration set for Kenyan soils. Data flows in the system were continuously checked to internal quality standards, and soil testing data were only released when checks were passed. Data presented are Organic Carbon (Org C), Total Nitrogen (Tot N), acidity (pH-$CaCl_2$), phosphorus stock (P stock), exchangeable calcium (exch. Ca), magnesium (exch. Mg) and potassium (exch. K), and contents of clay and sand (Table 1).

Fig. 2. SoilCares mobile soil testing laboratory.

The QUEFTS model (Janssen *et al.*, 1990), including modifications (Sattari *et al.*, 2014) was used to carry out scenario studies to calculate: i) the potential N, P and K supply from soil; ii) the N, P and K demand of different yield levels; and iii) the remaining fertilizer nutrient demand.

Scenario calculations were made for two maize yield levels (2 and 5 t ha^{-1}) and two levels of nutrient recovery fractions of applied fertilizer (normal and high). It was assumed that 22 kg N, 3.7 kg P, and 14.6 kg K need to be taken up by maize plants to produce 1 t of maize grains. If the necessary nutrients could not be supplied by the soil, the remaining nutrients were assumed to be applied by fertilizer (expressed as kg ha^{-1}). Calculated amounts of fertilizer nutrients were converted to N, P_2O_5 and K_2O for ease of comparison to blend compositions. For the two yield levels, at the normal level, it was assumed that fertilizer nutrient recovery by the crop was 50% of applied N, 10% of applied P, and 50% of applied K, whereas at the higher level it was 50% of applied N, 20% of applied P, and 75% of applied K. For fertilizer advice, calculations of soil pH values below 4.9 were set to 4.9 - assuming that lime was applied by the farmer prior to fertilization. This was done in order to exclude the effects of strongly acidic soils on nutrient supply and fertilizer use efficiency. In relation to calculations of potential soil nutrient supply, soil pH values determined in water were increased by 0.3 pH units above the original 0.01M $CaCl_2$ pH values.

Archetypal analysis was done using the archetype-package (Eugster & Leisch, 2009) within the R statistical environment (R core team, 2013). Input data were scaled (mean centred and divided by their standard deviation) before use. All named soil property data were taken as input for soil archetypal analysis. After the model building phase, each of the 2,107 soil samples was classified to one of the soil archetypes. Blend archetypes were calculated for the basal fertilizer application of 5 t yield aim and normal recovery fraction of applied fertilizer only; 30% of the total N rate was subtracted for the top-dressing application. Prior to blend archetypal analysis, the calculated amounts of N, P_2O_5 and K_2O (kg ha^{-1}) were converted to the blend ratios used for the blended products (e.g. NPK 16:23:7) subject to the assumption that the sum of N, P_2O_5 and K_2O should not exceed 46% in the blend (when urea is the leading N product with the highest nutrient content, any addition of other fertilizer will dilute the total nutrient content in the blend). After the model building phase, each of the 2,107 soil samples was classified to one of the blend archetypes. To assess the impact of not using the optimal nutrient rate but the selected archetype blend, for N, P_2O_5 and K_2O we calculated: i) the absolute nutrient residuals (fertilizer - plant need at planting); and ii) the relative nutrient residuals (absolute residuals $plant^{-1}$

Table 1. Soil characteristics (median and range) of the total dataset and for Uasin Gishu and Busia counties separately.

Soil characteristic	Unit	Total (n=2,107)		Busia (n=1,139)		Uasin-Gishu (n=968)	
		Median	Range	Median	Range	Median	Range
Organic C	g kg^{-1}	17	4-87	13	4-87	21	5-68
Total N	g kg^{-1}	1.5	0.3-4.9	1.2	0.3-4.5	1.9	0.5-4.9
Exch. Ca	mmol+ kg^{-1}	27	0-269	17	0-269	28	0-269
Exch. Mg	mmol+ kg^{-1}	13	0-63	12	0-63	15	2-63
Exch. K	mmol+ kg^{-1}	3.4	0-9.2	2.5	0-9.2	4.5	0.7-9.2
pH		4.9	4.0-6.6	4.9	4.0-6.6	4.8	4.1-6.0
Clay	g kg^{-1}	510	10-820	420	10-780	580	40-820
Sand	g kg^{-1}	300	70-840	340	70-840	270	70-820
P stocks	mmol P kg^{-1}	5	1-23	5	1-23	6	1-20

