Use of Limiting Nutrients for Reclamation of Non-responsive Soils in Northern Ghana

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A better understanding of soil fertility factors that constraint positive crop response to fertilizer inputs will facilitate the improvement of soil nutrient management. In this study, a nutrient omission trial was carried out in a greenhouse condition to identify soil chemical properties limiting in non-responsive soils and to ascertain their effect on soybean (Glycine max) production. The treatments evaluated were control (distilled water), complete nutrient solution (all nutrients), and complete solution with the omission of each of N, P, K, Ca, Mg, and S and micronutrients (Fe, Zn, Cu, Mn, B, and Mo) arranged in a completely randomized design with three replications. After the greenhouse study, the identified limiting nutrients were tested with or without FertiSoil (commercial compost) in a 3 year field experiment. Results of the soil analyses showed low fertility status of the non-responsive soils. The sufficiency quotient index revealed non-responsive soils in all the sites to be predominantly limiting in P and K. The occurrence of other limiting nutrients was also identified: Pishegu (Zn, B), Serekpere (Mg, S), Daffiama Saapare (Ca, Mg, S), and Naaga (Mg, S, Zn, B). The nutrient inputs positively influenced soybean yield response in all the locations. The application of PKZnB with FertiSoil and FertiSoil alone significantly increased soybean grain yields by 585 and 477 kg ha\(^{-1}\), respectively, at Pishegu. Soybean grain yields also increased by 585, 573, and 364 kg ha\(^{-1}\) under the FertiSoil, PKMgS\(+\)FertiSoil, and PKMgS applications at Serekpere, respectively. At Daffiama Saapare, the highest (103%) percent increase in soybean grain yield was recorded from the combined application of PKMgSCa and FertiSoil. However, the application of FertiSoil and PKMgSCa singly equally increased soybean grain yield by 77%. Percent soybean grain yield increases of 86, 84, and 74% were observed when PKMgSZnB + FertiSoil, PKMgSZnB, and FertiSoil were applied, respectively, at Naaga. In absolute terms, 83% of the fields had a positive response to mineral fertilizer and 93% to FertiSoil and mineral fertilizer + FertiSoil.
Soil degradation is a major global problem, but more prominent in developing countries where the majority of the populace depend on crop production for their livelihoods (1). Poor land management is the major cause of land degradation among biophysical, socioeconomic, and political factors (2). Continuous cropping with little or no nutrient replenishment has led to soil nutrient mining across sub-Saharan African (SSA) countries especially on smallholder farms (3). Consequently, crop yields obtained from smallholder farms are far below the potential yield resulting in yield gaps. Research efforts to improve soil fertility in SSA over the last three decades have mainly focused on N, P, and K fertilizers (4). However, continuous application of such fertilizers alone has contributed to the depletion of other essential nutrients such as B, Zn, Cu, Fe, and Mn (5), triggering lack of response to future fertilizer applications and reduction in crop yield. Non-responsive soils are soils that do not respond to fertilizer application due to other constraints besides the nutrients contained in the fertilizer (6). Non-responsiveness of a soil to mineral fertilizer application has been attributed to edaphic factors such as soil fertility gradients, nutrient depletion, soil type, low soil organic matter, acidity, and moisture stress and environmental factors (7, 8). Soils that are non-responsive to mineral fertilizer applications are increasingly becoming widespread in SSA. Kihara et al. (9) found 50% of the study sites in Tanzania, Malawi, Kenya, Mali, and Nigeria to be non-responsive to fertilizer application and organic amendments. Zerihun et al. (10) also found over 25% farm sites non-responsive to P fertilizers in western Ethiopia. Agronomical trials implemented by N2Africa project putting nitrogen fixation to work in northern Ghana observed 28% of fields with low crop response to P fertilizers (11). The occurrence of non-responsive soils increases the variability of crop responses to best-fit management practices that worsen the yield gap. To address the non-responsiveness of crops to fertilizer inputs, various diagnostic studies have revealed deficiencies of secondary and micronutrients (Ca, Mg, S, Cu, Zn, B) as a major cause (9, 12, 13). There is, however, lack of systematic and comprehensive knowledge about non-responsive soils, constraints in such soils, and their management in maximizing crop response to fertilizer inputs. In order to optimize crop response and nutrient efficiency, there is a need for proper nutrient management strategies that should be addressed. The Sustainable Development Goal 15.3 by the United Nations aims toward land degradation neutrality (LDN) and land restoration by the year 2030 (14). A credible option for restoring the productive capacity and quality of the soil is to identify the underlying limiting factors and address them. This can be achieved through a site-specific nutrient management with nutrient deficiency diagnosis. The aim of this study was to characterize and identify nutrient deficiencies of non-responsive soils and evaluate the effect of balanced nutrition on crop yield.

