Response of potato crop to selected nutrients in central and eastern highlands of Kenya

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Abstract: Low nutrients have been reported in potato-growing areas of Kenya, prompting a need for nutrient management research. A study was designed to determine the effect of omitting nutrients on potato growth, yield and harvest index. On-farm nutrient omission trials were set during the long rains (LR) and short rains (SR) of 2016 in which the treatments involve the judicious omission of N, P, K, S and B. Additional two treatments were included with one receiving all the nutrients and a control where no nutrients were added. The treatment was laid in a randomized complete block design with three replications. Potato yields reduced by 6.6 and 11.2 t ha⁻¹ in N-omitted treatments in LR and SR, respectively, when compared to the one receiving all the nutrients, while omitting P resulted in respective yield reductions of 3.8 and 2.0 t ha⁻¹. Stability analysis revealed that omission of N was more stable with a regression coefficient of 0.5; it was followed by P with a value of 1. Potassium, S and B were limiting nutrients only in some farms. N and P should continue to be included in potato nutrient management, while K, S and B should be added based on soil test.

Subjects: Agriculture; Environmental Sciences; Agronomy

Keywords: omission trial; potato response; nitrogen; phosphorus

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PUBLIC INTEREST STATEMENT

Soil fertility management is key to maximizing potato productivity and minimizing expense on fertilizers and environmental effects of excess nutrient application. Potato is an important food and cash crop in Kenya; thus, fertilization is necessary for better yields. Understanding crop response is a key step toward the implementation of 4 Rs in nutrient management, especially in Kenya where declining soil fertility is on the rise. This result adds to the soil fertility and crop response data to help in the development of crop-specific fertilizer blends.
1. Introduction

Potato crop is widely grown by many communities living in the highlands of eastern and southern Africa (Gildemacher, Demo et al., 2009). The increasing importance of the crop can be attributed to its potential contribution to income generation, nutrition and food security (Cromme et al., 2010). Reaching the potential of potato in terms of productivity has been elusive for smallholder farmers due to constraints such as inappropriate use of yield-enhancing inputs (Gildemacher, Demo et al., 2009; Janssens et al., 2013; Muthoni & Nyamongo, 2009). Farmers are facing yield detrimental effects due to nutrient mining (Kaguongo et al., 2008; Muthoni, 2016; Nyawade, 2015; S. Nyawade et al., 2018). Furthermore, harvesting of potato results in nutrient loss through erosion when soil particles are carried together with the tubers (Li et al., 2006; Parlak & Blanco-Canqui, 2015; Ruysschaert et al., 2007). On the other hand, tubers export nutrients out of the farm system; thus, replenishment of lost nutrient is paramount (Koch et al., 2019; Naumann et al., 2020). There is also the tendency of growing potatoes in close rotation or even in mono-cropping due to limited available land (less than 2 ha) and lack of other alternative high-value cash crops in most potato-growing areas of Kenya (Muthoni et al., 2013; Schulte-Geldermann et al., 2012). Under such conditions, improvement in soil fertility can play a major role in increasing potato production of smallholder farmers (Gildemacher, Kaguongo et al., 2009).

Soil fertility management in Kenyan highlands is key since recent surveys have indicated a lower level of nitrogen (N), phosphorous (P), potassium (K), sulphur (S) and boron (B) in major potato-producing regions such as Meru and Nyandarua (Mugo, 2013; Mugo et al., 2020; Kenya Soil Survey, 2014). The soil bulk density (g/cm$^3$) in the area averages 1.03, cation exchange capacity 18.48 meq 100 g$^{-1}$ and total organic carbon 3.5%, while over 50% of potato-producing farms have pH below 5.5; this can severely limit the availability of important plant nutrients (Mugo et al., 2020; Recke et al., 1997; Kenya Soil Survey, 2014). Farmers in the highlands apply inorganic fertilizer to boost their potato production, and potato ranks third to maize and wheat in terms of fertilizer used (Oseko & Dienny, 2015).

Reported fertilizer use among potato farmers, however, does not reflect the expected level of productivity since low yields are still reported in farmers’ fields (FAOSTAT, 2019); this has been attributed to underfertilization among other challenges. Survey results indicate the majority of farmers apply below half of the recommended fertilizer (90 kg N ha$^{-1}$) (Mugo, 2013; Mugo et al., 2020; Muthoni & Nyamongo, 2009). Farmers underfertilize the farms due to a complex of factors such as limited knowledge of soil status, high cost of fertilizers, poor quality manure, limited options on available fertilizer types, as well as low returns on investment in fertilizer application due to possible unresponsive soils (Bindraban et al., 2018; Fairhurst, 2012; Gildemacher, Demo et al., 2009). In addition, there could be unbalances of soil nutrient, which in turn affects the nutrient uptake, thus affecting crop response to nutrient additions (Gitari et al., 2020; Nyawade et al., 2020).