Table 2. Soil characteristics of each of 8 archetypes distinguished in the Uasin Gishu and Busia data set (n=2,107), division of soil samples over the 8 soil archetypes, and the number of sub-locations where a specific soil archetype is most common.

Soil characteristic	Archetypes							
	1	2	3	4	5	6	7	8
Organic C	8	73	11	6	22	28	7	27
Total N	0.7	4.3	0.8	0.5	2.1	1.3	1.0	2.6
Exch. Ca	34	157	0	12	26	231	18	8
Exch. Mg	14	36	4	6	18	56	5	8
Exch. K	1.7	8.7	0.5	2.0	5.1	5.9	1.0	5.1
pH $CaCl_2$	5.3	5.3	4.2	5.7	5.0	5.8	5.0	4.2
Clay	280	530	110	50	670	460	560	680
Sand	370	280	720	820	240	190	140	170
P stock	14	19	1	3	2	13	4	10
Number of soil samples classified to archetype	64	39	264	312	557	95	411	365
Number of sub-locations classified mainly to soil archetype	3	1	6	15	29	6	32	25

need at planting*100). Fertilizer nutrient recovery fraction was also taken into account. Knowing the N, P and K plant demand to provide 5 t of maize yield, the application rate (kg ha^{-1}) of the NPK blend was optimized. This was achieved by minimizing the sum of the N, P_2O_5 and K_2O absolute residuals over the range of possible nutrient application rates.

Geographical representations of the results were obtained using ArcGIS software.

Results

Soil

In total, 1,139 and 968 samples originated from Busia and Ushia Gishu counties, respectively. Table 1 provides a summary of the soil test values obtained.

The range within the soil characteristics measured was huge but seemed to be comparable for the sub-locations of Busia and Uasin Gishu counties. Nevertheless, soils in Uasin Gishu seemed to be more fertile, because median values for contents of Org C, Tot N, clay and exch. Ca, Mg and K were higher at a comparable pH value.

When archetypal analysis was applied to the whole soil data set, 8 different soil archetypes could be distinguished. Table 2 shows the soil characteristics per archetype. In most cases, 2 to 6 soil characteristics are decisive in differentiating between 2 archetypes. For example, archetype 5 has a lower Org C content, Tot N and exch. Ca, Mg and K as compared to archetype 7. The pH of these archetypes are the same.

When the 2,107 soil samples were classified according to the archetypes, fewer than 100 samples were classified to each of the soil archetypes 1, 2 and 6. Between 200 and 400 samples were classified to each of the soil archetypes 3, 4 and 8, and more than 400 samples to each of the soil archetypes 5 and 7.

The maps in Fig. 3 illustrate that in the sub-locations of the two counties, soil archetypes 3, 4, 6 and 7 were mainly present in Busia, whereas soil archetypes 5 and 8 were predominant in Uasin Gishu. Only 12% of the 117 sub-locations had only one soil archetype. In the other sub-locations, 2-7 archetypes were present. The distribution was as follows: 23% had 2 archetypes, 26% had 3 archetypes, 20% had 4 archetypes, 14% had 5 archetypes, 4% had 6 archetypes and 1% of sub-locations had 7 soil archetypes.

QUEFTS scenario studies

Fig. 4 and Table 3 present the result of the QUEFTS scenario studies in which the effect of maize yield level and P and K fertilizer efficiency on total N, P_2O_5 and K_2O fertilizer application rate were simulated for each of the 8 soil archetypes.