**INTRODUCTION**

**MATERIALS AND METHODS**

**Selection and Description of Poor Non-responsive Sites**

Study sites were purposively selected from N2Africa project area in the Northern, Upper West, and Upper East regions of Ghana for agronomic trials during cropping seasons of 2011 and 2012 (11). Soils non-responsive to P fertilizer application were determined by comparing the grain yield of P treated plots with the control plot, and where the control yields were significantly higher or equal to the P treated plots, the soils were designated as non-responsive (6). Seventy-four (74) fields were identified to be non-responsive to P fertilizer. The 74 fields were within 39 communities in the Northern (14), Upper East (15), and Upper West regions (10), respectively. The Northern region falls within the Guinea savannah, and the Upper East is of the Sudan savannah. The Upper West region is sub-divided into two (2) agro-ecological zones, the southern part being the Guinea savannah and the northern and north eastern part. The Guinea and Sudan Savannah agro-ecological zones are distinguished by a unimodal rainfall season. A 10 year average annual rainfall for Northern, Upper East, and Upper West regions was 1,122, 927, and 817 mm, respectively (15).

**Soil Sampling and Analyses**

Soil samples from each of the 74 non-responsive soil fields were collected for physico-chemical analyses. In each field, 10 soil samples were randomly taken from a 20 cm depth with an auger and thoroughly mixed to form a composite sample. A sub-sample was then taken and processed for soil physico-chemical properties at the Soil Science laboratory, Kwame Nkrumah University of Science and Technology (KNUST). Soil pH was determined in a 1:2.5 (soil:water) ratio, and total N was determined by the macro Kjeldahl method as described by Bremner (16), available P by the Bray 1 method (17), and organic carbon by the modified Walkley and Black procedure as described by Nelson and Sommers (18). Exchangeable K, Ca, and Mg were extracted by 1 M ammonium acetate (NH₄OAc) solution at pH 7 as described by Black (19). Iron, zinc, copper, and manganese were extracted with 0.005 M DTPA (20), and particle size distribution was determined by the hydrometer method (21).

**Assessment of Nutrients Limiting in Non-responsive Soils**

The double-pot technique (22) was used to identify nutrients in short supply in the selected non-responsive soils. A greenhouse trial was conducted on soils selected from six communities, two from each region. Nutrient solution was prepared according

**Keywords:** non-responsive soils, site-specific, nutrient sufficiency quotient, fertility, limiting nutrients
to the modified Hoagland’s half strength nutrient solution as described by Paradiso et al. (23) specific to soybean requirement. The rate of ion concentration for the nutrient solution was 7.5, 0.5, 3.0, 2.5, 1.0, 1.0 mM/L (N, P, K, Ca, Mg, S) and 60.0, 7.4, 0.96, 1.04, 7.13, 0.01 μM/L (Fe, Mn, Zn, Cu, B, Mo). The experiment consisted of eight different nutrient solutions and a control arranged in a completely randomized block design and replicated three times (eight nutrient solution × three levels) as presented in Table 1.