Over the years, constraints associated with fertilizer use by farmers ranging from the type of fertilizer, rates of application, patterns of application and nutrient status have thus been the focus of research (FURP, 1994; Kenya Soil Survey, 2014; Mugo, 2013; Recke et al., 1997). Mainly compound fertilizers, such as DAP, NPK 17:17:17, NPK 23:23:0 and calcium ammonium nitrate, have been evaluated in combination with organic sources (Muthoni & Kabira, 2011; Rap et al., 2019). The blanket recommended rate is 90 kg N ha$^{-1}$ and is mainly used as a reference, though application of 75 kg ha$^{-1}$ and above of N and P has, however, been reported to have yield responses on potatoes (Recke et al., 1997). In the recent past, the focus has been on limiting nutrients and crop responses which have revealed N and P as maize yield limiting (Kihara et al., 2016; Nziguheba et al., 2015). Further, surveys have revealed that more than 20% of farms have N, P, K, B Cu and B below critical level for crop production (Mugo et al., 2020; Vanlauwe et al., 2017; Wortmann et al., 2019). Thus, the question on what is the potato crop response to different nutrients remains unanswered.
Nutrient omission trials which follow Liebig’s law of minimum have been used on both pot and field trials to determine crop response to the addition of specific nutrient, thus determining the most limiting nutrient (Kihara et al., 2016; Njoroge et al., 2019; Rurinda et al., 2020; Valeva & Stamenov, 2017). One nutrient is omitted, while the rest are applied in adequate amount; the effect of the omitted nutrient on crop growth and yield indicates the limitation of the nutrient (Huising et al., 2011). Use of potato for nutrient omission trial has not been conducted in Kenyan highlands; thus, this study would add valuable information.

Unresponsiveness to the addition of limiting nutrients has been reported in studies using several crops (maize, sorghum, cassava beans and pigeon peas) in different areas and including non-response to both macro and secondary nutrients (Kihara et al., 2016). Unresponsiveness has been attributed to the nutrient being strongly fixed in the soil (especially P), thus being unavailable to the plant (Fixen & Bruulsema, 2014; Muindi et al., 2015; Wilhelm, 2009). Most farmers do not have enough knowledge of their farms’ soil fertility status (Muindi et al., 2016). This means they run a risk of continuously adding the nutrients without any meaningful response on yields. This study was therefore set purposely to evaluate the response of potatoes to the application of selected nutrients in two major potato-producing regions of Kenya using on-farm nutrient omission trials.

2. Materials and methods

The study was conducted during the long rains (LR) and short rains (SR) of 2016 in Meru and Nyandarua counties, which are among the largest potato-producing regions in Kenya. During LR, planting was done in mid-March and harvesting in early July, while in SR planting was done in mid-October and harvesting in January. Threesites were used, two in Meru [Meru 1:0.106°N, 37.513°E, 2,384 metres above sea level (MSL) and Meru 2:0.091°N, 37.500°E, 2348 MSL] and one in Nyandarua (Nyandarua: 0.363°S, 36.507°E, 2463 MSL). The sites were selected from a pool of previously sampled farms in a related study focusing on assessing the status of plant-available soil nutrients in potato fields in Meru and Nyandarua regions of Kenya (Mugo et al., 2020). The farms selected for the study had at least two major nutrients in an inadequate state for optimal potato production (Table 1). In Meru 1, P, S and B were below critical levels, while in Meru 2, P, K and B were below critical level; in Nyandarua, N, P and B were below critical level.

3. Soil chemical properties

Soil types in Meru sites are haplic nitisol which are reddish brown, very deep and well-drained friable clay (Spaargaren, 2008). On the other hand, the Nyandarua site has planosols as the dominant soil type, which is imperfectly drained with a pronounced and abrupt transition between relatively light-textured topsoil, part of which is whitish, and a heavy textured, compact and hard B-horizon. Chemical properties of the experimental site at 0–0.3 m depth are shown in Table 1.

2.2. Climate data

Rainfall in the two regions is bimodal, with the LR coming in March to July, while the SRs come in October to January. During the study period, the total rainfall per season was slightly high in Nyandarua (593 and 301 mm for LR and SR, respectively) region compared to the respective values of 359 and 227 mm for Meru. It was also slightly cool in Nyandarua with an average seasonal maximum temperature of 25°C compared to 28°C in Meru, while the respective average minimum temperatures were 17°C and 14°C (Figure 1).

4. Experimental design and treatments

The trials were laid out in a randomized complete block design with three replications. The plots measured 4.5 m long by 3 m wide, with potatoes planted at a spacing of 0.3 m within a row and 0.75 m between rows targeting a plant density of 44,444 plants ha⁻¹. The treatments are composed of (i) no nutrients supplied (control), (ii) all the tested nutrients supplied (NPKSB) and (iii) five treatments in which one of the tested nutrients was omitted at a time while other nutrients were applied at adequate levels (Table 2). The nutrients tested were N, P, K, S and B. The rate of each nutrient applied was calculated based on the nutrient requirement for a target yield of 40 t ha⁻¹ as
Nitrogen was supplied using urea, P by triple superphosphate (TSP), K by murate of potash (MOP), S by sulphate of potash (SOP) and boron by solubor (disodium octaborate tetrahydrate).