It is clearly visible that samples belonging to one soil archetype are restricted to a specific location in the three dimensional representation of the nutrient application rates. Nevertheless, there is an overlap between different soil archetypes. Yield levels and rates of nutrient recovery have a strong influence on recommended amounts of nutrients. For example, high nutrient use efficiency at yield level 5 t ha^{-1} (Fig. 4d) showed reduced total

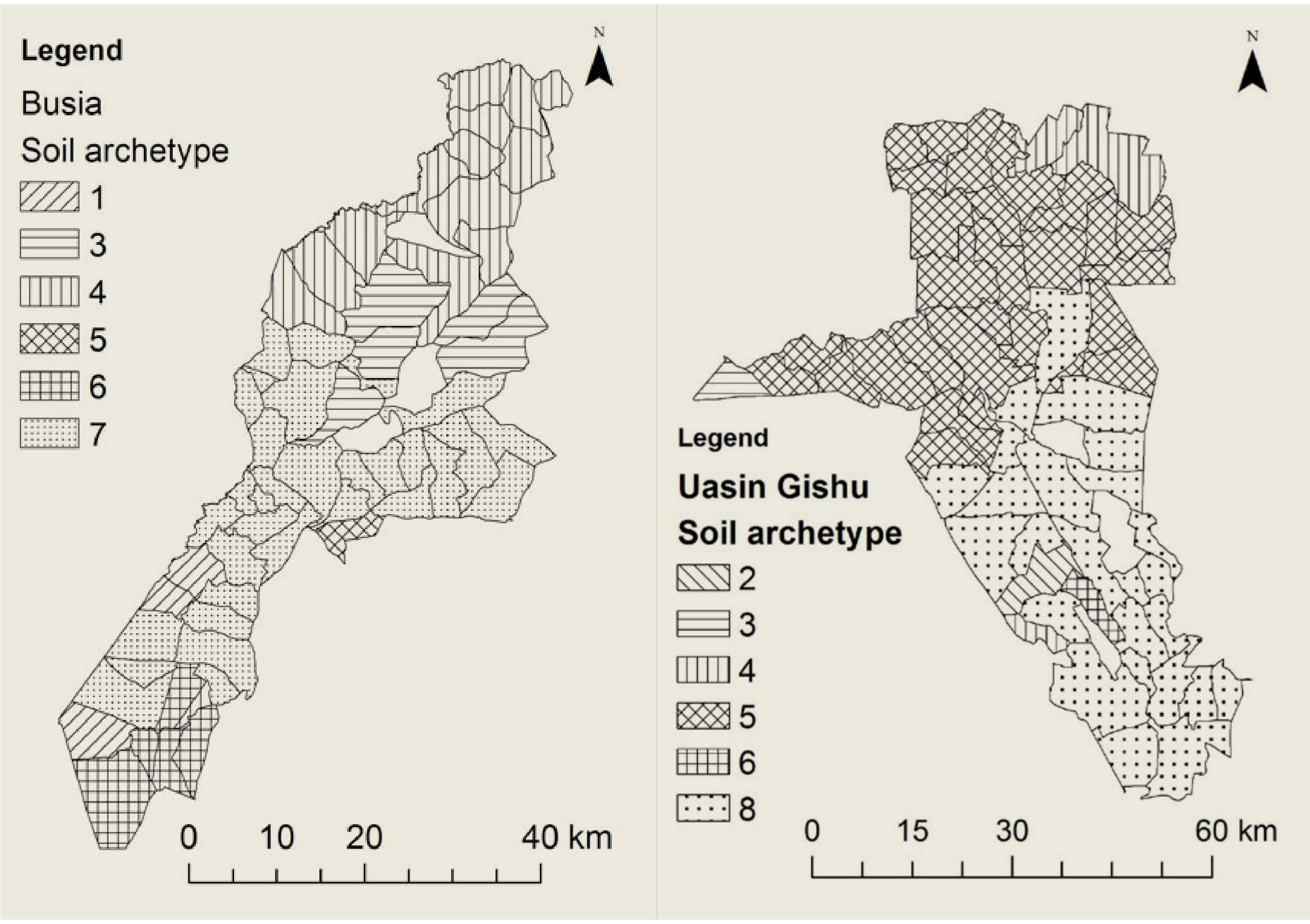

Fig. 3. Main soil archetypes represented in each of the counties of Uasin Gishu and Busia (defined by Global Administrative Areas (GADM); http://www.gadm.org/).