**Growth and Nutrient Sufficiency**

Soybean shoots (one shoot per pot) were measured at 24 and 34 days after sowing (DAS). Regular observations were made to detect visual nutrient deficiency symptoms on foliar parts of plants. At 24 and 34 DAS, measurements were taken to establish the relative growth rate (Rs) and nutrient sufficiency quotients. The relative growth rate measurement was determined by dry matter increase using the pairing method developed by Evans (24) as follows:

\[
Rs = \frac{\ln(W2) - \ln(W1)}{t2 - t1}
\]

where \(Rs\) is the relative growth rate (g g\(^{-1}\) day\(^{-1}\)), \(ln\) is natural logarithm, and \(W2\) and \(W1\) are mean shoot dry weights in grams per pot at times \(t2\) and \(t1\) of growing period.

To measure the availability of a nutrient, the sufficiency quotient (SQ) as an index was used to determine the differences in growth between plants on an omitted nutrient solution and the complete solution (25). When the value of SQ is 1, the availability of that particular nutrient in the soil was considered as high as that in the solution. Nutrients with SQ values of 0–0.25, 0.25–0.5, 0.5–0.75, and >0.75 were most limiting, limiting, moderately limiting, and sufficient, respectively (22, 26). To ease interpretation, results were expressed as percentage, with the complete solution taken as 100%. The SQ is expressed as:

\[
SQx = \frac{(Rs) - X}{(Rs)C}
\]

where \(SQx\) is the sufficiency quotient for an omitted nutrient, \((Rs)C\) is the relative growth rate of plants growing on a complete solution, and \((Rs)-X\) is the relative growth of plants growing on an omitted nutrient solution.

**Application of Mineral Nutrients and Compost to Rehabilitate Non-responsive Soils**

Following the results obtained from the nutrient omission trial, a 3 year field experiment was conducted on non-responsive soils in Northern, Upper West, and Upper East regions of Ghana to determine the impact of the identified limiting nutrient applications on the non-responsive soils. The experiment evaluated four (4) treatments; (i) control (no input), (ii) mineral fertilizer as per identified limiting nutrients in each location, (iii) FertiSoil (commercial compost) only, and (iv) mineral fertilizer + FertiSoil. Compost samples were air-dried, milled, and sieved through a 2 mm mesh for analyses (Table 2). Organic C (Walkley and Black wet oxidation method), total N (Kjeldahl method), phosphorus (Bray P 1), and potassium ammonium acetate flame photometry method of the samples were determined. Lignin content was determined using the Acid Detergent Fiber (ADF) method as described by Van Soest and Wine (27) and polyphenol content by the Folin–Denis method (28). Dry matter content was also determined. The compost used for the study was a commercialized product called FertiSoil produced by DeCo! sustainable farming in Tamale, region, Ghana.

The field layout consisted of 12 plots of 5 × 5 m dimension separated by a 1 m buffer. Four treatments were tested in a randomized complete block design with three replications. Mineral fertilizers were applied in bands with triple super phosphate (TSP) at a rate of 30 kg P ha\(^{-1}\), muriate of potash (MOP) at a rate of 20 kg K ha\(^{-1}\), and magnesium sulfate (MgSO\(_4\)) for Mg and S at a rate of 2.5 and 0.5 kg ha\(^{-1}\), respectively. Calcium sulfate (CaSO\(_4\)) was applied at a rate of 15 kg Ca ha\(^{-1}\), zinc sulfate (ZnSO\(_4\)) at a rate of 2.5 kg Zn ha\(^{-1}\), and fertibor at a rate of 0.5 kg B ha\(^{-1}\) at 2 weeks after sowing. FertiSoil was applied at a rate of 5 t ha\(^{-1}\) to the respective plots and mixed with the top soil prior to planting. Soybean cultivar “Jenguma” (TGx series) was sown at two seeds per hill at a distance of 75 cm × 10 cm. A *bradyrhizobium* inoculant (Nodumax) was applied to the seed at a rate of 5 g kg\(^{-1}\), and sowed after air drying for 30 min. Soybean plants were harvested at full maturity (R\(_8\) stage), threshed, and winnowed. Grain yield was then calculated on per hectare basis.