Potato variety Shangi was planted from well-sprouted seed. The variety is semi erect–medium tall, that is, an early maturing and planted by the majority of farmers (NPCK, 2019). At planting, potatoes were supplied with the respective fertilizer elements (Table 2). Urea was applied in two splits to avoid excessive leaching. Also, 168 g TSP, 405 g MOP, 112.5 g SOP and first split of urea (191 g) fertilizer were band applied and mixed with the soil properly before placing the tubers. Foliar application of B was done 15 days after emergence (DAE), while the second split of urea was applied 15 DAE.
Table 2. Amount of pure nutrients supplied for each treatment

| Treatment | Nitrogen (kg ha⁻¹) | Phosphorus (kg ha⁻¹) | Potassium (kg ha⁻¹) | Sulphur (kg ha⁻¹) | Boron (kg ha⁻¹) |
|-----------|-------------------|----------------------|---------------------|------------------|----------------|
| Control   | 0                 | 0                    | 0                   | 0                | 0              |
| Minus N   | 0                 | 100                  | 224                 | 15               | 0.2            |
| Minus P   | 130               | 0                    | 224                 | 15               | 0.2            |
| Minus K   | 130               | 100                  | 44                  | 15               | 0.2            |
| Minus S   | 130               | 100                  | 224                 | 15               | 0.2            |
| Minus B   | 130               | 100                  | 224                 | 15               | 0.2            |
| NPKSB     | 130               | 100                  | 224                 | 15               | 0.2            |

First, weeding and hilling up for potato was carried out manually at 15 DAE, while the second weeding and hilling up was done at 30 DAE. Potatoes were sprayed with Ridomil Gold MZ 68 WG (mefenoxam 40 g kg⁻¹ + mancozeb 640 g kg⁻¹) alternated with Dithane M45 WP (mancozeb (dithiocarbamate) 800 g kg⁻¹) after every 14 days starting at 15 DAE to control late blight. The trials were conducted under rain-fed conditions. However, supplemental irrigation was done in site 2 during LR and in site 1 in SR.

5. Growth and yield determination

Leaf area index (LAI) was measured using LAI-2200 plant canopy analyzer (LI-COR, Lincoln, NE, USA) at 30 and 45 DAE and used as an indicator of potato growth. The measurement was made when the sky was clear with minimal uniform clouds at around midday local time. Destructive sampling of six plants in the inner rows was done at 60 DAE to collect samples for the determination of fresh and dry weight of plant and tubers. Fresh weight was measured in the field, and then, a sub-sample of 500 g weighed, oven-dried at 60 °C for 72 h and eventually reweighed for dry weight determination. The final yield was determined by harvesting the 33 remaining inner plants at full maturity between 90 and 100 DAE. Yield response was calculated for each of the nutrient treatments for every site using Equation 1.

\[
\text{Yield response(%) = } \frac{(y - y_0)}{y_0} 
\]

where \( y \) is the tuber yield of respective nutrient plots (t ha⁻¹) and \( y_0 \) is the tuber yield of the control (no fertilizer) (t ha⁻¹) of nutrient omission plots.

Harvest index (HI) was determined using data obtained during sequential harvest using Equation 2.

\[
\text{Harvest index} = \frac{\text{TuberDW}}{\text{TuberDW} + \text{HaulmDW}} \tag{2}
\]

6. Data analysis

The effect of the treatments on potato LAI, HI and yield was tested using mixed model where season, site and the treatments were considered as fixed terms, while replications were considered random. Analysis was done in R Software version 3.5.2 (R Core Team, 2018). The treatment means were compared using least significant difference (LSD) at \( p \leq 0.05 \). The effect of the treatment was regressed and plotted against the environmental/site yield calculated as the mean yield as described in stability analysis approach (Raun et al., 1993). Stability analysis was done to determine how treatments were stable to the environmental factors by observing the linear regression coefficient. The smaller the regression coefficient, the more stable the treatment effect (Raun et al., 1993).
7. Results

7.1. Leaf area index
Crop growth measured in terms of the LAI was significantly affected by nutrient omissions (Table 3). The effect was significant at both growth stages in the two seasons \( (p < 0.001) \). At flowering, the treatment in which all nutrients were added (NPKSB) had slightly lower LAI compared to the treatment where K and S were omitted; however, N and P had lower LAI compared to NPKSB treatment. On average, omitting N lowered potato growth the most at bulking stage (LAI of 0.75 and 1.01 in LR and SR, respectively) followed by P that lowered the LAI at bulking by 0.71 and 0.88 in LR and SR, respectively. NPKSB treatment increased potato growth as revealed by increased LAI from the control (no nutrient applied) treatment by 37% and 70% in LR and SR, respectively, at flowering stage and 43% and 38% LR and SR, respectively, at tuber bulking stage. Sites did not significantly influence potato growth at both flowering and bulking stages during the two seasons. The seasonal differences could only be detected at the flowering stage and not at the tuber bulking stage.