Table 3. Total maize fertilizer nutrient needs per soil archetype with a projected 5 t ha^{-1} maize yield per ha and normal nutrient recovery fraction of applied fertilizer (50% of N, 10% of P and 50% of K taken up by the plant). Median, minimum and maximum nutrient needs for all soil samples belonging to one soil archetype are presented.

Soil archetype	Total fertilizer N			Total fertilizer P_2O_5			Total fertilizer K_2O		
	Median	Min	Max	Median	Min	Max	Median	Min	Max
	kg ha^{-1}								
1	159	97	186	306	144	359	0	0	81
2	78	0	111	255	90	320	36	0	97
3	172	88	200	398	307	411	40	0	176
4	170	71	199	377	276	411	0	0	172
5	146	5	178	366	276	411	0	0	31
6	106	0	158	273	121	339	0	0	103
7	139	69	193	368	290	411	7	0	172
8	135	0	166	334	253	388	0	0	98

P_2O_5 and K_2O nutrient needs compared to normal nutrient use efficiency at the same yield level (Fig. 4c).

Further analysis was restricted to the 5 t of maize per ha yield scenario with normal nutrient recovery rates (Table 3). The study showed that total N, P_2O_5 and K_2O application rates ranged from 78-159, 90-411 and 0-176 kg N, P_2O_5 and K_2O ha^{-1} respectively. Distinct differences existed between the soil archetypes, again with overlap occurring between soil archetypes.

Four NPK blend archetypes could be distinguished for fertilization at planting (Table 4). Archetype 3 is a pure P fertilizer. Archetypes 1 and 4 are NP blends and archetype 2 is an NPK blend. 49% of soil samples were classified as archetype 1; 38% as archetype 4; 8% as archetype 3; and 6% as archetype 2. Blend archetype 1 was the

