OPTIMIZING PRODUCTIVITY OF MAIZE IN THE NORTHERN NIGERIAN SAVANNA: INFLUENCE OF NUTRIENT LIMITATIONS AND IMBALANCES

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> *Edith Wharton (1902)*

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Summary

Maize (*Zea mays* L.) is the most widely cultivated cereal crop in Nigeria, owing to its wide suitability boundaries and numerous socio-economic uses. The savanna of Northern Nigeria constitutes the most suitable area because of a favorable combination of adequate rainfall, low night temperatures and less pests and diseases pressure. Despite these favorable conditions, maize yield in the region is low (< 2 t ha^{-1}) which is far below the potential of the crop. For Nigeria to be self-sufficient in maize production; to meet the demand of the rapidly growing human population and even provide for an export surplus, it is important for maize yield to increase. Low soil fertility and inadequate nutrient management have been among the leading factors limiting maize yield in the Northern Nigerian savanna. Most Nigerian soils are highly weathered with low activity clays (such as kaolinite) which makes them more vulnerable to fertility degradation under intensive arable use with poor nutrient replenishment. On top of this, the use of inorganic fertilizers to improve the soil fertility has been conventionally promoted through 'blanket" fertilizer recommendations which did not even consider spatial (field to field) and temporal variabilities. This type of fertilizer recommendations is bound to create unbalanced crop nutrition, low fertilizer use efficiency and ultimately small yields. Overall, this research was conducted to evaluate nutrient related limitations and imbalances at scale, where and why they occur, and to design feasible ways to counteract them in a demand to optimize maize yield in the Northern Nigerian savanna. On-farm diagnostic nutrient omission trials (NOTs) were conducted in 198 fields spread over 14 sites (districts) in the Northern Nigerian savanna during 2015 and 2016 rainy seasons. Altogether the districts fell within two agro-ecological zones, i.e., the Northern Guinea savanna (NGS) and the Sudan savanna (SS). The NGS is the more humid zone with an average annual rainfall of 1129 mm, while the SS is the relatively drier one with an average annual rainfall of 744 mm over the two years of the study, respectively. Two sets of trials were conducted side by side, one with an open pollinated maize variety (OPV) and the other one with a hybrid maize variety, and each set had the same six nutrient application treatments (NA). The nutrient application treatments (NA) comprised (i) control without nutrients applied (control), (ii) N omitted with P and K applied (-N), (iii) P omitted with N and K applied (-P), (iv) K omitted with N and P applied (-K), (v) treatment with all the three nutrients applied (NPK), and (vi) a treatment where secondary macronutrients (S, Ca and Mg) and micronutrients (Zn and B) were applied in addition to the NPK (NPK+).

First, soil and yield data from the NOTs were used to quantify the extent and status of variability in soil and maize yield response to nutrient application. Apart from pH and exchangeable acidity (Al^{3+}+H^{+}), all the studied soil properties displayed moderate to high variability (CV ≥16%) among the studied fields. Accordingly, cluster analysis revealed three distinct yield-nutrient response classes common for the two types of maize varieties. These defined classes were fields that have (i) no-response to any nutrient (ii) a large response to N and P and (iii) a large response to N alone. Although overall yield performance of OPV and hybrid varieties was similar, a distinct fourth class was identified for the hybrid variety, i.e., (iv) fields with a large response to N and secondary macro- and micro-nutrients. The results indicate the large variability in soil nutrient related constraints need to be accounted for to optimize maize yield in the Northern Nigerian savanna. The development of field- and site-specific fertilizer recommendations using simple decision support tools that consider variable soil fertility conditions and heterogenous yield responses is highly needed.

Secondly, we used yields and nutrient concentrations (N, P, K, S, Ca, Mg, Fe, Mn, Zn, Cu and B) in the ear leaves from the NOTs to diagnose nutrient limitations and imbalances using the compositional nutrient diagnosis (CND) tool. Significant positive correlation was observed between maize grain yield and ear leaf nutrient concentrations except for Fe in NGS and Mg in SS, respectively. About 40% and 42% of study experimental plots in NGS and SS, respectively, fell within the ‘low yield and nutrient imbalanced’ category (LYI). The experimental plots in the LYI were dominated by the control (without any nutrient applied), N omitted (-N) and P omitted (-P) treatment plots. The significantly limiting nutrients in decreasing order of importance were: N, P > S > Cu, Mn > B in NGS and N, S > Cu > P > Mn, B in SS. Despite K, was not among the deficient nutrients in the control (unfertilized) plots of the nutrient imbalanced fields, application of N and P alone resulted to K deficiency in 60-100% in these fields. This implies that application of K is nevertheless required to achieve balanced nutrient supply in the Northern Nigerian savanna. These findings suggest the consideration of S, Cu, B and Mn in addition to the N, P and K in the nutrient and fertilizer management strategies to optimize nutrient limited maize yield in the Northern Nigerian savanna.

Thirdly, we used soil, yield and nutrient concentrations in the grain and stover from the NOTs to parameterize and validate the model QUEFTS (QUantitative Evaluation of Fertility of Tropical Soils). If successfully parametrized and validated, the model can be used to obtain balanced nutrient requirements (particularly N, P and K) for maize production at scale in the Northern Nigerian savanna to enable effective implementation of site-specific nutrient recommendation practices. We

focused on N, P and K only because with the present data these are the only nutrients which can be implemented. The parameters of maximum accumulation (*a*) and dilution (*d*) in kg grain per kg nutrient for the QUEFTS model obtained from our study were respectively 35 and 79 for N, 200 and 527 for P and 25 and 117 for K in the NGS zone; 32 and 79 for N, 164 and 528 for P and 24 and 136 for K in the SS zone; and 35 and 79 for N, 199 and 528 for P and 24 and 124 for K when the data of the two zones were combined. There was a close agreement between observed and parameterized QUEFTS predicted yields in each of the agro-ecological zone ($R^2 = 0.69$ for the NGS and 0.75 for the SS). Although with a slight reduction in the prediction power, a good fit between the observed and model predicted grain yield was also detected when the data for the two agro-ecological zones were combined ($R^2 = 0.67$). Therefore, across the two agro-ecological zones, the model predicted a linear relationship between grain yield and above-ground nutrient uptake until yield reached about 50 to 60% of the yield potential. When the yield target reached 60% of the potential yield (i.e. 6.0 t ha^{-1}), the model showed above-ground balanced nutrient uptake of 20.7, 3.4 and 27.1 kg N, P, and K, respectively, for one ton of maize grain. These results suggest an average NPK ratio in the plant dry matter of about 6.1:1:7.9. We concluded the QUEFTS model can be used for balanced nutrient requirement estimations and development of site-specific fertilizer recommendations for maize intensification in the Northern Nigerian savanna. Further nutrient omission and fertilizer response trials are needed involving the other identified limiting nutrients (i.e. S, Cu, Mn and B) highlighted in the second segment of this study above. This will enable validation of the impact of those nutrients, and equally this will allow for parametrization of the identified additional limiting nutrients in the QUEFTS model for site-specific management and recommendations to optimize maize yield limiting nutrient in the study region.

Finally, we investigated the influence of nutrient limitations and rainfall abundance on ^{13}C isotope discrimination (Δ) in the Northern Nigerian savanna. This was based on hypothesis that Δ values can be a proxy for the evaluation of nutrient and water stresses vis-à-vis their dynamics. Field experimental data (particularly yield) and ^{13}C isotope discrimination (Δ) in the maize ear leaves from the NOTs were used to achieve this aim. A significant effect (p-value <0.01) of nutrient application (NA) on Δ was observed, with N and P limitations (-N and -P) decreasing the Δ. A weak but significant negative correlation was observed between rainfall abundance and Δ at the critical first 25 days of growing period. In addition, genotypic characteristics also influenced the Δ (p-value < 0.01), as a larger Δ was observed in the open-pollinated variety compared to hybrid variety groups used in this study. These findings envisage that observations on Δ can potentially be used as a proxy to assess and monitor the N, P and water limitations in maize in the Northern Nigerian savanna. But, to quantify the changes in Δ due to N, P and water limitations that will enable practical application of the Δ values as a proxy for a nutrient and water limitations evaluation in maize in the Northern Nigerian savanna, further studies are needed. Such studies should involve a varying level of N, P and water limitations and involving all commonly grown maize cultivars.

Samenvatting

Maïs (*Zea mays* L.) is het meest gecultiveerde graangewas in Nigeria, vanwege de brede geschiktheidsgrenzen en tal van sociaal-economische toepassingen. De savanne in het noorden van Nigeria is het meest geschikte gebied vanwege de gunstige combinatie van voldoende regenval, lage nachttemperaturen en een lage druk van ziekten en plagen. Ondanks deze gunstige omstandigheden is de opbrengst van maïs in de regio laag (<2 t ha^{-1}), wat ver onder het potentieel van het gewas ligt. Als Nigeria zelfvoorzienend wil zijn in maïsproductie, om aan de vraag van de snelgroeiende bevolking te voldoen en zelfs voor een exportoverschot te zorgen, is het belangrijk dat de opbrengst van maïs toeneemt. Lage bodemvruchtbaarheid en onvoldoende beheer van nutriënten zijn enkele van de belangrijkste factoren die de opbrengst van maïs in de noordelijke Nigeriaanse savanne beperken. De meeste Nigeriaanse bodems zijn sterk verweerd en hebben kleisoorten met lage activiteit (zoals kaoliniet) waardoor ze gevoeliger zijn voor een sterke daling van de bodemvruchtbaarheid ten gevolge van een meer intensieve akkerbouw met onvoldoende voorziening van voedingsstoffen. Bovendien is het gebruik van anorganische meststoffen om de bodemvruchtbaarheid te verbeteren conventioneel gepromoot via 'algemene' bemestingsaanbevelingen die geen rekening houden met ruimtelijke (veld tot veld) en tijdelijke variabelen. Dit type bemestingsaanbevelingen leidt ongetwijfeld tot een onevenwichtige gewasvoeding, een lage efficiëntie van het gebruik van meststoffen en uiteindelijk tot lage opbrengsten. Over het algemeen is dit onderzoek uitgevoerd om de nutriëntengerelateerde beperkingen en onevenwichtigheden op schaal te evalueren, te kijken waar en waarom ze voorkomen, en om haalbare manieren te ontwerpen die deze opbrengst limiterende beperkingen tegen gaan en de maïsopbrengst in de noordelijke Nigeriaanse savanne optimaliseren. Diagnostische proeven met een selectief weglaten van voedingsstoffen (NOT's) op het veld werden uitgevoerd in 198 velden, verspreid over 14 locaties (districten) in de noordelijke Nigeriaanse savanne tijdens de regenseizoenen van 2015 en 2016. Alle districten vielen binnen twee agro-ecologische zones, d.w.z. de Noord-Guinese savanne (NGS) en de Sudan savanne (SS). De NGS is de meer vochtige zone met een gemiddelde jaarlijkse regenval van 1129 mm, terwijl de SS de relatief drogere zone is met een gemiddelde jaarlijkse regenval van 744 mm gedurende de twee jaar van het onderzoek. Twee sets van proeven werden naast elkaar uitgevoerd, één met een open bestoven maïsvariëteit (OPV) en de andere met een hybride maïsvariëteit. Elke set had dezelfde zes behandelingen met voedingsstoffen (NA). De behandelingen voor het aanbrengen van