Table 3. Potato leaf area index (LAI) at flowering and tuber bulking stages

| Site    | Treatment | Flowering stage (30 DAE) | Bulking stage (45 DAE) |
|---------|-----------|--------------------------|------------------------|
|         |           | 2016 LR | 2016 SR | 2016 LR | 2016 SR |
| Meru 1  | Control   | 0.36b   | 0.34b   | 1.2a    | 1.3a    |
|         | Minus N   | 0.40b   | 0.49b   | 1.0a    | 1.3a    |
|         | Minus P   | 0.64ab  | 0.89a   | 0.8a    | 1.3a    |
|         | Minus K   | 0.81ab  | 1.16a   | 0.7a    | 2.53a   |
|         | Minus S   | 1.01a   | 1.22a   | 1.4a    | 1.92a   |
|         | Minus B   | 0.57ab  | 1.04a   | 0.9a    | 2.49a   |
|         | NPKSB     | 0.48ab  | 1.14a   | 1.5a    | 2.56a   |
| Meru 2  | Control   | 1.63a   | 0.25d   | 1.14a   | 1.11bcd |
|         | Minus N   | 1.39a   | 0.29d   | 1.25a   | 0.74d   |
|         | Minus P   | 1.47a   | 0.75c   | 1.70a   | 1.05cd  |
|         | Minus K   | 2.17a   | 1.21ab  | 1.89a   | 1.90ab  |
|         | Minus S   | 2.64a   | 1.33a   | 2.11a   | 2.25a   |
|         | Minus B   | 1.21a   | 0.93bc  | 1.38a   | 1.78abc |
|         | NPKSB     | 2.54a   | 0.99abc | 2.63a   | 2.02a   |
| Nyandarua| Control | 0.44a   | 0.17a   | 0.55a   | 1.17a   |
|         | Minus N   | 0.80a   | 0.19a   | 0.73a   | 0.73a   |
|         | Minus P   | 0.69a   | 0.48a   | 0.63a   | 0.84a   |
|         | Minus K   | 1.14a   | 0.46a   | 1.13a   | 0.94a   |
|         | Minus S   | 0.42a   | 0.37a   | 0.79a   | 0.85a   |
|         | Minus B   | 1.17a   | 0.79a   | 1.43a   | 1.23a   |
|         | NPKSB     | 0.85a   | 0.42a   | 1.07a   | 1.23a   |

Analysis of variance \( (p \text{ values}) \)

| Factor              | S    | SI   | T    | S*SI | S*T  | SI*T  | S*S*I*T |
|---------------------|------|------|------|------|------|-------|---------|
| Flowering stage     | <0.001 | ns   | <0.001 | ns   | ns   | ns    | ns      |
| Bulking stage       | ns   | ns   | <0.001 | ns   | ns   | ns    | <0.01   |
S: season; SI: site; T: fertilizer treatment; DAE: days after emergence. Means followed by the same letter (within the same column and same site) are not significantly different (p ≤ 0.05) by LSD test.

7.2. Haulm dry weight and harvest index

Haulm dry weight was significantly different in Meru 1 during LR and in Meru 2 during SR (Table 4). Significant differences in Meru 1 were mainly because of the effect of control and omission of N treatments in relation to other treatments in which they reduced growth from NPKSB treatment by 41% and 37%, respectively. In Meru 2, the significant differences were between control, omission on N and omission on P against other treatments where they reduced growth from NPKSB treatment by 47%, 56% and 48%, respectively. Omission of B did not reduce potato growth in Meru 1 and Nyandarua. Treatment effects were significant between the seasons and between the sites. The HI was significantly lower in the control plots when compared to omission of other nutrients in most sites during SR. It was lower from the NPKSB treatment by 15% in Meru and 30% in Nyandarua. The omission of N also lowered the HI in all the sites during the two seasons apart from Meru 1 in the LR. The reduction was high (25%) in Meru 2 in SR. The effect of omitting other nutrients varied with sites and seasons. The effects of sites and season were found to be significant.

Table 4. Haulm dry weight (DW) and harvest index for potato at tuber bulking stage

| Site    | Treatment | 2016 LR | 2016 SR | 2016 LR | 2016 SR |
|---------|-----------|---------|---------|---------|---------|
| Meru 1  | Control   | 8.81 c  | 25.88a  | 0.74a   | 0.64b   |
|         | Minus N   | 9.39bc  | 27.03a  | 0.70a   | 0.68ab  |
|         | Minus P   | 21.50a  | 25.16a  | 0.69a   | 0.79a   |
|         | Minus K   | 22.28a  | 37.62a  | 0.68a   | 0.77ab  |
|         | Minus S   | 14.32abc| 36.21a  | 0.67a   | 0.74ab  |
|         | Minus B   | 17.47ab | 41.26a  | 0.64a   | 0.69ab  |
|         | NPKSB     | 14.94abc| 38.67a  | 0.67a   | 0.76ab  |
| Meru 2  | Control   | 28.15a  | 21.30c  | 0.75ab  | 0.48bc  |
|         | Minus N   | 27.03a  | 13.92c  | 0.72b   | 0.42c   |
|         | Minus P   | 35.65a  | 21.03c  | 0.70b   | 0.67a   |
|         | Minus K   | 24.59a  | 36.83ab | 0.83a   | 0.63ab  |
|         | Minus S   | 39.90a  | 45.69a  | 0.75ab  | 0.54abc |
|         | Minus B   | 25.21a  | 34.19b  | 0.74ab  | 0.62ab  |
|         | NPKSB     | 36.70a  | 40.40ab | 0.73ab  | 0.56abc |
| Nyandarua| Control  | 12.93a  | 20.93a  | 0.65ab  | 0.47b   |
|         | Minus N   | 23.81a  | 17.20a  | 0.55bc  | 0.56ab  |
|         | Minus P   | 21.65a  | 16.31a  | 0.58abc | 0.66a   |
|         | Minus K   | 23.84a  | 18.36a  | 0.68a   | 0.53ab  |
|         | Minus S   | 26.29a  | 17.12a  | 0.54c   | 0.62ab  |
|         | Minus B   | 27.84a  | 23.81a  | 0.64abc | 0.68a   |
|         | NPKSB     | 24.80a  | 21.94a  | 0.58abc | 0.68a   |