### Table 1 | Treatment composition used in the nutrient omission trial.

| Treatment          | Nutrient solution | Nutrients supplied                      |
|--------------------|-------------------|----------------------------------------|
| Control            | Control           | Distilled water (No nutrients)         |
| Complete + N       | N added           | N, P, K, Mg, Ca, S, Na, Micronutrients  |
| Complete – N       | N omitted         | P, K, Mg, Ca, S, Na, Micronutrients*    |
| Complete – P       | P omitted         | K, Mg, Ca, S, Na, Micronutrient        |
| Complete – K       | K omitted         | P, Mg, Ca, S, Na, Micronutrients       |
| Complete – Ca      | Ca omitted        | P, Mg, S, Na, Micronutrients           |
| Complete – Mg      | Mg omitted        | P, K, Ca, S, Na, Micronutrients        |
| Complete – S       | S omitted         | P, K, Mg, Ca, S, Na, Micronutrients    |
| Complete – Micro   | Micronutrient omitted | P, K, Mg, Ca, S, Na               |

*Micronutrients (Fe, Zn, Cu, Mn, B, Mo).

### Table 2 | Selected chemical properties of FertiSoil.

| Parameter          | FertiSoil |
|--------------------|-----------|
| Organic C (%)      | 32.09     |
| Total N (%)        | 2.43      |
| Total P (%)        | 1.20      |
| Total K (%)        | 1.24      |
| C:N ratio          | 13.24     |
| Lignin content     | 5.68      |
| Polyphenol         | 0.60      |
**Statistical Analyses**

All statistical analyses were conducted with JMP® Pro 13.0.0 (SAS Institution Inc., Cary, NC, 1987–2007). A descriptive statistic was performed on three replicates of each soil sample after laboratory to determine the mean and standard deviation of soil physico-chemical properties. Data in the nutrient omission trial were subjected to analysis of variance (ANOVA), where overall treatment means were significant at \( p < 0.05 \) and the means were separated with Tukey HSD test. A mixed effect linear model was performed to assess the effect of nutrient inputs on grain yield. Location and nutrient input were the fixed factors, and the cropping year and replication were the random factors.

Cumulative probability curves of absolute and relative yield response to nutrient application with reference to the control per individual farms were calculated (29).

**RESULTS**

**Nutrient Status of Non-responsive Soils**

Table 3 shows the soil physico-chemical properties of the study locations. Soil pH levels revealed soils to be moderately acidic (5.53–6.10) in all the soil samples from the Northern, Upper East, and West regions. In all the sites, the soil organic C (<1%) and total N contents (<0.1%) were very low, whereas available P content (7.51–8.51 mg kg\(^{-1}\)) was below the critical value for soybean that is 15 mg kg\(^{-1}\) (30) across regions. Exchangeable K content of the soils in the study locations varied from 0.08 to 0.20 cmol\((+)\) kg\(^{-1}\). The mean values in Northern region were moderate and low in Upper East and West regions. Exchangeable Ca content of all the soil sampled from the Northern, Upper East, and West regions were moderate (2.14–4.13 cmol\((+)\) kg\(^{-1}\)). The Mg content in soils of the study locations varied from low to moderate (0.72–1.21 cmol\((+)\) kg\(^{-1}\)). Exchangeable Mg levels in the soil samples were found to be low (<1 cmol\((+)\) kg\(^{-1}\)) in the Upper East and West regions and moderate (1.21 cmol\((+)\) kg\(^{-1}\)) in the Northern region. Extractable Fe concentration in all the soils sampled were found to be low (1.56–2.79 mg kg\(^{-1}\)) with very low (<1 mg kg\(^{-1}\)) Zn concentrations in Northern, Upper East, and West regions. The textural class of soils experimented on in Northern and Upper East regions was sandy loam with sand contents of 69 and 75%, respectively, while soils from the Upper West had the highest sand percentage (90%).