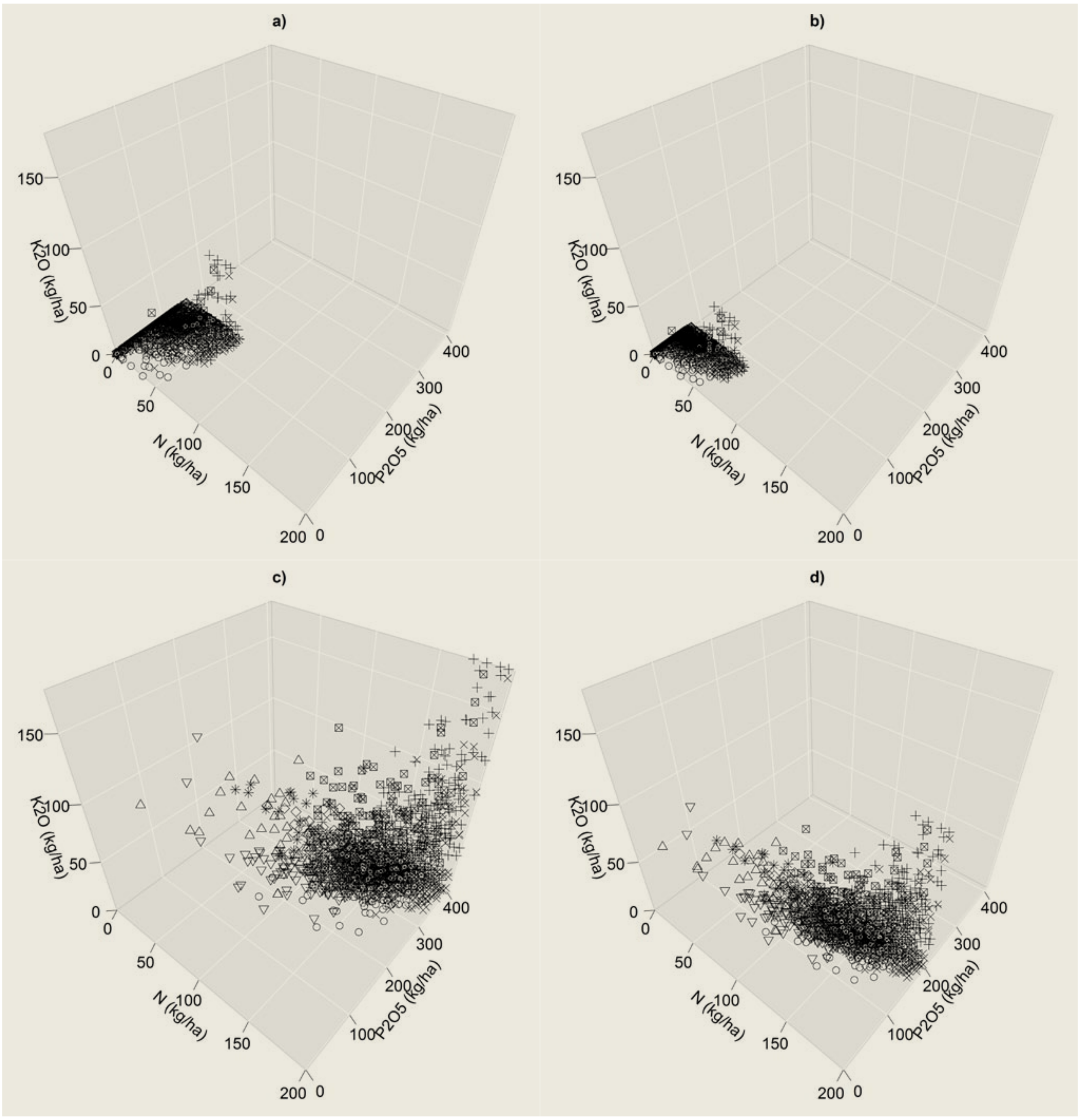

Fig. 4. 3D total fertilizer nutrient application rates for: i) 2 t maize yield (graph a and b); ii) 5 t maize yield (graph c and d); iii) normal nutrient recovery fraction (graph a and c); and iv) high nutrient recovery fraction (graph b and d). Different symbols refer to soil archetypes as mentioned in Table 2 and Fig, 3.

major blend in 59% of the sub-location areas. Nevertheless, in one sub-location more than one blend archetype was advised (Fig. 5). Only in 6% of the sub-locations did all soil samples from this sub-location have the same blend archetype. All the other sub-locations had two to four blend archetypes; 38% of sub-locations had two blend archetypes; 33% of sub-locations had three blend archetypes; and all four blend archetypes were present in 22% of the sub-locations.

When the classified blend archetype at planting is applied in a per sample optimized amount to the field, a shortage or excess amount of N, P_2O_5 or K_2O may occur because the blend composition does not fit perfectly to the specific NPK fertilizer demand of maize on that field. For all samples, the excess/shortage of N, P_2O_5 and K_2O was calculated. Table 5 gives the summary statistics of the calculated absolute nutrient residuals at planting in kg N, P_2O_5 and K_2O ha^{-1} for the soil samples leaving out the 10% lowest and 10% highest residues (10-90% percentiles). In addition, the relative nutrient residuals at planting (residuals/plant need at planting*100%) are presented for this 10-90% percentile.

Table 4. Description of blend archetypes at planting for 5 t maize yield per ha and normal nutrient recovery fraction.