Analysis of variance (p values)

| Factor | S    | SI   | T    | S*SI | S*T  | SI*T | S*S*I*T |
|--------|------|------|------|------|------|------|---------|
| Haulm DW | 0.003| <0.001| 0.001| 0.001| ns   | ns   | ns      |
| HI     | 0.001| <0.001| 0.012| <0.001| <0.001| ns   | ns      |
S: season; SI: site; T: fertilizer treatment; HI: harvest index. Means followed by the same letter (within the same column and same site) are not significantly different (p ≤ 0.05) by LSD test.

7.3. Haulm macronutrient uptake

Uptake of N, P and K was significantly different in the three sites, and only N uptake was significant between the seasons and nutrient omission treatment (Table 5). In Meru 1, the omission of N resulted in 10, 0.6 and 1.2 t ha⁻¹ lower N, P K uptake, respectively, compared with the wholly fertilized treatment (NPKSB) in 2016 LR, whereas the respective values for SR were 30, −0.6 and 1.2 t ha⁻¹. In Meru 2, significant uptake was experienced for N and P, while there was no significant uptake of K. Omission of N and control reduced uptake of N, P and K, while omission of S treatment mostly had high N, P and K uptake compared to NPKSB. There were no significant differences in uptake of N, P and K in Nyandarua in all the two seasons. Omission of S and B mostly had higher N, P and K uptake compared to NPKSB treatment.

S: season; SI: site; T: fertilizer treatment; HI: harvest index. Means followed by the same letter (within the same column and same site) are not significantly different (p ≤ 0.05) by LSD test.

| Site       | Treatment | N (t ha⁻¹) | P (t ha⁻¹) | K (t ha⁻¹) |
|------------|-----------|------------|------------|------------|
|            | 2016 LR   | 2016 SR    | 2016 LR    | 2016 SR    | 2016 LR    | 2016 SR    |
| Meru 1     | Control   | 13.64b     | 40.26a     | 1.50b      | 4.39a      | 3.36b      | 8.78a      |
|            | Minus N   | 14.06b     | 39.28a     | 1.20b      | 4.64a      | 2.06b      | 6.85a      |
|            | Minus P   | 32.17a     | 38.01a     | 3.85a      | 4.25a      | 6.41ab     | 4.46a      |
|            | Minus K   | 32.32a     | 60.21a     | 3.53a      | 4.59a      | 9.89a      | 8.58a      |
|            | Minus s   | 21.47ab    | 57.75a     | 2.14ab     | 4.49a      | 6.78ab     | 11.93a     |
|            | Minus B   | 26.01ab    | 61.54a     | 2.38ab     | 5.63a      | 4.10b      | 8.07a      |
|            | NPKSB     | 24.15ab    | 58.56a     | 1.82ab     | 3.95a      | 4.25b      | 8.05a      |
| Meru 2     | Control   | 43.72ab    | 29.42c     | 4.82a      | 3.15 cd    | 8.91a      | 8.02a      |
|            | Minus N   | 39.70b     | 14.14d     | 4.77a      | 2.09d      | 7.59a      | 3.64a      |
|            | Minus P   | 54.64ab    | 28.94c     | 6.22a      | 2.46 cd    | 7.44a      | 6.36a      |
|            | Minus K   | 57.88ab    | 51.30ab    | 4.61a      | 6.44a      | 10.27a     | 10.15a     |
|            | Minus s   | 63.38a     | 62.45a     | 5.59a      | 8.30a      | 14.69a     | 9.48a      |
|            | Minus B   | 37.84b     | 43.37b     | 3.12a      | 4.75bc     | 5.05a      | 11.44a     |
|            | NPKSB     | 55.27ab    | 61.12a     | 4.26a      | 4.01bcd    | 8.48a      | 9.52a      |
| Nyandarua  | Control   | 17.8a      | 24.30a     | 1.85a      | 1.81a      | 4.80a      | 5.03a      |
|            | Minus N   | 32.46a     | 21.76a     | 3.35a      | 3.09a      | 2.59a      | 5.83a      |
|            | Minus P   | 29.80a     | 22.48a     | 2.81a      | 1.74a      | 6.19a      | 4.73a      |
|            | Minus K   | 33.19a     | 23.09a     | 4.20a      | 1.47a      | 6.28a      | 4.66a      |
|            | Minus s   | 35.86a     | 18.63a     | 4.84a      | 2.37a      | 4.98a      | 4.56a      |
|            | Minus B   | 36.45a     | 27.15a     | 4.17a      | 2.16a      | 7.29a      | 6.17a      |
|            | NPKSB     | 33.03a     | 25.10a     | 3.55a      | 3.26a      | 7.24a      | 6.28a      |