**Assessment of Nutrients Limiting in Non-responsive Soils**

**Effect of Mineral Nutrient Solutions on Relative Growth Rate (Rs)**

Significant variations \(( p < 0.05 \)) in relative growth rates were recorded from growth analysis of the various treatments across locations except for Daffiama-Dakyea (Table 4). Relative growth rate decreased with each nutrient omitted from the Complete recording the highest 0.153 g g\(^{-1}\) day\(^{-1}\) at Pishegu. At Serekpere, Rs decreased significantly with the omission of macronutrients,
except N. A similar observation was made at Daffiama-Sapaare, where significant relative increase of 272 and 188% in Rs were recorded for Complete and Micronutrient omitted nutrient solutions, respectively. The differences in Rs among different nutrient solution compositions were not significantly (p = 0.285) different at Daffiama-Dakyea. The Complete nutrient solution had the highest Rs of 0.159 g g$^{-1}$ day$^{-1}$ and was significantly (p < 0.001) different from the omitted nutrient solutions at Naaga.

### Nutrient Sufficiency Quotient of Limiting Nutrients From Study Sites

Nutrient sufficiency quotients of nutrients in the study locations are as presented in Table 5 in relation to the Complete nutrient solution. To ease interpretation, the results were expressed in percentages. Nutrients solution without P, K, Micronutrients, and the Control had sufficiency quotient below 50% at Pishegu. At Serekpere, plants grown in the Control, P, K, Mg, and S omitted solutions had lower sufficiency quotients ranging from 30 to 41%. Potassium omitted nutrient solution had the lowest sufficiency quotient of 21% followed by 27% for the control, 33% for Mg, 37% for S, and 38% for P omitted treatments in Daffiama-Sapaare. On the contrary, nutrient omitted solutions in Daffiama-Dakyea and the Control were all in the third quartile of 100%. All plants grown on the nutrient omitted solutions including the Control except for N and Ca omitted pots were generally low with <40% in sufficiency quotient at Naaga.

### Soybean Responses to Mineral Fertilizers and Organic Amendment Application

Results on the effect of mineral fertilizers and FertiSoil on soybean grain yield are shown in Table 6. Significant (p < 0.05) differences in soybean grain yield were observed among treatments across sites. The application of PKZnB + FertiSoil and FertiSoil significantly (p = 0.002) increased soybean grain yield by 55 and 45% over the control, respectively, at Pishegu. The nutrient inputs significantly (p < 0.001) increased soybean grain yield compared to the control at Serekpere. Addition of PKMgS increased soybean grain yield by 364 kg ha$^{-1}$, whereas PKMgS + FertiSoil increased grain yield by 573 kg ha$^{-1}$ and 585 kg ha$^{-1}$, which was also obtained with FertiSoil application. At Dafiaama Saapare, the combined application of PKMgSCa and FertiSoil significantly (p = 0.004) increased soybean grain yield by 103%, while PKMgSCa and FertiSoil separately, equally produced a grain yield increase of 77%. Soybean response to PKMgSzB and/or FertiSoil also varied significantly (p < 0.001) at Naaga (Table 6). The highest (1,201 kg ha$^{-1}$) grain yield was produced under the PKMgSzB + FertiSoil treated plots, followed by PKMgSzB (1,188 kg ha$^{-1}$) and FertiSoil (1,122 kg ha$^{-1}$).

The absolute response (treatment yield minus control yield) and relative response (treatment yield minus control yield divided by the control yield, multiplied by 100) are presented in Figures 1A, B. Cumulative soybean yields over the three cropping seasons show a large variation of crop response to mineral fertilizers and fertisoil across farms and within treatments (Figure 1). In absolute terms, 63, 72, and 89% of the fields had a positive response to mineral fertilizer + fertisoil, fertisoil, and mineral fertilizer applications, respectively, in relation to the control (Figure 1A). Fifty percent of the farmers increased their soybean grain yield by 712.50 kg ha$^{-1}$ or more with fertisoil application. In absolute terms, 54% of farmers increased their soybean grain yields by 715.65 kg ha$^{-1}$ or more with mineral fertilizer + fertisoil application. Sixty-seven percent of the farmers had absolute increase in soybean grain by 700 kg.