voedingsstoffen (NA) omvatten (i) controle zonder toegevoegde voedingsstoffen (controle), (ii) N weggelaten met aangebracht P en K (-N), (iii) P weggelaten met aangebracht N en K (-P), (iv) K weggelaten met N en P aangebracht (-K), (v) behandeling met alle drie toegepaste voedingsstoffen (NPK), en (vi) een behandeling waarbij secundaire macronutriënten (S, Ca en Mg) en micronutriënten (Zn en B) werden aangebracht naast de NPK (NPK +).

Ten eerste werden bodem- en opbrengstgegevens van de NOT's gebruikt om de mate en status van variabiliteit in bodem- en maïsopbrengstrespons op de toediening van voedingsstoffen te kwantificeren. Afgezien van de pH en de uitwisselbare zuurheid (Al^{3+} + H^{+}), vertoonden alle bestudeerde bodemeigenschappen matige tot hoge variabiliteit (CV≥16%) tussen de bestudeerde velden. Daarbij identificeerde een clusteranalyse drie verschillende opbrengst-voedingsstofresponsklassen die van toepassing zijn voor de twee soorten maïsvariëteiten. Deze gedefinieerde klassen waren velden die (i) geen respons hebben op een voedingsstof (ii) een grote respons op N en P en (iii) een grote respons maar dan alleen op N. Hoewel de totale opbrengstprestaties van OPV en hybride variëteiten vergelijkbaar waren, kon een vierde klasse worden onderscheiden voor de hybride variëteit, d.w.z. (iv) velden met een grote respons op N + secundaire macro- en micronutriënten (NPK+). De resultaten geven aan dat rekening moet worden gehouden met de grote variabiliteit in de beperkingen van bodemvoedingsstoffen om de opbrengst aan maïs in de noordelijke Nigeriaanse savanne te optimaliseren. De ontwikkeling van veld- en locatiespecifieke bemestingsaanbevelingen met behulp van eenvoudige beslissingsondersteunende instrumenten die rekening houden met variabele bodemvruchtbaarheidscondities en heterogene opbrengstresponsen is dus broodnodig.

Ten tweede hebben we opbrengsten en voedingsstofconcentraties (N, P, K, S, Ca, Mg, Fe, Mn, Zn, Cu en B) in de kolfbladeren van de NOT's gebruikt om nutriëntbeperkingen en onevenwichtigheden te diagnosticeren met behulp van de compositorische voedingsstofdiagnose (CND) tool. Significante positieve correlatie werd waargenomen tussen maïskorrelopbrengst en de voedingsstofconcentraties, behalve voor Fe in respectievelijk NGS en Mg in SS. Ongeveer 40% en 42% van de experimentele plots in respectievelijk NGS en SS vielen in de categorie ‘low yield en nutrient disbalanced’ (LYI). De experimentele plots in de LYI werden gedomineerd door de controle (zonder enige voedingsstof aangebracht), en de plots waarin N werd weggelaten (-N) en P werd weggelaten (-P). De beperkende voedingsstoffen in afnemende volgorde van belangrijkheid waren: N, P> S> Cu, Mn> B in NGS en N, S> Cu> P> Mn, B in SS. Ondanks dat K niet tot de deficiënte voedingsstoffen behoorde in de controle (niet bemeste) plots van de onevenwichtige velden , resulteerde toediening van N en P alleen in K tot een tekort van 60-100% in deze velden. Dit houdt in dat K niettemin moet worden toegepast om een evenwichtige beschikbaarheid van voedingsstoffen in de noordelijke Nigeriaanse savanne te bekomen. Deze bevindingen suggereren de toediening van S, Cu, B en Mn als aanvulling op de N, P en K als een strategie voor het beheer van voedingsstoffen en meststoffen om de beperkte nutriëntenmaïs in de noordelijke Nigeriaanse savanne te optimaliseren.

Ten derde hebben we bodem-, opbrengst- en voedingsstofconcentraties in het graan en de gewasresten uit de NOT's gebruikt om het model QUEFTS (Kwantitatieve Vruchtbaarheid van Tropische Bodems) te parametriseren en te valideren. Indien met succes geparametriseerd en gevalideerd, kan het model worden gebruikt om evenwichtige nutriëntbehoeften (met name N, P en K) te verkrijgen voor maïsproductie in de noordelijke Nigeriaanse savanne om een effectieve implementatie van locatie-specifieke aanbevelingen mogelijk te maken. We hebben ons alleen gericht op N, P en K omdat met de huidige gegevens dit de enige voedingsstoffen zijn die kunnen worden geïmplementeerd. De parameters van maximale accumulatie (a) en verdunning (d) in kg graan per kg voedingsstof voor het QUEFTS-model verkregen uit onze studie waren respectievelijk 35 en 79 voor N, 200 en 527 voor P en 25 en 117 voor K in de NGS-zone ; 32 en 79 voor N, 164 en 528 voor P en 24 en 136 voor K in de SS-zone; en 35 en 79 voor N, 199 en 528 voor P en 24 en 124 voor K wanneer de gegevens van de twee zones werden gecombineerd. Er was een nauwe overeenkomst tussen waargenomen en geparametriseerde QUEFTS-model voorspelde opbrengsten in elk van de agro-ecologische zone (R^2 = 0,69 voor de NGS en 0,75 voor de SS).Er was een goede overeenkomst tussen de waargenomen en de gemodelleerde graanopbrengst (hoewel met een lichte vermindering van het voorspellingsvermogen), wat ook gedetecteerd werd wanneer de gegevens voor de twee agro-ecologische zones werden gecombineerd (R^2 = 0,67). Daarom voorspelde het model over de twee agro-ecologische zones een lineair verband tussen graanopbrengst en de opname van bovengrondse voedingsstoffen totdat de opbrengst ongeveer 50 tot 60% van het opbrengstpotentieel bereikte. Toen de opbrengstdoelstelling 60% van de potentiële opbrengst bereikte (dwz 6.0 ton ha^{-1}), vertoonde het model bovengrondse evenwichtige opname van voedingsstoffen van respectievelijk 20,7, 3,4 en 27,1 kg N, P en K voor een ton maïs. Deze resultaten suggereren een gemiddelde NPK-verhouding in de droge stof van de plant van ongeveer 6,1: 1: 7,9. We concludeerden dat het QUEFTS-model kan worden gebruikt voor een evenwichtige schatting van de behoefte aan voedingsstoffen en de ontwikkeling van locatiespecifieke bemestingsaanbevelingen voor het intensiveren van maïsproductie in de noordelijke Nigeriaanse savanne. Verdere proeven met weglating van voedingsstoffen en respons op meststoffen zijn nodig met betrekking tot de andere geïdentificeerde beperkende voedingsstoffen (d.w.z. S, Cu, Mn en B) die in het tweede segment van deze studie zijn gemarkeerd. Deze proeven zullen een validatie van de impact van die voedingsstoffen mogelijk maken, en evenzo zal parametrisering van de geïdentificeerde aanvullende beperkende voedingsstoffen in het QUEFTS-model mogelijk worden gemaakt om locatiespecifiek beheer van voedingsstoffen in de onderzoeksregio te optimaliseren en zo de opbrengst van maïs te verhogen.

Tot slot onderzochten we de invloed van nutriëntenbeperkingen en overvloed aan regenval op ^{13}C-isotoopdiscriminatie (Δ) in de noordelijke Nigeriaanse savanne. Dit was gebaseerd op de hypothese dat Δ waarden een proxy kunnen zijn voor de evaluatie van voedings- en waterbeschikbaarheid ten opzichte van hun dynamiek. Experimentele veldgegevens (met name opbrengst) en ^{13}C-isotoopdiscriminatie (Δ) in de maïsbladeren van de NOT's werden gebruikt om dit doel te bereiken. Een significant effect (p-waarde <0,01) van toediening van voedingsstoffen (NA) op Δ werd waargenomen, waarbij N- en P-beperkingen (-N en -P) de Δ verminderden. Een zwakke maar significante negatieve correlatie werd waargenomen tussen de Δ en een overvloedige regenval tijdens de kritieke eerste 25 dagen van de groeiperiode. Bovendien beïnvloedden genotypische kenmerken ook de Δ (p-waarde <0,01), omdat een grotere Δ werd waargenomen in de open bestoven variëteit in vergelijking met hybride variëteitgroepen die in deze studie werden gebruikt. Deze bevindingen suggereren dat deze ^{13}C-isotoopdiscriminatie inderdaad mogelijk als proxy kunnen worden gebruikt om de N-, P- en waterbeperkingen in maïs in de noordelijke Nigeriaanse savanne te beoordelen en bij te sturen. Maar om de veranderingen in Δ als gevolg van N-, P- en waterbeperkingen te kwantificeren die praktische toepassing van de Δ-waarden mogelijk maken als proxy voor een evaluatie van voedingsstoffen en waterbeperkingen in maïs in de noordelijke Nigeriaanse savanne, zijn verdere studies nodig. Zulke studies moeten een variërend niveau van N, P en waterbeperkingen omvatten, alsook alle algemeen geteelde maïscultivars omvatten.