Analysis of variance (p values)

| Factor     | S | SI | T | S*SI | S*T | SI*T | S*S*SI*T |
|------------|---|----|---|------|-----|------|----------|
| Haulm N    | 0.04 | <0.001 | <0.001 | ns | 0.018 | ns |
| Haulm P    | ns  | 0.002 | ns | <0.001 | ns | ns | ns |
| Haulm K    | ns  | 0.029 | ns | ns | ns | ns | ns |
7.4. Effects of omitted nutrient on potato yield

The yield was generally low in all the sites apart from where irrigation was done. Omitting N reduced yield most. For instance, in LR, omission of N reduced the yield by 3.3 t ha\(^{-1}\) (32%) and 6.6 t ha\(^{-1}\) (37%) at sequential and final harvest, respectively, while in SR the reduction was 8.9 t ha\(^{-1}\) (65%) and 11.2 t ha\(^{-1}\) (64%) compared to NPKSB during sequential and final harvests, respectively (Table 6). Phosphorus, which was the second most limiting nutrient, reduced yield from NPKSB treatment by 2% and 19% in LR and SR, respectively, during sequential harvest and 21% and 11% in LR and SR, respectively, at final harvest. The final yield reduction from NPKSB with omission of N was significant (\(p < 0.05\)) in sites 1 and 2 during SR in which it reduced yield by more than 10 t ha\(^{-1}\).

S: season; SI: site; T: fertilizer treatment; DAP: days after planting. Means followed by the same letter (within the same column and same site) are not significantly different (\(p \leq 0.05\)) by LSD test.

| Site   | Treatment | 2016 Long rains |         | 2016 Short rains |         |
|--------|-----------|-----------------|---------|------------------|---------|
|        |           | Sequential harvest (60 DAE) |         | Final harvest (60 DAE) |         |
|        |           | t ha\(^{-1}\) |         | t ha\(^{-1}\) |         |
| Meru 1 | Control   | 4.92a           | 5.29b   | 8.25a            | 10.79b  |
|        | Minus N   | 4.76a           | 4.92b   | 9.26a            | 11.84b  |
|        | Minus P   | 11.36a          | 10.57ab | 19.58a           | 28.17ab |
|        | Minus K   | 10.69a          | 13.87a  | 23.2a            | 32.95a  |
|        | Minus S   | 6.06a           | 12.68ab | 21.01a           | 33.76a  |
|        | Minus B   | 7.31a           | 11.32ab | 19.86a           | 39.04a  |
|        | NPKSB     | 6.90a           | 11.69ab | 23.50a           | 32.37a  |
| Meru 2 | Control   | 13.31a          | 20.99a  | 3.88bc           | 4.82bc  |
|        | Minus N   | 12.02a          | 17.93a  | 1.86 c           | 2.53 c  |
|        | Minus P   | 14.94a          | 21.98a  | 8.16ab           | 11.92ab |
|        | Minus K   | 19.05a          | 22.82a  | 11.53a           | 15.44a  |
|        | Minus S   | 18.65a          | 28.84a  | 10.28a           | 15.01a  |
|        | Minus B   | 12.03a          | 20.41a  | 10.22a           | 13.54a  |
|        | NPKSB     | 19.01a          | 26.71a  | 10.00a           | 13.41a  |
| Nyandarua | Control | 3.69a          | 5.53b   | 3.22b            | 3.62b  |
|         | Minus N   | 4.98a           | 11.4ab  | 3.58b            | 4.66ab  |
|         | Minus P   | 4.99a           | 10.13ab | 5.91ab           | 6.82ab  |
|         | Minus K   | 8.57a           | 14.87a  | 4.08b            | 4.58ab  |
|         | Minus S   | 5.20a           | 14.29a  | 5.65ab           | 7.34a  |
|         | Minus B   | 8.02a           | 12.44ab | 9.29a            | 7.26a  |
|         | NPKSB     | 5.89a           | 15.71ab | 7.89a            | 6.98ab  |

Analysis of variance (p values)

| Factor     | S         | SI        | T         | S\*SI  | S\*T    | SI\*T   | S\*SI\*T |
|------------|-----------|-----------|-----------|--------|---------|---------|----------|
| Sequential harvest | 0.005     | <0.001   | <0.001   | ns     | ns      | ns      | <0.001   |
| Final harvest       | ns       | <0.001   | <0.001   | ns     | ns      | <0.001  |          |
7.5. Comparisons of omitted nutrient treatments to control (no nutrient applied)