Fertilizer	Blend archetype			
	1	2	3	4
N	12	6	0	13
P_2O_5	25	22	40	33
K_2O	0	14	0	0
Number of samples classified to blend archetype	1,032	130	153	792
Number sub-locations classified mainly to blend archetype	67	2	7	41

When the recommended blend archetype was applied in an optimized amount, the analysis showed the median residual N, P_2O_5 and K_2O was 37, -37 and 0 kg ha^{-1} respectively. Eighty percent of the soil samples (10-90% percentile) had deviations from the recommended N application rate between -30 and 59 kg ha^{-1}. For P_2O_5 and K_2O, this ranged between -57 and 0, and -36 to 0 kg ha^{-1}, respectively. This translated into median relative residuals of 36%, -10% and 0% for N, P_2O_5 and K_2O.

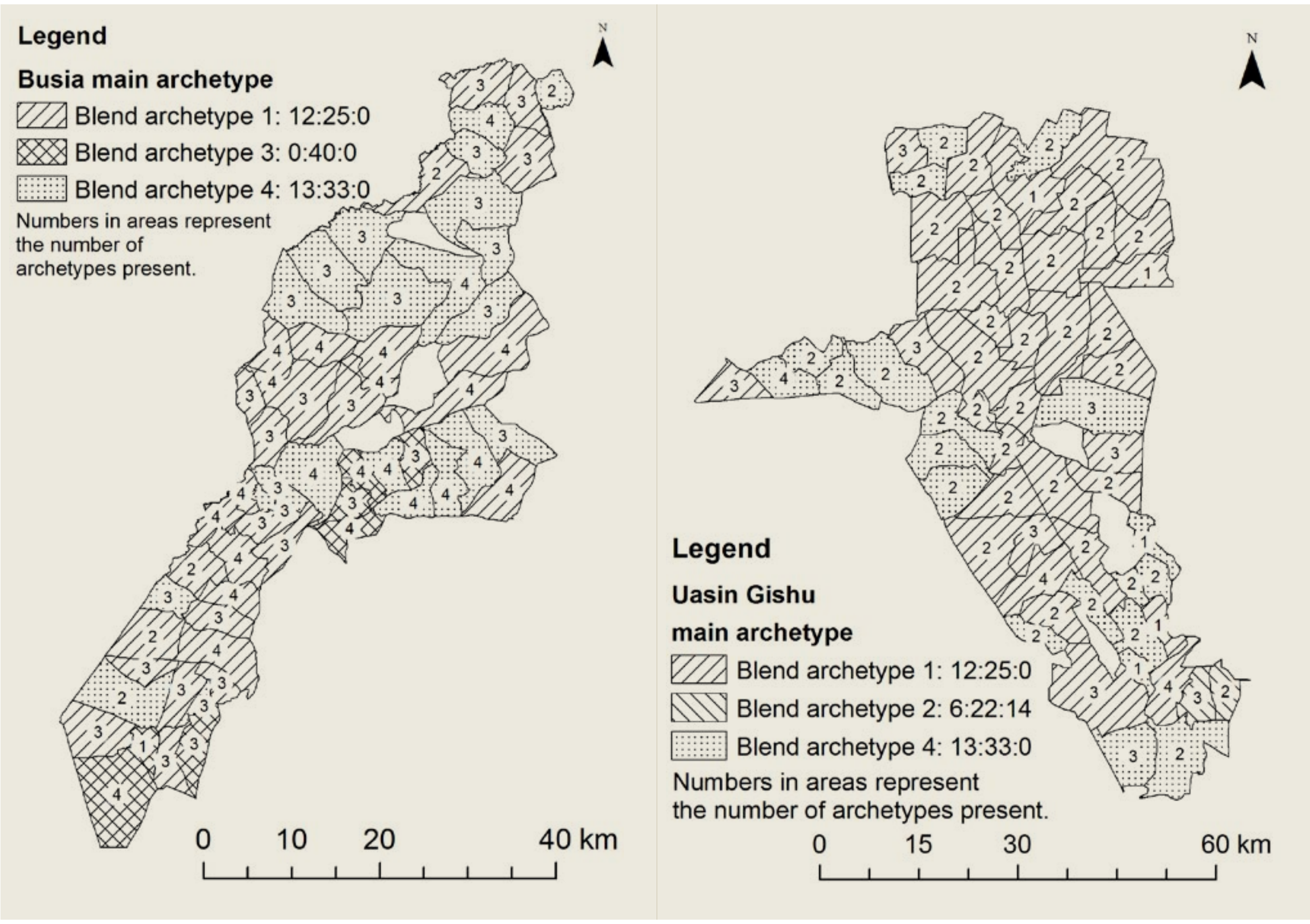

Fig. 5. Distribution of main planting blend archetypes in the sub-locations of Busia and Uasin Gishu.