List of abbreviations

AEZ	agro-eclogical zone
AICc	corrected Akaike Information Criterion
CM	Cumulative rainfall
CND	compositional nutrient diagnosis
CVA	critical value approach
DAE	days after emergence
DFP	days from planting
DRIS	diagnosis recommendation and integrated system
GDP	gross domestic product
GHI	grain harvest index
HYB	high grain yielding and nutrient balanced subpopulation
HYI	high grain yielding and nutrient imbalanced subpopulation
HSD	honestly significant difference test
HY	high grain yielding subpopulation
Hybrid	hybrid variety
ICP-OES	inductively coupled and plasma optical emission spectroscopy
IRMS	isotope ratio mass spectrometer
-K	a potassium omitted nutrient application treatment with nitrogen and phosphorus applied
KHI	potassium harvest index
LYB	low grain yielding and nutrient balanced subpopulation
LBL	lower boundary limit
LYI	low grain yielding and nutrient imbalanced subpopulation
LY	low grain yielding subpopulation
-N	a nitrogen omitted nutrient application treatment with phosphorus and potassium applied
NA	nutrient application
NGS	Northern Guinea savanna
NHI	nitrogen harvest index
NOTs	diagnostic on-farm nutrient omission trials
NPK	a nutrient application treatment with nitrogen, phosphorus and potassium applied
NPK+	a nutrient application treatment where secondary macro- and micro-nutrients (sulphur, calcium, magnesium, zinc and boron) where applied in addition to the nitrogen, phosphorus and potassium
OPV	open-pollinated variety
-P	a phosphorus omitted nutrient application treatment with nitrogen and potassium applied
PBIAS	percent bias
PCA	principal component analysis
PHI	phosphorus harvest index
QUEFTS	quantitative evaluation of fertility of tropical soils
RMSE	root mean square error
SMM	secondary macro- and micro-nutrients

SSA	sub-Saharan Africa
SS	Sudan savanna
SSNM	site-specific nutrient management
UBL	upper boundary limit
VG	variety group

List of symbols

symbol	**description**	**unit**
Δ	^{13}C isotope discrimination	‰ “per mil”
a	physiological efficiency at maximum accumulation of nutrient	kg grain per kg nutrient
clr	row-centered log ratios	-
CND r^2	compositional nutrient diagnosis imbalance index	-
CV	coefficient of variability	%
d	physiological efficiency at maximum dilution of nutrient	kg grain per kg nutrient
d-index	index of agreement	-
EA	soil exchange acidity (Al+H) of soil	$\text{cmol}_c\ \text{kg}^{-1}$
ECEC	soil effective cation exchange capacity of soil	$\text{cmol}_c\ \text{kg}^{-1}$
Ev_Y	environment mean grain yield	tons per hectare (t ha^{-1})
F_v	plant filling value	%
I	Shannon rainfall distribution index	-
N_{tot}	total nitrogen content of soil	g kg^{-1}
OC_{tot}	total organic carbon content of soil	g kg^{-1}
P_{av}	Mehlich-3 soil available phosphorus content	mg kg^{-1}
PhE	plant physiological efficiency of nutrient	kg grain per kg nutrient
R^2	coefficient of determination	-
R_i	average fertilizer recovery efficiency of ith nutrient	kg uptake of ith nutrient per kg ith fertilizer nutrient applied
r_i	minimum uptake of ith nutrient to produce any grain	kg ha^{-1}
S_{av}	soil available sulphur content	mg kg^{-1}
S_i	supply of available ith nutrient	kg ha^{-1}
U_i	total plant uptake of ith nutrient	kg ha^{-1}
Y_u	QUEFTS model ultimate yield estimate	kg ha^{-1}

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Chapter 1: Research background, objectives, hypothesis and thesis outline

1.1 Research background

1.1.1 Maize production in Nigeria (an overview)

Nigeria is situated in West Africa between 4°N and 14°N latitudes and 2°2'E and 14°30'E longitudes and occupies a total area of 923,770 km^2 (Figure 1.1). Nigeria is bordered to the east by Cameroon, to the west by Benin, to the north by Niger, northeast by Chad and to the south by an Atlantic Ocean. Climate and vegetation cover varied from humid Mangrove rain forest (per-humid) in the coastal southern border to near-desert (semi-arid) condition in the northern border of the country. The country is endowed with extensive arable land, suitable climates and water resources, which have provided the nation's agricultural sector a vast potential for increased growth (Ahungwa et al., 2014). In fact, agriculture accounted for 24.4% of Nigeria's gross domestic product (GDP) in 2017 (NBS, 2017) and close to 49% of the population depends on agriculture as their primary source of livelihood (WBD, 2019). The agricultural sector of Nigeria is dominated by crop production which constitutes 90% of the output, with livestock, fishery and forestry accounting for the remaining 10% (CBN, 2015). But, despite the vast agricultural potential of Nigeria, food security in the country is at risk due to rapid growth of human population. Currently, the country is the most populous country in Africa with a population of 200 million people and projected to grow to about 400 million by 2050 (UN DESA, 2019). Therefore, ensuring food security to this rapidly growing population through improvement of domestic food production is the principal aim of the Nigeria's agricultural transformation agenda (FMARD, 2011) and also the main approach to meet the second sustainable development goal "end hunger, achieve food security and improve nutrition and promote sustainable agriculture" (UN DESA, 2015).

Maize (*Zea mays* L.) or corn is one of the most important cereal crops in Nigeria with a diverse use as food, feed and industrial raw material. Maize is additionally the only food source available during the hunger period in the Nigerian savanna which occurs every year around July when at the end of the dry period all other food reserves are depleted and the new crop of the current growing season is not ready for harvest (Badu-Apraku et al., 2015). Factors like wide suitability boundaries and high productivity make maize an attractive crop for farmers and the most widely grown cereal in Nigeria. Nigeria was the 14th largest producer of maize

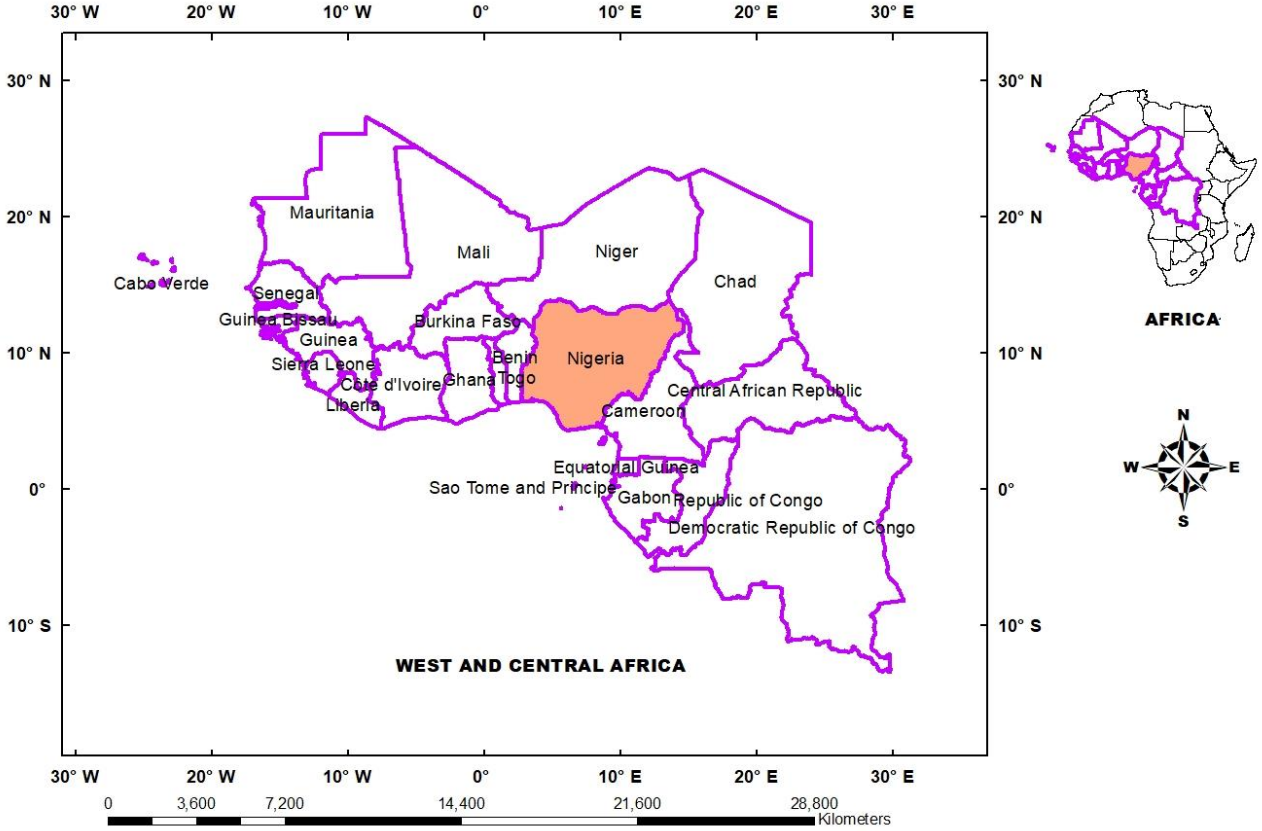


Figure 1.1: Map of West and Central Africa showing the location of Nigeria. Adapted from map library (http://www.maplibrary.org/library/stacks/Africa/index.htm).

in the world and second largest producer in Africa after South Africa in 2017 (FAOSTAT, 2018a). Therefore, the crop has a pivotal role in the Nigeria's food security, agricultural policy and development, and wider in the West and Central Africa.