The omission of various nutrients led to reduced potato yields compared to the treatment where all the tested nutrients were applied. In reference to the sequential harvest yields, omission of various tested nutrients gave higher yields than control apart from omission of N that had lower yields than control in Meru 2. Nitrogen was the most limiting since the yields in plots where N was omitted were lower or slightly higher than plots with no nutrients added (Figure 2). Apart from Nyandarua in SR, the effects of the application of 44 kg K ha$^{-1}$ gave a high percent yield difference from the control. The increasing K application from 44 to 224 kg ha$^{-1}$ lowered the yield slightly. In Meru 1, omission of P had a higher yield than NPKSB treatment during LR. All the other sites revealed P as the second most limiting nutrient after N since it had second lowest percent difference from the control (20% Meru2, 40% Nyandarua during LR and 130% Meru 1, 100% Meru 2 and 80% Nyandarua during SR). Sulphur also proved to be a key nutrient influencing potato growth. Its omission revealed the third lowest yield increase when compared to control in Meru 1 (25%) and Nyandarua (40%) in LR. Boron only seemed to affect potato yield in Meru 2 in LR and in Meru 1 in SR.

Figure 2. Percent potato yield response to omission of N, P, K, S and B compared to no fertilizer application treatment at 60 days after emergence in 2016 long rains (a) and 2016 short rains (b).
At the final harvest, the effect of omitting N had a yield gap of more than 5 t ha\(^{-1}\) when compared to application of all nutrients (Figure 3). The effect of S was observed as the third most limiting nutrients of the tested nutrient elements and was not observed on analysing the final yield data since the percent yield difference from the control was mostly higher than that of all the nutrient applied. Potassium was only found to be most limiting in site 3 in SR where it had a yield difference of 26% compared to the control, while omission of N at the same farm gave a percent yield difference of 28%. The effect of omitting boron gave varied results between the seasons and the sites. For instance, in site 2 in the LR, omitting B leads to the crop not responding to the addition of other nutrients, while in SR, there were no negative yield effects when it was omitted for site 1.

7.6. **Comparisons of omitted nutrient treatments to NPKSB (all tested nutrients)**

Nitrogen significantly decreased yield from NPKSB in all the sites in the two seasons (Figure 4). The yield gap was low (27%) in Nyandarua in LR and highest (81%) in site 2 during SR. Phosphorus also reduced potato yields at 60DAE in all the sites in both seasons, and the yield reduction ranged...
from 3% to 35%. There was no yield reduction with omission of K in Meru 1, but reductions were experienced in Nyandarua. Sulphur omission also did not affect potato yield in all the sites.

At 90 DAE, variations were observed between the seasons on most of the nutrient omission treatments. Apart from omission of N which reduced potato yields in all the sites, omission of P on average reduced in Meru 2 and Nyandarua by about 20%, but no yield reduction was experienced in Meru 1 during LR (Figure 5). Omission of S was found to reduce the final yield from NPKSB treatment, but B was found to have no major negative effect on the potato yield.

8. Stability analysis
Stability analysis revealed relatively low regression coefficient for all the treatments. The control and minus N had the lowest regression coefficient of 0.6 and 0.5, respectively (Figure 6). Boron had the highest regression coefficient of 1.3, implying that potato yield was affected differently by B omission in different sites. The coefficient for NPKSB and minus S treatments was 1.2, while that of minus K was 1.1. All regression equations were significant ($p < 0.05$) though the $R$ squared for minus N and control equations was relatively low (0.48 and 0.45, respectively). Omission of $S$ had a better performance in all the environments, while minus B performed better in a high yielding environment as compared to a low yielding environment.

9. Discussion
The response of potato crop to the omission of N was imminent as indicated by uptake and yield parameter results, portraying N as the most limiting nutrient in potato-growing areas of Kenya. Nitrogen as one of the major nutrients is responsible for key plant process that influences the growth and yield of potato (Lamb et al., 2014). The soils in the Kenyan highlands have been
Figure 5. Percent potato yield response to omission of N, P, K, S and B compared to NPKSB treatment at final harvest in 2016 long rains (a) and 2016 short rains (b).

Figure 6. Regression of potato yields for various treatments against the environmental yield (EY) mean for the 2016 long and short rain seasons.

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continually farmed which results in lots of N mining as well as losses through erosion and leaching (Gitari et al., 2019; Nyawade et al., 2020). Similar results have been reported from multi-location trials on different soil types, in several African countries including Kenya (Kihara et al., 2016). In slightly acidic to moderately acidic soils, higher response to N and P addition has been identified (Shehu et al., 2018). While using potato as a test crop, Banerjee et al. (2016) reported N as the most limiting yield. Nitrogen management dynamic is thus crucial and the levels in customized fertilizers are highly significant. Omission of N in some sites leads to lower yields than the control; this might be as a result of the synergistic effect of N with other nutrients (Aulakh & Malhi, 2005). Nitrogen and P addition has been shown to have synergetic and additive effects on crop yield (Aulakh & Malhi, 2005; Rietra et al., 2017). Aulakh and Malhi (2005) also summarized the interaction on N and K and concluded that they are largely synergetic. Nitrogen and S affect many plant growth and tuber quality attributes since they are components of protein and thus affect the uptake and efficiency of each other (Singh et al., 2016). The effect of N omission thus affected the yield the most; as a result, the application of N resulted in high agronomic nitrogen use efficiency.