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**Table 5** Nutrient sufficiency quotients (%) of mineral nutrients in non-responsive soils.

| Nutrient solution | Pishegu | Serekpere | Daffiama-sapaare | Daffiama-dakyea | Naaga |
|-------------------|---------|-----------|-----------------|----------------|-------|
| Control + N       | 30      | 30        | 27              | 81             | 29    |
| Complete – N      | 80      | 74        | 71              | 89             | 75    |
| Complete – P      | 100     | 100       | 100             | 100            | 100   |
| Complete – K      | 23      | 34        | 38              | 86             | 27    |
| Complete – Ca     | 29      | 38        | 21              | 79             | 31    |
| Complete – Mg     | 75      | 70        | 28              | 78             | 73    |
| Complete – S      | 83      | 39        | 33              | 87             | 33    |
| Complete – Micro  | 73      | 41        | 37              | 76             | 36    |

**Table 6** Average soybean grain yields response as influenced by mineral fertilizer and FertiSoil in northern Ghana.

| Site              | Nutrient input | Grain yield (kg ha$^{-1}$) |
|-------------------|----------------|---------------------------|
| Pishegu           | Control        | 1063$^a$                  |
|                   | PKZnB          | 1346$^{ab}$               |
|                   | FertiSoil      | 1540$^b$                  |
|                   | PKZnB + FertiSoil | 1648$^{b}$               |
|                   | P-value        | 0.002                     |
| Serekpere         | Control        | 385$^a$                   |
|                   | PKMgS          | 749$^a$                   |
|                   | FertiSoil      | 970$^a$                   |
|                   | PKMgS + FertiSoil | 958$^b$              |
|                   | P-value        | <0.001                    |
| Daffiama saapare  | Control        | 477$^a$                   |
|                   | PKMgSCa        | 843$^a$                   |
|                   | FertiSoil      | 844$^a$                   |
|                   | PKMgSCa + FertiSoil | 967$^b$        |
|                   | P-value        | 0.004                     |
| Naaga             | Control        | 645$^a$                   |
|                   | PKMgSzB        | 1188$^b$                  |
|                   | FertiSoil      | 1122$^b$                  |
|                   | PKMgSzB + FertiSoil | 1201$^b$              |
|                   | P-value        | <0.001                    |

Different letters within the same column show significant differences at p < 0.05 (Tukey HSD), otherwise statistically at par. Dystric Plinthosol (Pishegu), Gleyic Lixisol (Serekpere), Ferric Lixisol (Daffiama-Sapaare), Lithic Leptosol (Daffiama-Dakyea), Dystric Leptosol (Naaga).
FIGURE 1 | Cumulated probability graph of individual non-responsive farms in northern Ghana (years 1, 2, and 3): (A) soybean absolute response and (B) soybean relative response to mineral fertilizers and/or FertiSoil in comparison to the control.

ha⁻¹ or more with mineral fertilizer application. Gains of over 1,000 kg ha⁻¹ of soybean grain yield were obtained by 11, 28, and 37% fields with mineral fertilizer, FertiSoil, and mineral fertilizer + FertiSoil application, respectively (Figure 1A). There was a 2% probability chance of achieving a negative response due to the application FertiSoil and mineral fertilizer + FertiSoil. Farmers regard a 10% or more increase in grain yield by a treatment as the least observable increment. A relative increase of 10% or more occurred on 80, 94, and 96% fields treated with mineral fertilizer, mineral fertilizer + FertiSoil, and FertiSoil, respectively (Figure 1B).

DISCUSSION

Physical and chemical characteristics of soil are important soil quality indicators that directly or indirectly affect the quality of plant growth and its products. The nutrient levels of non-responsive soils in northern Ghana were generally below critical levels for crop production (Table 3). The result confirms the low inherent fertility status of soils of the Guinea and Sudan savannah agro-ecological zones of Ghana (31). Practices such as intensive cultivation (32), poor farming practices (33), overgrazing (34), and bushfires (35) further deplete the soil of its essential plant nutrients in varying degrees. In a related study, Fermont et al. (36) observed that low soil fertility limited cassava response to N, P, or K fertilizers in East Africa.