Examining the production trend over the last six decades, annual maize production quantity in Nigeria increased by almost tenfold from 1.1 million metric tons in 1961 to about 10.4 million metric tons in 2017 (FAOSTAT, 2018a) (Figure 1.2). There was an alignment between maize production and area harvested (except between 2000 and 2010) (Figure 1.2) which highlighted the increase in maize production in Nigeria was largely due to increase in cultivated area rather than intensification. Increase in demand amidst growing utilization by food processing industries and livestock feed mills (Omobolanle et al., 2005; Girei and Galadima, 2016) and the development of early and extra early varieties which permitted production in the drier agro-ecological zones (Kamara et al., 2009) are among the critical

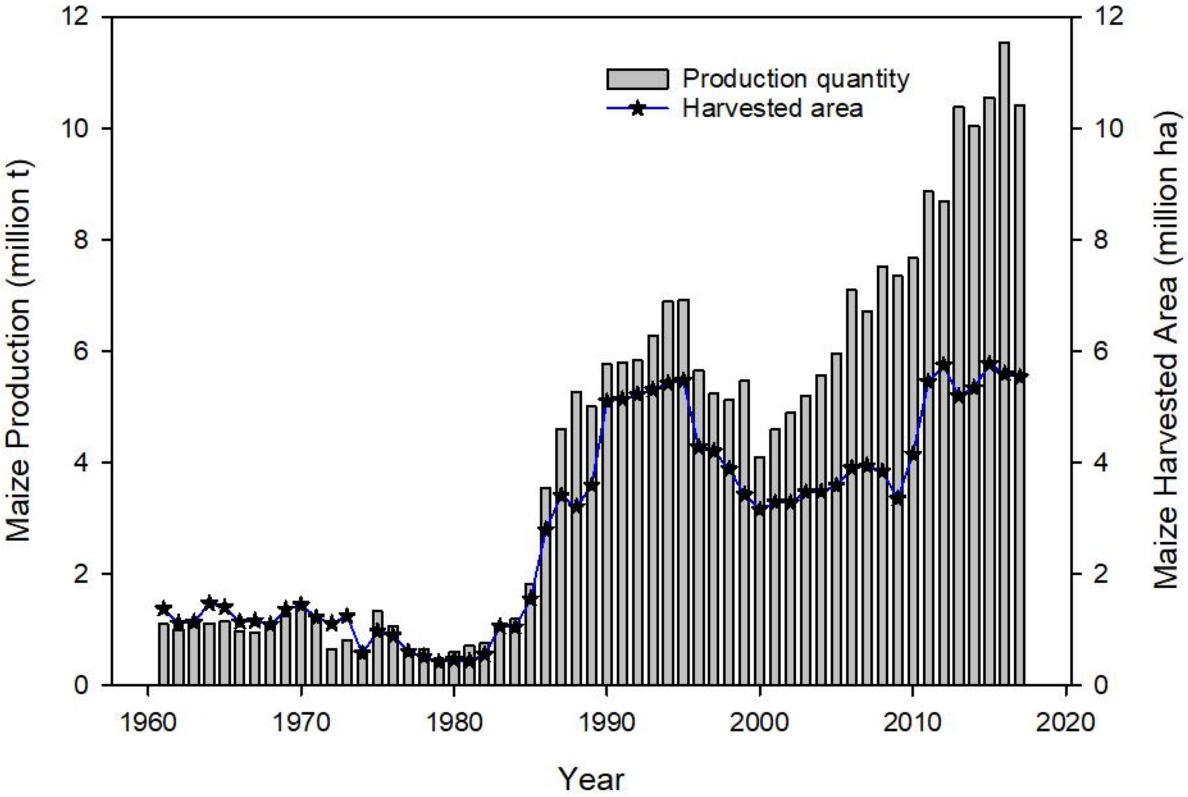


Figure 1.2: Evolution in production quantity and harvest area of maize in Nigeria (FAOSTAT, 2018a).

factors responsible for an increase in the cultivated area of maize in Nigeria. Indeed, the increase in production, despite stagnant harvested area observed between 2000 and 2010 can be related to the increased access to the subsidized fertilizer and improved varieties by the farmers (Cadoni and Angelucci, 2013).

Despite the increase in production, however, maize production in Nigeria has not kept pace with population growth and market demands (Ado et al., 2007). Average maize grain yield in Nigeria has stagnated below 2 tons per hectare (t ha^{-1}) (Figure 1.3). This represents less than 19% and 29% of the water limited potential yield (GYGA, 2017) and well-managed experimental station attainable yield (Fakorede and Akinyemiyu, 2003; Sileshi et al., 2010a), respectively.

Simultaneously, opportunities for further increase in the cultivated area in Nigeria are limited due to demographic and other non-agriculture related pressures (Bojo, 1996). This implies that further increase in maize production will be largely derived from increasing output per unit area. Therefore, for Nigeria to become self-sufficient in maize production, responding to

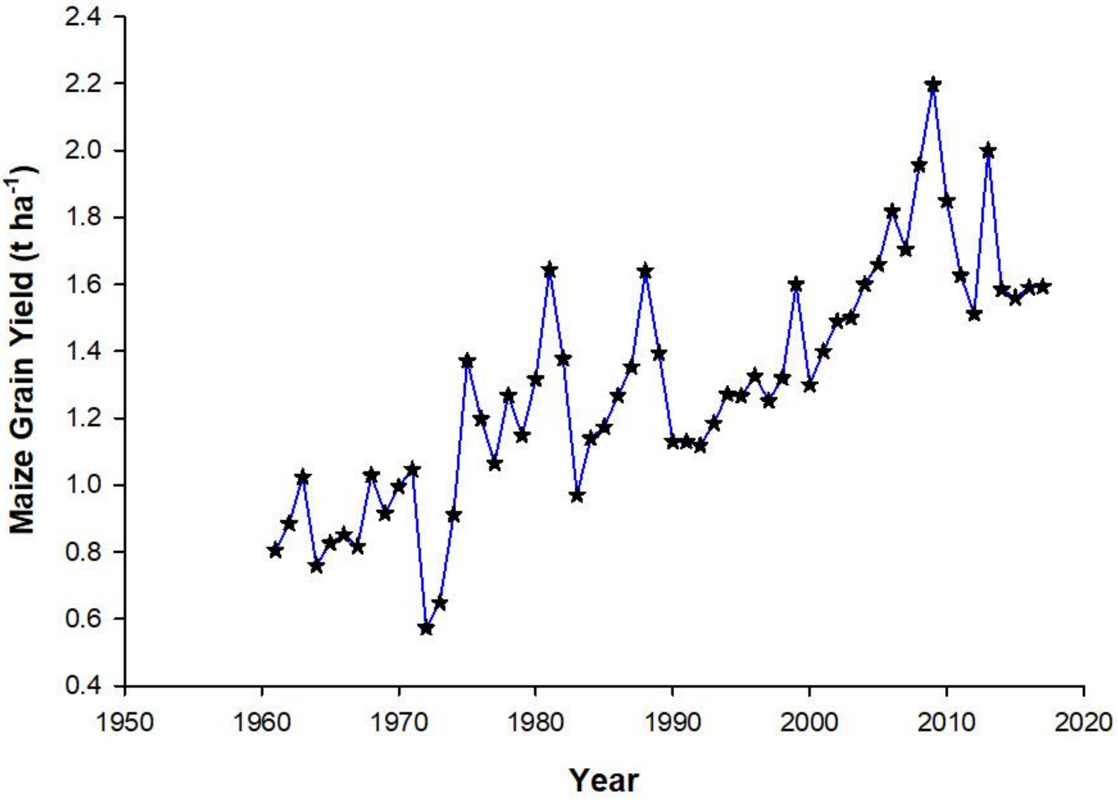
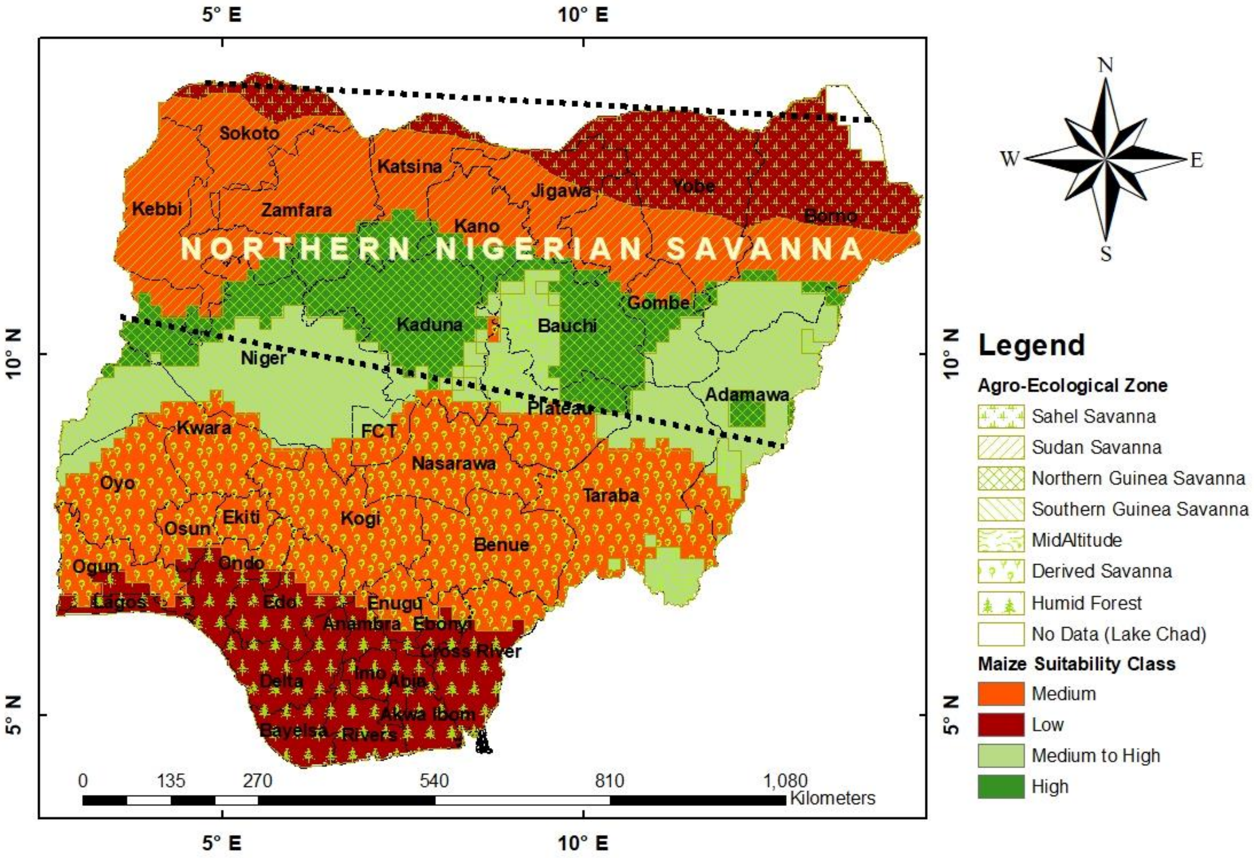


Figure 1.3: Evolution in maize grain yield in Nigeria (FAOSTAT, 2018b)

the internal demand and even provide for an export surplus, it is important for the low and stagnant yield to increase.