The soil in most potato-growing regions of Kenya is mainly acidic. This has been attributed to the volcanic ash parent material as well as continued use of acidifying fertilizers such as ammonia-based fertilizers (FAO, 2001; Pansu & Gautheyrou, 2003; Recke et al., 1997; Spaargaren, 2008). Phosphorous is largely affected by the soil pH in which it is bound by the Al and Fe ions in low pH (Ekelöf et al., 2014; Ndou, 2017). As a result, P was found to be a limiting nutrient to potato growth and yields as indicated by the percentage yield reduction from NPKSB treatment. This was also clear in the minus P regression line in the stability analysis graph; it lay in the middle after that of minus N and control treatments. Phosphorous has a role in root development and provides energy for photosynthesis factors that have an influence on the growth of the crop (Ekelöf, 2007; Ndou, 2017). Phosphorous application increases P uptake, leading to increased tuber numbers and yields, and thus is the reason for reduced yields from NPKSB by over 15% with P omission. Omission of P has been found to affect the uptake of most of the essential plant nutrients on acidic to slightly acidic soils (Adalton Mazetti Fernandes et al., 2017; Borges et al., 2016; Kumar et al., 2018); this in turn affects most plant processes, thus reducing the yield. Higher uptake of N, K, Ca, Mg, S, B, Cu and Fe has been associated with P fertilization as a result of its effect on plant biomass (Fernandes et al., 2015; Fernandes et al., 2017; Soratto et al., 2020).

Potassium is a key nutrient in potato crop, and it is actually the nutrient needed in the highest amount by potatoes (Westermann, 2005). It leads to an increase in yield as well as the quality aspects of the product (Bhattarai & Swarnima, 2016). Despite this, the effect of reduction of K applied was not significant in most of the areas in terms of the LAI, haulm and yield. Application of 224 kg K ha⁻¹ demonstrated to decrease potato growth and yield in some sites; this could be because of excessive uptake of K since the initial soil K levels were above critical level for potato growth (Mbuvi et al., 2013; Rozo & Ñuste, 2011). Over application of K (over 150 K₂O kg ha⁻¹) has been shown to reduce growth and yield parameters in some potato varieties (Rozo & Ñuste, 2011; Zelelew et al., 2016). The minimal effect on potato growth and yield parameter could imply that the application of 44 kg K ha⁻¹ was adequate for potato growth and also reinstates the fact that tropic soil is mostly K sufficient (Kanyanjua et al., 2006; Mbuvi et al., 2013; Wekesa et al., 2014). This would mean K needed in customised fertilizers is minimal. A recent study on tropical clay soil has shown that the benefits of K in improving uptake of other nutrients are reduced under medium and adequate levels of K in the soil (Soratto et al., 2020).

The effect of omitting S was experienced at bulking stage, in both LAI and the tuber yield but not during the final harvest. The stability analysis equation for minus S was highest in all the environments, an indication of no negative effect on the yield when S was omitted; this was contrary to results from Ethiopia that have indicated responses to S addition (Mekashaw et al., 2020). The less effect of omission of S may be attributed to the initial soil test since only Meru 1 site had low levels of S. Boron was found to reduce potato yields in the 2016LR; this effect was however not noticed in 2016SR and led to a higher slope coefficient in the stability analysis. Boron has been shown not to
have yield increases even in soils with as low as 0.5 mg kg\(^{-1}\) of boron (Hopkins et al., 2007); however, other studies have reported a slight yield increase (Moinuddin et al., 2017). The adequate range of boron sufficiency is narrow with negative effects experienced at both extremes; potato crop can however adapt to excess levels of B (Ayvaz et al., 2016; Tariq & Mott, 2007). Variability of potato responses to omission of the nutrients was experienced in various sites as indicated by variation of measured parameters. Variability between sites is common for many omission trials (Kihara et al., 2016; Shehu et al., 2018). This emphasizes the need for site-specific nutrient management which has been advocated by other studies (Rurinda et al., 2020; Vanlauwe et al., 2017).

10. Conclusions
This study shows that nitrogen and phosphorous were the most limiting nutrients in the central highlands of Kenya. Potassium and boron were responsive in some of the sites. Potato crop was found to be unresponsive to the omission of sulphur fertilization. The response also varied between sites. Based on these results, for a potato-specific fertilizer to be formulated for the Kenyan highlands, N and P should continue to be included, while K and B should only be added based on soil test or just for fertility maintenance.

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Authors’ contributions
JNM conceptualized the study, collected and analyzed the samples and interpreted the data. NKK, CKG, KD, HG and ESG participated in the design and coordination. All the authors reviewed the draft of the manuscript and approved the final version for submission.

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