Table 5. Summary statistics on absolute and relative nutrient fertilizer residuals at planting.

Type of residual	Population characteristic	N	P_2O_5	K_2O
Absolute nutrient residuals: fertilizer – plant needs (kg ha^{-1})	10% percentile	-30	-57	-36
	Median	37	-37	0
	Mean	35	-29	-4
	90% percentile	59	0	0
Relative nutrient residuals: absolute residuals/plant needs (%)	10% percentile	-27	-16	-100
	Median	36	-10	0
	Mean	34	-8	-26
	90% percentile	63	0	0

Discussion

Routine soil testing using infrared technology in combination with the SoilCares mobile laboratory is a promising first step to decreasing the crop yield gap experienced by smallholders. In this Uasin Gishu - Busia project, more than 2,100 samples provided by smallholder farmers were analyzed by one bus run by a team of three people within eight weeks. All smallholders received a field and crop specific fertilizer recommendation within about three hours of presenting their samples.

The data plotted at the sub-location level of Uasin Gishu and Busia are useful to obtain recent, detailed information on actual soil fertility status. Soil test data of soil samples, in combination with the calculated optimal NPK application rate according to the QUEFTS fertilization model, provide a data set which can be used to derive optimal fertilizer blend compositions using the archetype approach.

The soil samples from Uasin Gishu and Busia could be classified to eight soil archetypes with unique soil property combinations. Mainly different soil archetypes were found in the two counties. Nevertheless, huge soil variability was encountered even at sub-location level. There appeared to be no direct relationship between the soil archetypes and the well-known soil types on soil maps. The reason for this is probably that on common soil maps only general static soil characteristics are included. When dynamic soil characteristics are incorporated, more detailed and precise soil fertility maps can be produced. These changes in the dynamic soil characteristics are probably the outcome of recent farm, fertilizer or crop residue management, but this statement needs further investigation.

Soil archetypes, as derived in this study, provide a very useful starting point for assessing soil fertility status and advising on fertilizers and their rates of application. However, this is only possible when the soil archetypes remain constant for a long period. If this is not the case, communication and knowledge transfer on soil fertility status and fertilizer application rates becomes more challenging. Future research should also address this point.

Fig. 4 and Table 4 (exemplary for the maize yield of 5 t ha^{-1} assuming normal nutrient recovery fraction) showed the huge variation that can be expected in the optimal N, P_2O_5 and K_2O application rates because of differences in soil archetype. However, when the archetype approach is used for the calculated N, P_2O_5 and K_2O rates of all samples. An optimization step needs to be included to derive the optimal amount of blend that should be applied to a single field. Each of the 2,107 soil samples was classified to one blend archetype. Calculations showed that, although N, P_2O_5 and K_2O residuals existed, the magnitude (absolute and relative) was acceptable.

This study showed that the SoilCares mobile soil testing concept is a good starting point for minimizing the yield gap. The infrared technology is an affordable soil testing method for smallholders and the QUEFTS calculation model has a good scientific basis for deriving field and crop specific N, P_2O_5 and K_2O recommendations. Results are returned within three hours. As described in this paper, data can also be analyzed in more detail to define soil advice and blend archetypes. This new information is a good basis for knowledge transfer to smallholders, as well as for the economic production of NPK blends potentially of use for large areas of agricultural land and crops.

Acknowledgement

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The paper "Soil Fertility Status and NPK Blends at Planting for Maize Growing in the Western Kenyan Counties Uasin Gishu and Busia" also appears on the IPI website at:

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