1.1.2 Northern Nigerian savanna: A major maize production belt in Nigeria

The Northern Nigerian savanna spans the entire Northern states of Nigeria involving four sub-savanna agro-ecological zones (i.e. Southern Guinea savanna, Northern Guinea savanna, Sudan savanna and Sahel savanna) and some spots of mid-altitude zone in the mountainous areas (Figure 1.4). The Southern Guinea savanna is wettest sub-zone with an annual rainfall between 1300-1700mm located in the southern part of the region (Ayanlade, 2009). The Northern Guinea savanna sub-zone is sub-humid to moist semi-arid zone with an annual rainfall of 900-1400mm (Ayanlade, 2009). In the Sudan savanna zone annual rainfall range from about 600-1000mm with a dry season of 6-8 months (FDF, 2019). The Sahelian zone is dry semi-arid to arid zone with annual rainfall of less than 600mm and a dry season exceeding 8 months (FDF, 2019). The mid-altitude zone is located in the montane areas like Jos Plateau



The maize suitability map was adapted from: Plan for maize transformation (www.unaab.edu.ng)

Figure 1.4: Map of Nigeria showing Northern Nigerian savanna and maize suitability classification.

with high altitude (> 1200m), annual average annual rainfall of 1450mm and have the lowest annual average temperature of 21°C (Sowunmi and Akintola, 2010). The major soil types in the Southern Guinea savanna are Lixisols and Nitisols, while in the Northern Guinea savanna are the same Lixisols but with Plinthosols, although presence of some spots of Cambisols are noticeable across the two sub-savanna zones (Figure 1.5). Plinthosols, Lixisols and Arenosols forms the major soil types in the Sudan savanna zone, while in the dry Sahelian zone Arenosols and Fluvisols are the major soil types (Figure 1.5). In the montane areas (i.e. mid-altitude zone), Nitisols, Luvisols and Acrisols are the major soil types (Figure 1.5).

The Northern Nigerian savanna region constitutes the largest maize suitability area. In fact, it contain the Northern Guinea savanna which is regarded as the maize belt of the country owing to its favorable combination of adequate rainfall, high solar radiation, low night temperature and less incidence of biotic stresses, all of which are considered most suitable for maize production (Badu-Apraku et al., 2015). Five years study by Fakorede *et al*. (1989) observed a higher grain yield, taller plants and shorter grain filling duration in maize in the

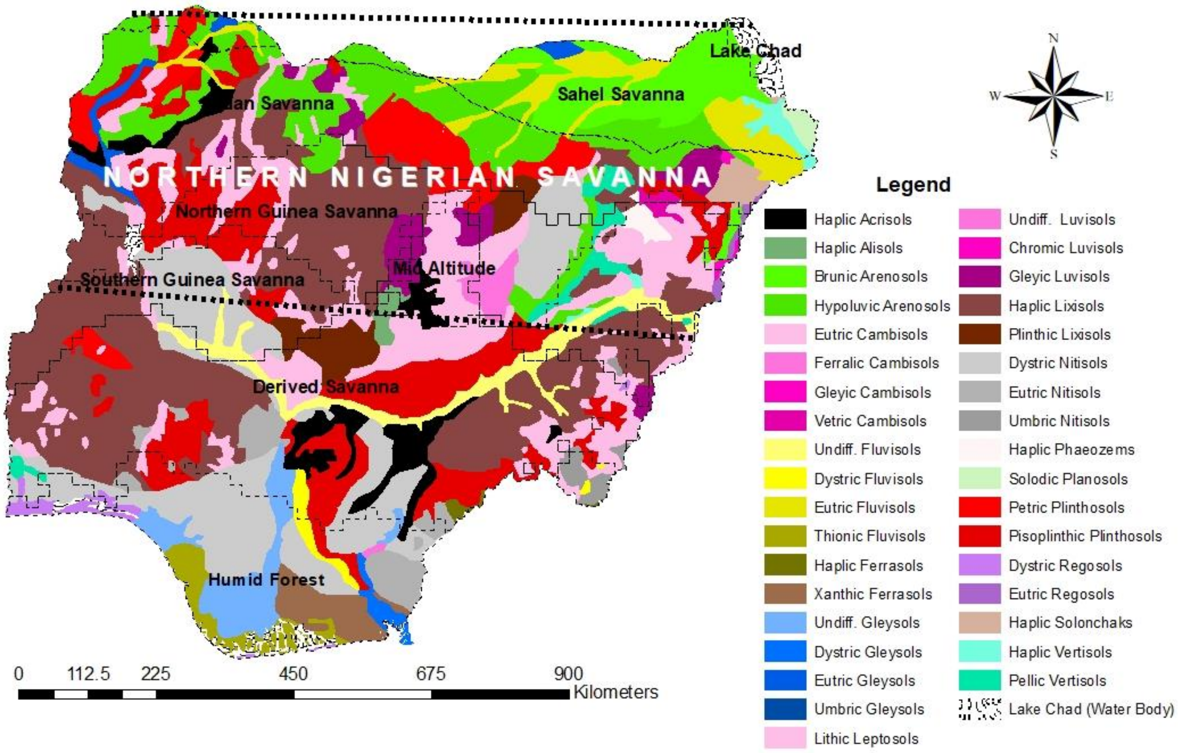


Figure 1.5: Major of Nigeria showing agro-ecological zones and major soil types. Map of soil types was adapted from Soil Atlas of Africa "https://esdac.jrc.ec.europa.eu/content/soil-map-soil-atlas-africa" (Dewitte et al., 2013).

Northern Nigerian savanna compared to the Southern forest zone. The development of extra early and early maturing varieties have made the low rainfall Sudan savanna zone also a suitable agro-ecology for maize production (Kamara et al., 2009). However, the dry Sahelian zone of the Northern Nigerian savanna is less suitable for maize production owing to small amount of rainfall hardly reaching 600 mm per annum (Sharon, 2013).

1.1.3 Constraints of maize production in Northern Nigerian savanna

The potential of maize production in the Northern Nigerian savanna has been constrained by many biophysical and socio-economic factors. Most of the constraints also applied to neighboring countries of West and Central Africa with similar ecological and climatic characteristics.

Biophysical constraints (pests and diseases, inadequate moisture and poor soil fertility)

The low yield of maize in the Northern Nigerian savanna (average of 1 to 2 t h^{-1} in farmers' fields) has been largely attributed to multiple biotic and abiotic stresses (Kamara, 2017). The most important biotic constraints are the parasitic *S. hermonthica* (witchweed) weed and infestation by stem borer complex (Kamara, 2017). While the abiotic constraints are erratic rainfall pattern with unpredictable recurring seasonal drought and fragile soils with small organic matter and nutrients contents (Kamara, 2017).

Pests and diseases

In many parts of the West African savannas, *S. hermonthica* remain a notorious weed parasite constituting a great threat to maize production. *S. hermonthica* is estimated to have infested about 2.4 to 4 million ha of land under maize production in SSA, causing yield losses of 30 to 80% (Gressel et al., 2004; Ejeta, 2007). In the Northern Nigerian savanna, Dugje et al. (2006) found *S. hermonthica* infestation in about 77% of the fields. The number of *S. hermonthica* plants per ha was significantly higher ($p<0.05$) in the Sudan savanna than in the more humid ecologies of Northern and Southern Guinea savannas (Dugje et al., 2006). To reduce yield losses due to the *S. hermonthica* infestation, various *S. hermonthica* tolerant maize varieties have been developed across SSA (Kim, 1991; Garba et al., 2017).

Inadequate moisture

Maize production is largely done under rainfed condition in the Northern Nigerian savanna, therefore the amount and duration of rainfall determines the growth and yield of maize. In most parts of the West African savanna including the Northern Nigerian savanna, rainfall is unreliable (Kamara, 2017) and frequently less than that required to meet the 450-600mm of soil available water for an optimal maize growth and productivity (Plessis, 2003). Droughts occurs in three forms in the Northern Nigerian savanna (Eckebil, 1991). In the Southern Guinea savanna where rainfall is higher relative to the other savanna zones, instability in the establishment of the rains occurs frequently and sometimes late establishment of the rain compels farmers to replant the maize. In the Northern Guinea savanna, owing to the instability of onset and cessation of rain, mid-season and terminal drought conditions do repeatedly occur. In the Sudan savanna, an early season and terminal drought situations are almost an annual event. Annual maize loss due to recurrent drought is approximately about 10-25% in SSA and localized losses in the savanna might be considerably higher (Edmeades et al., 1995; Fisher et al., 2015). Although more work is still required, to manage the water stress, early and extra early drought tolerant varieties have been developed across SSA including the Northern Nigerian savanna through the project called “Drought Tolerant Maize for Africa (DTMA)” between 2007 and 2013 (Fisher et al., 2015).