All the sites surveyed in northern Ghana were critically low in organic C, N, and P. This is in line with findings of Antwi et al. (37), Asei et al. (38), and Tetteh et al. (39) on soil fertility levels in the Guinea and Sudan savannah zone of Ghana. This is attributable to the dominant soil groups of the region, which are highly weathered with poor soil texture, characterized by low organic matter content and low cation exchange capacity, thereby causing low nutrient levels (40). The low carbon, N, and P contents can also be explained by the low vegetative cover, low input application, biomass removal, regular annual bush fires, erosion, and leaching during rainy seasons (41, 42). The high temperatures of the northern savanna zones further exacerbate the low carbon content by increasing the rate of mineralization, which decreases carbon accumulation (43).

According to Lal (44), an optimum range of soil organic carbon (SOC) is required to improve water and nutrient retention capacities. This is also in line with results obtained by Musinguzi et al. (45) that low fertility fields (<1.2% SOC) had lowest response to mineral fertilizer N application on a Ferralsol. Such low SOC soils are vulnerable to N leaching, and hence, the soils are less responsive to N fertilizers (46). Additionally, Benbi and Brar (47) also found no response to P fertilizer application under low SOC soils and which Bationo et al. (48) attributed to the high P sorption of soils low in SOC.

Exchangeable cations (K⁺, Ca²⁺, and Mg²⁺) were found to be moderate in some communities of the three regions except Mg, which were moderate for all the sites. However, few sites in the Chereponi district of the Northern region had high Mg levels. The results obtained in this study are consistent with results obtained by Tetteh et al. (49) who reported low to moderate nutrient levels and higher values for exchangeable cations in soils of the northern part of Ghana. The substantial differentiation of soil nutrient levels across communities confirms the heterogeneity of smallholder farms in SSA (50).

Iron and Zn levels varied from low to very low across all the study locations. In contrast, Awuni and Reynolds (51) reported medium to optimum levels for Fe and Zn in some sites of
northern Ghana attesting to the high variability in Fe and Zn contents of the soils. Copper levels were low in soils in the Northern and Upper West regions except Upper East, which was medium. Previous research by Oluwadare et al. (52) has also shown Cu deficiency in the Guinea savannah soils of Nigeria. Medium levels of Mn were observed in all the soil samples. The soils studied by Boateng et al. (53) also showed moderate Mn levels in the Guinea savannah zone of Ghana. A review by Dimkpa and Bindraban (54) documented that micronutrient deficiencies affect the optimal function of plant metabolism processes of N, P, and K and crop responses.

The pH range (5.5–6.0) observed in the study (Table 3) was within the pH values obtained by Tetteh et al. (49) in a study to evaluate soil suitability indices for cereal production in northern Ghana (5.0–7.5). The soil pH level influences the solubility and availability of nutrients. Ch’ng et al. (55) and Miller (56) reported soil with pH below 6 to be deficient in P, as soil P is adsorbed to Al and Fe oxides, rendering it insoluble and unavailable to plants. The high P fixation in soils having a moderately acidic pH is primarily due to the presence of acid-forming cations associated with H⁺, Al³⁺, Fe²⁺, and Fe³⁺ and the high levels of sand with low buffering capacity (57). This may partly explain the lack of response to P fertilizers. The texture of the soils was sandy and is mainly accounted for by the parent material (58). The high mean sand percentages observed in this study correspond with the findings of Ziblim et al. (59) and MacCarthy et al. (60). The dominance of sand in the northern savannah agro-ecological zones of Ghana is because the soils are mostly developed from granite and Voltanian sandstone (61). Zheng et al. (62) studied the influence of soil texture on P fertilizer and observed that soils with high sand and low clay content affect P uptake; such soils have lower P supply, available water, and P diffusion rates compared to fine textured soils.