Poor soil fertility

Poor soil fertility has been reported as one of the most significant abiotic constraints contributing to the persistent small yields in SSA including the Northern Nigerian savanna (Henao and Baanante 2006; Vanlauwe et al., 2006). As presented above (Figure 1.6), the dominant soils in the Nigerian savanna soils are highly weathered Lixisols, Plinthosols, Arenosols, Cambisols and Nitisols. With an exception of Cambisols, the soils are characterized by low activity clays, small organic matter contented and low in nutrient reserves (Jones and Wild 1975; FDALR 1999; FFD 2012). Due to the presence of excessive amount of active iron (Fe) in Nitisols, high phosphate fixation represents another significant limitation of this soil. Additionally, Cambisols are among the most fertile soils in Africa, the highly weathered ones also have limited amount of nutrients (Dewitte et al., 2013). On top of this, intensive agriculture through continuous and at the same time inappropriate cropping systems and poor soil management have also resulted in serious degradation of the fragile soils resulting in poor crop performance. In SSA, maize is largely produced in smallholder farms of less than 2 ha with inadequate fertilizer use and/or organic resources (Giller et al., 2011). The crop residues after harvest are completely removed from the soil for livestock and other needs or at times burnt, with the harvested nutrients significantly never returned to the soil (J D Kwari et al., 2011). Annual soil nutrient losses are high in Nigeria and estimated at 36 kg N ha^{-1}, 11 kg P_2O_5 ha^{-1}, and 40 kg K_2O ha^{-1} (Henao and Baanante, 1999). Even in situations where adequate fertilizer is available to the farmers, the fertilizer use is still being promoted through blanket and regional based recommendation in Nigeria (FFD, 2012). This recommendation remains semi-site specific focusing on mainly three primary macronutrients (N, P and K). Semi-site specificity here resides in the fact that recommendation was estimated based on few data for large areas, which did not consider inter-field spatial and temporal variability of soil fertility. This type of recommendation generally leads to inappropriate fertilizer use, which eventually results in nutrient imbalances which affect the overall soil fertility, the maize productivity and in turn farmer's returns. Snapp et al. (1998) reported that cultivation of maize with low and unbalanced nutrient application remain the underlying agronomic cause of soil fertility decline and large yield gaps in SSA. Therefore, to optimize the productivity of maize in the Northern Nigerian savanna zone, evaluation of site-specific nutrient related constraints and viable ways to counteract such constraints become imperative.

Socio-economic constraints

Socio-economic condition and policies affect the accessibility, availability and type of crop production inputs the farmers can use and in turns their production potentials. Inadequate infrastructure, poor access to credit facilities, high cost of inputs, inadequate storage facilities, poor producer prices and inconsistency of government policies and regulations constitute the major socio-economic problems affecting farmers' maize production activities in the Northern Nigerian savanna (Tahirou et al., 2009; Issa et al., 2016; Ufiobor, 2017; Girei et al., 2018). Limited or poor quality of infrastructure like roads and rail transportation inhibit timely access to inputs, increase costs of input and decrease access to output markets located in the major cities (Phillip et al., 2009). Access to credit facilities has been linked positively to agricultural productivity in various studies. Issues of collateral and high interest rates leave out small-holder farmers from accessing bank loans (Phillip et al., 2009). Maize as a high nutrient demanding crop, fertilizer is the most important input needed by farmers in the Northern Nigerian savanna. However, the cost of fertilizer is high due to poor infrastructure and the government subsided fertilizer is hugely inadequate and often available very late in the cropping season (WBD, 2019). In Nigeria, agricultural policies and programs undergone several changes since the nation's independence from colonialism till date merely due to changes in government or administration (Iwuchukwu and Igbokwe, 2012). This implies there has not been continuity of existing policies and programs by incumbent and new admiration so that the impact of those policies/programs can be fully realized (Iwuchukwu and Igbokwe, 2012).

1.1.4 The concept and dynamics of nutrient limitations and imbalances

Plants transform light energy into biomass via photosynthesis and produce a variety of products of an economic value (grain, fiber, nuts, fruits, vegetable and fodder) among others (Roy et al., 2006). To perform this function, plants need adequate light, suitable temperature, and other substances including water, CO_2, oxygen and several essential nutrients. A total of 16 elements are essential for the growth and development of higher green plants (Table 1.1) according to the criteria laid down by Arnon and Stout (1939):

- Omission of the element in question must result in abnormal growth, failure to complete the life cycle or premature death of the plant.
- The element must be specific and not replaceable by another.
- The element is involved directly in the nutrition of the plant quite apart from its possible effects in correcting some unfavorable microbiological or chemical condition of the soil or other culture medium.

Plants require a sustained and optimal supply of these essential nutrients during the growing season for an optimal growth and yield. But a variety of natural (biophysical) and human induced (management) factors can lead to an imbalance of one or more of the nutrients, thus limiting crop growth and yield. The imbalance of the nutrient(s) here refers to a condition when the supply of one or more nutrients to the plant becomes inadequate (deficient) or in excess (toxic) which can retard crops growth, productivity or quality. According to Vitousek et al. (2010) nutrient limitation occurs “when meaningful additions of an essential element in biologically available forms cause an increase in the rate of a biological process (such as primary productivity) and/or in the size of an important ecosystem compartment (such as biomass)”. In plant nutrition, there is a law known as *Liebig’s law of the minimum*. The name was derived after the law inventor i.e. Justus von Liebig, who said the growth of a plant is limited by the nutrient that is in shortest supply (in relation to plant need). Once the supply of the most limiting nutrient is improved, the next nutrient in the shortest supply controls plant growth. The Liebig’s concept has been described in many ways. One of such is to imagine a barrel with staves of different height (Figure 1.6). Such a barrel can only hold water to a maximum of its shortest stave. The barrel can be full only when all its staves are of the same size and at the same time at their maximal height. However, plants require the supply of the limiting nutrient(s) to be balanced, as imbalance supply triggers nutrient interactions which

Table 1.1: Essential plant nutrients elements by form utilized and their biochemical function (Jones Jr, 2012)

Essential Element	Form Utilized	Biochemical Function
C, H and O	CO_2, H_2O	Are combined in the photosynthesis process to form a carbohydrate that becomes the physical structure of the plant
N, S	NO_3^-/NH_4^+, SO_4^{2-}	Combine with carbohydrates to form amino acids and proteins that become involved in enzymatic processes
P	PO_4^{3-}, $H_2PO_4^-$, HPO_4^{2-}	Involved in the energy transfer reactions
B	H_3BO_3, BO_3^{3-}	Involved in carbohydrate reactions
K, Mg, Ca, Cl	K^+, Ca^{2+}, Mg^{2+}, Cl^-	Involved in the osmotic potentials, balancing anions, controlling membrane permeability and electro-potentials
Cu, Fe, Mn, Zn, Mo	Cu^{2+}, Fe^{2+}/Fe^{3+}, Zn^{2+}, MoO_4^{2-}	Enable electron transport by valency change

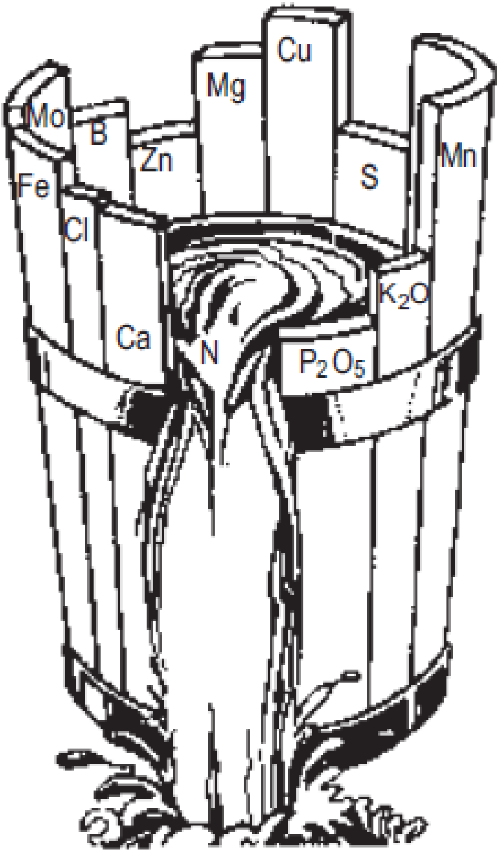


Figure 1.6: Demonstration of the law of the minimum using a barrel with staves of different heights (adopted from Roy et al., 2006)

can impede the absorption and utilization of other nutrient(s), thus affecting plants growth and productivity. In translation, plant can only produce to its fullest (potential) of nutrient limited yield when all the essential nutrients are at an optimal and balanced level i.e. without any deficiencies or excesses (Roy et al., 2006). Therefore, to optimize nutrient limited crop yield, plant nutrition requires a steadfast effort to eliminate limiting factors and provide balanced nutrition in the optimal range. In a broader sense, the law of minimum can be extended to include all production factors, not only the nutrients.

The evaluation and assessment of soil and plant nutrient status are conceivably the most decision-making tool for an effective and balanced nutrient management. There are three basic techniques for evaluating the soil/plant nutrient status which include: i) plant visual observations in the field, ii) soil testing, and iii) plant analysis or tissue testing. Visual observations of deficiency symptoms are a qualitative technique to diagnose nutrient stress. If detected early enough in the season, deficiency symptoms can be considered when to decide whether addition of the deficient nutrient(s) through fertilizer is required or not. But the fact that many nutrients deficiencies might appear similar and/or some nutrient deficiencies does not always result into physical symptoms (in the case of marginal deficiency or hidden hunger) limits the effectiveness of visual observation approach. Soil and plant analysis are the most effective quantitative approaches for diagnosing the nutrient status, where the concentration of nutrient is compared with the established sufficiency or critical concentration ranges for a specific crop species. Below the critical or sufficiency ranges the nutrient in question is considered deficient and above is in excess. Although, plant and soil analysis complement each other, but nutrients critical or sufficiency ranges are more precise and easier to be developed from plant tissue rather soil concentrations. This is due to the lack of an easily soil a measurable index for nutrients like N and significant impact of soil extraction method on the availability of some nutrients like P and micronutrients. Soil tests for the plant available N (ammonium N “NH_4^+” and nitrate N “NO_3^-”) gives only information at the time measurement and do not quantify the overall availability in the soil do to their high fluctuations with changes in soil condition such as temperature and moisture (Horneck et al., 2011). Previous studies (Fernandes et al., 1999; Csathó et al., 2005; Wuenscher et al., 2015) observed a significant difference in the soil available P content among different extraction methods. In the same vein, various studies such as Vocasek and Friedericks (1994); García et al. (1997); Fonseca et al. (2010) have documented a significant difference in the quantity of the extracted available micronutrients (Cu, Zn, Mn and Fe) among different extraction methods.

The plant nutrient critical or sufficiency ranges can be developed from nutrient omission experiments or fertilizer response experiments using various nutrient composition diagnostic approaches like Critical Value Approach “CVA” (Bates, 1971), Diagnosis Recommendation and Integrated System “DRIS” (Walworth and Sumner, 1987), and Compositional Nutrient Diagnosis “CND” (Parent and Dafir 1992; Parent et al. 1993; Khiari et al. 2001).

1.2 Research objectives and hypotheses

1.2.1 Objectives

Nutrient limitations and imbalances are among the most fundamental constraints contributing to small and stagnant maize yield in the Northern Nigerian savanna. This doesn’t merely limit the maize yield potential but also limits the farmer’s income and livelihood as maize is the most widely cultivated crop in the region. Therefore, the broad objective of this research was to evaluate those nutrient related limitations and imbalances, where and why they occur, and design feasible ways to counteract them in a demand to optimize maize yield in the Northern Nigerian savanna. The specific objectives were to:

1. Quantify inter-field variability of soil fertility and maize yield response to nutrient application in the Northern Nigerian savanna.
2. Diagnose nutrient limitations and imbalances in maize in the Northern Nigerian savanna.
3. Parameterize and validate the QUEFTS model for balanced and site-specific nutrient requirements for maize in the northern Nigerian savanna.
4. Assess the suitability of ^{13}C isotope discrimination as a proxy for evaluating nutrient and water limitations in maize in the Northern Nigerian savanna.

1.2.2 Hypotheses

1. Maize farmer’s fields are highly heterogenous in soil nutrient contents in the Northern Nigerian savanna. A regional based blanket fertilizer recommendation strategy for maize not is an appropriate approach.

2. Nutrient balances in maize cropping system in the Northern Nigerian savanna are predominantly negative.
3. The QUEFTS model can be employed as a tool for making site-specific nutrient requirements and recommendations to improve maize nutrient balances and yield in the Northern Nigerian savanna.
4. Differential ^{13}C isotopic discrimination can be used as a tracer for nutrient and water limitations in maize in the Northern Nigerian savanna.

1.3 Outline of the thesis

The outline of this thesis is dramatically presented in Figure 1.7 below. **Chapter 1** elucidates the background of the study comprising evolution of maize production in Nigeria and later confined to the maize production potential and associated constraints in the Northern Nigerian savanna. Subsequently, the concept of nutrient limitations and imbalances was discussed. The latter section of this chapter outlines the objectives and hypotheses of the study, with the concluding part presenting the outline of this thesis. **Chapter 2** addresses objective 1 and hypothesis 1. Specifically, this chapter reveals the extent and status of inter-field variability of soil fertility and delineates associated diverse classes of maize yield response to nutrient application in maize based-cropping systems in the Northern Nigerian savanna. **Chapter 3** deals with objective 2 and hypothesis 2 where detailed methodology and results of diagnosis of nutrient limitations and imbalances were presented. **Chapter 4** reports the parametrization and validation results of the model QUEFTS (QUantitative Evaluation of Fertility of Tropical Soils) for balanced and site-specific nutrient requirements and recommendations in the Northern Nigerian savanna which addresses objective 3 and hypothesis 3. **Chapter 5** assesses the relationship between ^{13}C isotope discrimination and nutrient limitations/rainfall abundance in a quest to use ^{13}C isotope discrimination as a proxy for nutrient limitation diagnosis in the study area (objective 4 and hypothesis 4). **Chapter 6** contains the general conclusions, recommendations and future outlooks derived from this study.

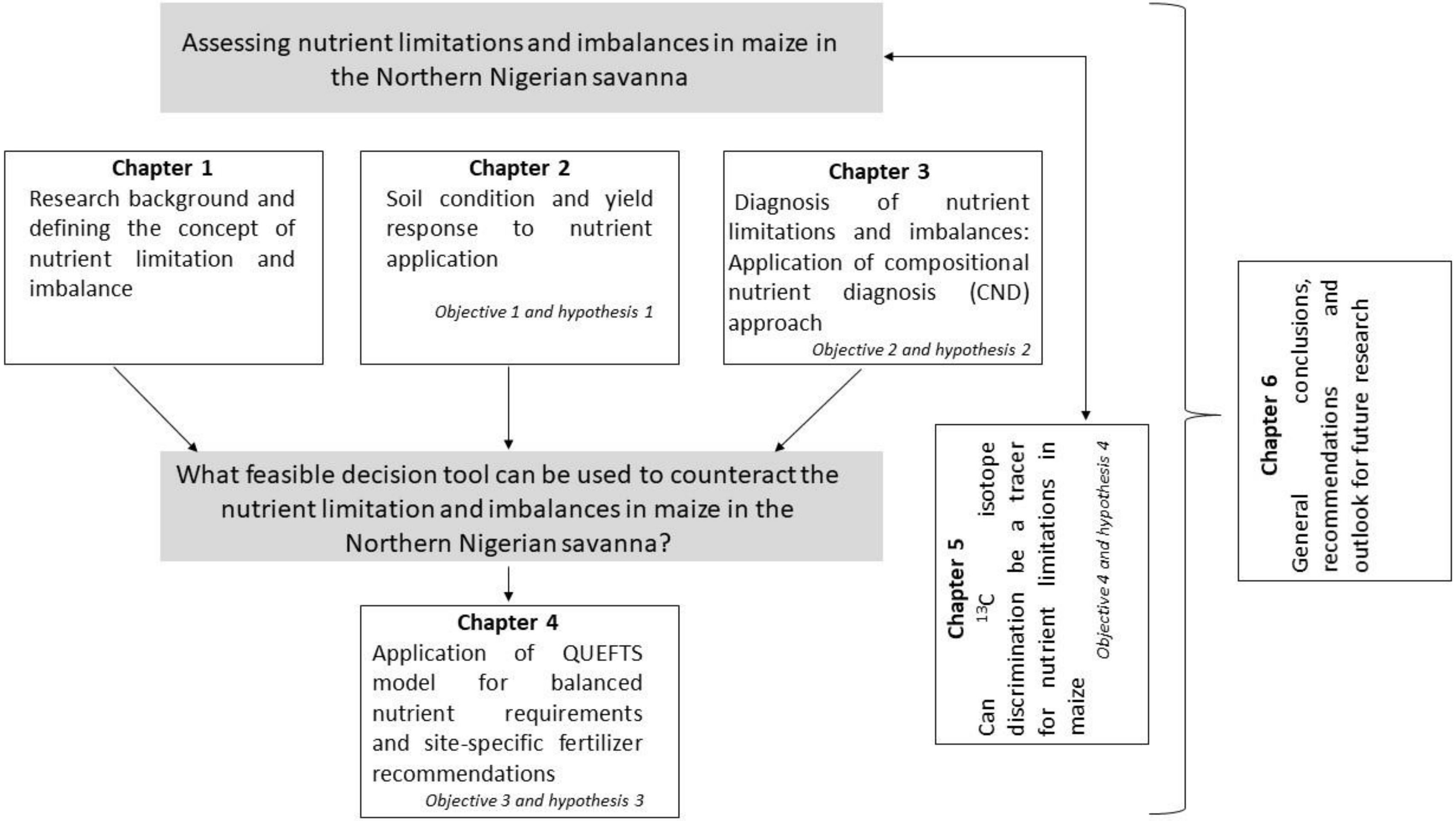


Figure 1.7: Diagram depicting the structure of this thesis.

Chapter 2: Quantifying inter-field variability in maize yield response to nutrient applications in the Northern Nigerian savanna

Adapted from: Shehu, B.M., Merckx, R., Jibrin, J.M., Kamara, A.Y., Rurinda, J., 2018. Quantifying variability of maize yield response to nutrient applications in the Northern Nigerian savanna. *Agronomy* ***8***(2), 18. **https://doi.org/10.3390/agronomy8020018**

Summary

Diagnostic on-farm nutrient omission trials were conducted over two cropping seasons (2015 and 2016) to assess soil nutrient related constraints to maize yield in the Northern Nigerian savanna agro-ecological zone and to quantify their inter-field variability. Two sets of trials were conducted side by side, one with an open pollinated maize variety (OPV) and the other one with a hybrid maize variety and each set had six equal treatments laid out in 198 farmers' fields. The treatments comprised (i) a control, (ii) a PK ('−N,' without N), (iii) an NK ('−P,' without P), (iv) an NP ('−K,' without K), (v) an NPK and (vi) an NPK + S + Ca + Mg + Zn + B ('NPK+' NPK plus secondary macro- and micro-nutrients). Moderate to large variability in most soil characteristics was observed among the studied fields. Consequently, cluster analysis revealed three distinct yield-nutrient response classes common for the two types of maize varieties. These classes were fields that have (i) no-response to any nutrient, (ii) a large response to N and P and (iii) a large response to N alone. Although overall yield performance of OPV and hybrid varieties was similar, a distinct fourth class was identified for the hybrid variety i.e. (iv) fields with a large response to N and secondary macro- and micro-nutrients. The results indicate that the large inter-field variability in soil nutrient related constraints need to be accounted for to optimize maize yield in the Northern Nigerian savanna. The development of field- and area-specific fertilizer recommendations is highly needed, using simple decision support tools that consider variable inter-field soil fertility conditions and yield responses as obtained from this study.