To estimate the availability of a particular nutrient, the sufficiency quotient, which measures the relative growth rate between a seedling on a complete and an omitted nutrient solution, was determined (22, 26). Soils of Pishegu were found to be limiting in P, K, and micronutrients (Zn, B) (Table 5). Essential nutrients like P, K, Mg, and S were found to be limiting in both Serekpere and Daffiama Saapare, with SQ indices ranging from 21 to 41%. However, the index showed nutrient levels in Daffiama-Dakyea to be sufficient, with SQ values >75. It is also worth noting that the Daffiama Dakyea site was within the community a few meters away from the farmer's house. According to Vanlauwe et al. (63), such fields have high soil fertility status and are unlikely to respond to added inputs. Kihara et al. (9) classified such fields as fertile non-responsive soils.

Nutrient sufficiency quotient for all omitted nutrients were below 50% indicating P, K, Mg, S, and Micronutrients (Zn and B) to be limiting at Naaga. Nutrients with SQ of <50 require their application to soils to obtain optimum soybean growth. Foli (64) observed omitted micronutrients, Mg, P, and K nutrient solutions to have SQ values of 14–39%, specifying these nutrients to be deficient, while those above 75% had sufficient availability in the soils of northern Nigeria. The identified secondary and micronutrient (Mg, S, Zn, B) limitations correlated fairly with those of Wortmann et al. (65) and further supported the concept of balanced fertilizer application in SSA (66).

Targeting fertilizer use to variable soil fertility conditions combined with organic amendments is necessary for efficient crop response in smallholder farms in SSA (67). After the three cropping season, the combined application of FertiSoil and mineral fertilizers accounted for the highest improved grain yield at Pishegu, Serekpere, Daffiama Saapare, and Naaga (Table 6). The response of soybean yield to sole organic input or in combination with inorganic fertilizers is consistent with other studies that confirm that the soybean and maize yield increased with the integration of compost and mineral fertilizer application or sole compost application (68–70). Brempong et al. (71) reported improved synergism and synchronization between nutrient release and plant uptake upon the integrated application of organic and inorganic nutrient sources, which resulted in better crop growth and yield. Furthermore, Sileshi et al. (72) also observed through the integrated application of organic amendment and mineral fertilizer that nutrient use efficiency is enhanced resulting in higher crop grain yields. Blanchet et al. (73) also reported highest yield with organic amendment incorporation and attributed it to increasing SOC content and soil biological properties. Additionally, Adeli et al. (74) explained the effect of organic amendment on grain yield increase to improved nutrient availability for plant uptake and enhanced soil physical, chemical, and biological properties leading to improved crop yields. Generally, the improved grain yield to the applied limiting nutrients suggests that these nutrients were hindering crop response to P fertilizer on soils that were previously not responsive to it (75). This observation could be described as the Liebig-synergism where increased yield is as a result of applying most limiting nutrients and resolving deficiencies (76). Soil fertility restoration is necessary to increase agricultural production, food security, economic development, land conservation, and environmental protection (77).

The performance of each nutrient option on non-responsive soils was demonstrated by the cumulative probability curves (Figure 1) and provides the farmer with information on the outcome of maintaining or switching management practices (78).

**CONCLUSIONS**

Non-responsive soils in northern Ghana are widespread, which are characterized by varying nutrient levels low in SOC. The nutrient omission trial revealed P and K to be most limiting in all the soils of the three regions, followed by Mg, S, Zn, and B. In this research, application of balanced fertilization and/or organic input improved soybean grain yield. Nutrient deficiencies are the major causes of poor crop response to fertilizer inputs, which further hinder crop productivity, and addressing these limitations is one of the key mechanisms of bridging crop yield gap. This information will assist knowledge of crop response to fertilizer and implementation of fertilizer recommendation and soil fertility management strategies for optimum and sustainable crop production.
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DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

RA, RCA, AO, SA-N, and PA-A conceived the research. RA, RCA, and AO set up the experiment. RA collected and analyzed the data. RA drafted the manuscript. RCA, AO, SA-N, and PA-A edited, revised, and made significant contributions. All authors contributed to the article and approved the submitted version.

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Non-responsive Soils Reclamation
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