2.1 Introduction

Factors such as wide suitability boundaries and multiple socioeconomic uses make maize (*Zea mays* L.) the most widely grown cereal in Nigeria (Adesoji et al., 2016). According to FAO (Food and Agriculture Organization) data (FAOSTAT, 2017a), the land area planted to maize in Nigeria increased from 1.38 to 5.20 million hectares (1961–2013). This substantial expansion of the land area devoted to maize cultivation resulted in an increase in production from 1.10 to 10.40 million metric tons over the same period (FAOSTAT, 2017a). However, maize yield per unit area in Nigeria is still low, at about 2 t ha^{-1} (FAOSTAT, 2017a) which is far below yields observed in well-managed field experiments of more than 7 t ha^{-1} (Fakorede and Akinyemiyu, 2003; GYGA, 2017; Sileshi et al., 2010b). Meanwhile, studies from many parts of the country have shown an increasing demand for maize amidst growing utilization by food processing industries and livestock feed mills (Girei and Galadima, 2016; Omobolanle et al., 2005). Since opportunities to expand the cultivated area are limited (Bojo, 1996), further increases in maize production will be derived from sustainable intensification on existing farmland.

Inherent low soil fertility and poor nutrient management have been two of the major factors limiting maize yield in Nigeria (Ekeleme et al., 2014). Most Nigerian soils are highly weathered with low activity clays (such as kaolinite) which makes them more vulnerable to fertility degradation under continuous arable use with poor nutrient replenishment (Jones and Wild, 1975; FDALR, 1999; FFD, 2012). Deficiencies in soil primary macronutrients (particularly N, P and K) are widespread and have been reported in most parts of the country (Ekeleme et al., 2014; Hengl et al., 2017; Manu et al., 1991; Shehu et al., 2015). In addition, deficiencies of S and some micronutrients have also been reported in some Nigerian savanna soils (Lombin, 1987; Nziguheba et al., 2009; Hassan, 2016). Poor soil fertility is currently being addressed by blanket fertilizer recommendations developed based on agro-ecological zones and focused mainly on three primary macronutrients (N, P and K) introduced in the early 1970s by the government of Nigeria (FFD, 2012). These recommendations were developed for large areas based solely on limited, on-station fertilizer experiments conducted between 1950 and 1970 (FFD, 2012). For instance, a rate of 120/60/60 in kg ha^{-1} for $N/P_2O_5/K_2O$, respectively, is recommended for maize in the Northern Guinea savanna region. Although annual fertilizer consumption in Nigeria has increased from 154 to 550 thousand tonnes (FAOSTAT, 2017b) from 2002 to 2013, its use efficiency has remained low due to the inability of current blanket recommendations to account for variability in soil fertility between and within farmer's fields (Morris et al., 2007; Nziguheba et al., 2009; Sheahan and Barrett, 2014). Variability in soil fertility may be (i) inherent due to differences in soil forming factors including parent material, local climate and vegetation (Deckers, 2002) (ii) and/or due to differences in cropping history and soil management practices depending on farmer's production potentials and other socio-economic factors (P. Tittonell et al., 2005; Vanlauwe et al., 2010). Additionally, some of the reasons why optimal nutrient use efficiency is rarely achieved in farmer's fields despite the NPK addition, may be due to other nutrient limitations (Nziguheba et al., 2009), together with other factors like water stress, pest and diseases, management, etc. For example, responses of maize to S and some micronutrients have been documented in some savanna soils of western and southern Africa (Friesen, 1991; Nziguheba et al., 2009; Ojeniyi and Kayode, 1993; Weil and Mughogho, 2000). To develop a more robust and effective fertilizer recommendation approach that targets specific field conditions or growing environments, quantifying the inter-field variation of soil fertility status and associated responses to nutrient applications is critical.

Multiple location nutrient omission trials conducted in farmer's fields offer the most effective and simple way to study these variations in response. Thereafter, multivariate cluster analysis may provide an insight into the magnitude, extent and governing factors that are responsible for these variability patterns (Perez-Quezada et al., 2003). Multivariate cluster analyses group fields with similar responses to nutrient application into distinct classes (Fridgen et al., 2004). Previous studies by Kihara et al. (2016) attempted to understand the extent and distribution of variability in maize response to fertilizer and amendments in sub-Saharan Africa (SSA). However, Kihara et al. (2016) covered only one village (Pampaida, Ikara located in the Northern Guinea savanna of Nigeria) while their findings were invoked as representative for the entire maize production zone in Nigeria. Given the huge variability, this generalization seems insufficient to arrive at proper site-specific fertilizer formulations and recommended application rates to improve fertilizer use efficiency in Nigeria. Therefore, this study was conducted in major maize production areas in the Northern Guinea and Sudan savanna zones of Nigeria to: (i) assess the status and the extent of inter-field variability of soil fertility in maize-based cropping systems, (ii) understand the extent and distribution of different classes of maize yield response to nutrient applications and (iii) delineate soil properties that are responsible for the different yield-nutrient response classes.

2.2 Materials and Methods

2.2.1 Site selection and description

Diagnostic on-farm nutrient omission trials (NOTs) were conducted across fourteen study sites (districts) in three administrative states of Northern Nigeria: Kaduna (with experimental fields in Lere, Kauru, Soba, Ikara, Makarfi and Giwa local government areas), Katsina (with experimental fields in Funtua, Dandume, Faskari and Bakori) and Kano (with experimental fields in Tofa, Bunkure, Tudun Wada and Doguwa) (Table 2.1, Figures 2.1 and 2.2). The study and field experimental sites were purposefully selected to cover a wide range of maize growing conditions in major maize production potential areas and to cover areas where research for development can support extension programs engaged in maize value chain initiatives. The Northern Guinea savanna (NGS) is the main agro-ecological zone common to all the study sites except Tofa and Bunkure that belong to the Sudan savanna (SS) agro-ecological zone (Figure 2.1). In each of the fourteen study sites, one to two (depending on the size of the study site) 10 km × 10 km grid-cells were randomly generated using ArcGIS version 10.2.2 software (Environmental System Research Institute, Redlands, California, USA). Then, within each of these 10 km × 10 km grid-cells, five 1 km × 1 km sub grid-cells were randomly distributed. In each of the 1 km × 1 km sub grid-cells, one experimental field was randomly selected based on the availability of land for the trial set-up. Ninety-five (95) and one hundred and three (103) experimental fields were selected in the 2015 and 2016 rainy seasons, respectively (Table 2.1 and Figure 2.1). In each of the selected experimental field, two sets of trials were established side by side; one with an open pollinated maize variety “OPV” and the other one with a hybrid maize variety “hybrid.”

2.2.2 Experimental design, management and laboratory analyses

The on-farm diagnostic field trials were conducted using a nutrient omission trial design consisting of six treatments. The treatments included a control (“Control”) without nutrients applied, N omitted (“−N”) with P and K applied, P omitted (“−P”) with N and K applied, K omitted (“−K”) with N and P applied, NPK treatment (“NPK”) and a treatment (“NPK+”) where

Table 2.1: Description of study sites and number of experimental fields where the on-farm diagnostic nutrient omission trials (NOTs) were conducted in the Northern Nigerian savanna in the 2015 and 2016 cropping seasons

Study Sites	State	Agro-Ecological Zone	No. of Experimental Fields	Year (Season)
Bakori	Katsina	NGS	20	2015 & 2016
Bunkure	Kano	SS	15	2015 & 2016
Dandume	Katsina	NGS	15	2015 & 2016
Doguwa	Kano	NGS	20	2015 & 2016
Faskari	Katsina	NGS	10	2016
Funtua	Katsina	NGS	19	2015 & 2016
Giwa	Kaduna	NGS	10	2016
Ikara	Kaduna	NGS	18	2015 & 2016
Kauru	Kaduna	NGS	5	2016
Lere	Kaduna	NGS	15	2015 & 2016
Makarfi	Kaduna	NGS	14	2015 & 2016
Soba	Kaduna	NGS	18	2015 & 2016
Tofa	Kano	SS	5	2016
Tudun Wada	Kano	NGS	14	2015 & 2016
		Total	198	

NGS = Northern Guinea savanna agro-ecological zone, SS = Sudan savanna agro-ecological zone.

secondary macronutrients (S, Ca and Mg) and micronutrients (Zn and B) were applied in addition to the NPK.

The primary macronutrients (N, P and K) were applied at 140 kg N ha^{-1}, 50 kg P ha^{-1} and 50 kg K ha^{-1} for NGS sites; and at 120 kg N ha^{-1}, 40 kg P ha^{-1} and 40 kg K ha^{-1} for SS sites. The secondary macronutrients and micronutrients were applied at 24 kg S ha^{-1}, 10 kg Ca ha^{-1}, 10 kg Mg ha^{-1}, 5 kg Zn ha^{-1} and 5 kg B ha^{-1} in all sites. NPK fertilizer nutrients were applied at rates considered to be sufficient to achieve the expected attainable yield without nutrient limitation in each agro-ecological zone. Nitrogen (N) was applied in three equal splits, i.e. at planting (basal), at 21 and 42 days after emergence (DAE). All other nutrients were applied at planting. Nutrients applied at planting were applied using band row placement and incorporated, while the 2nd and 3rd N splits were applied by side dressing and earthen-up. The field trials were established and managed by researchers.

The OPV varieties used were *IWD C2 SYN F2* (with 105–110 days to maturity) and *EVDT W STR* (with 90–95 days to maturity) in NGS and SS study sites, respectively. While hybrid varieties used were *OBA SUP-9* (with 105–110 days to maturity) and *OBA SUP-1* (with 105–118 days to maturity) for 2015 and 2016 seasons, respectively in all study sites. The treatment plot size was 5 m × 6 m (30 m^2) with a plant spacing of 0.75 m (inter-row) × 0.25 m (intra-row).

Four auger soil samples were collected at 0–20 cm depth from each field during trial

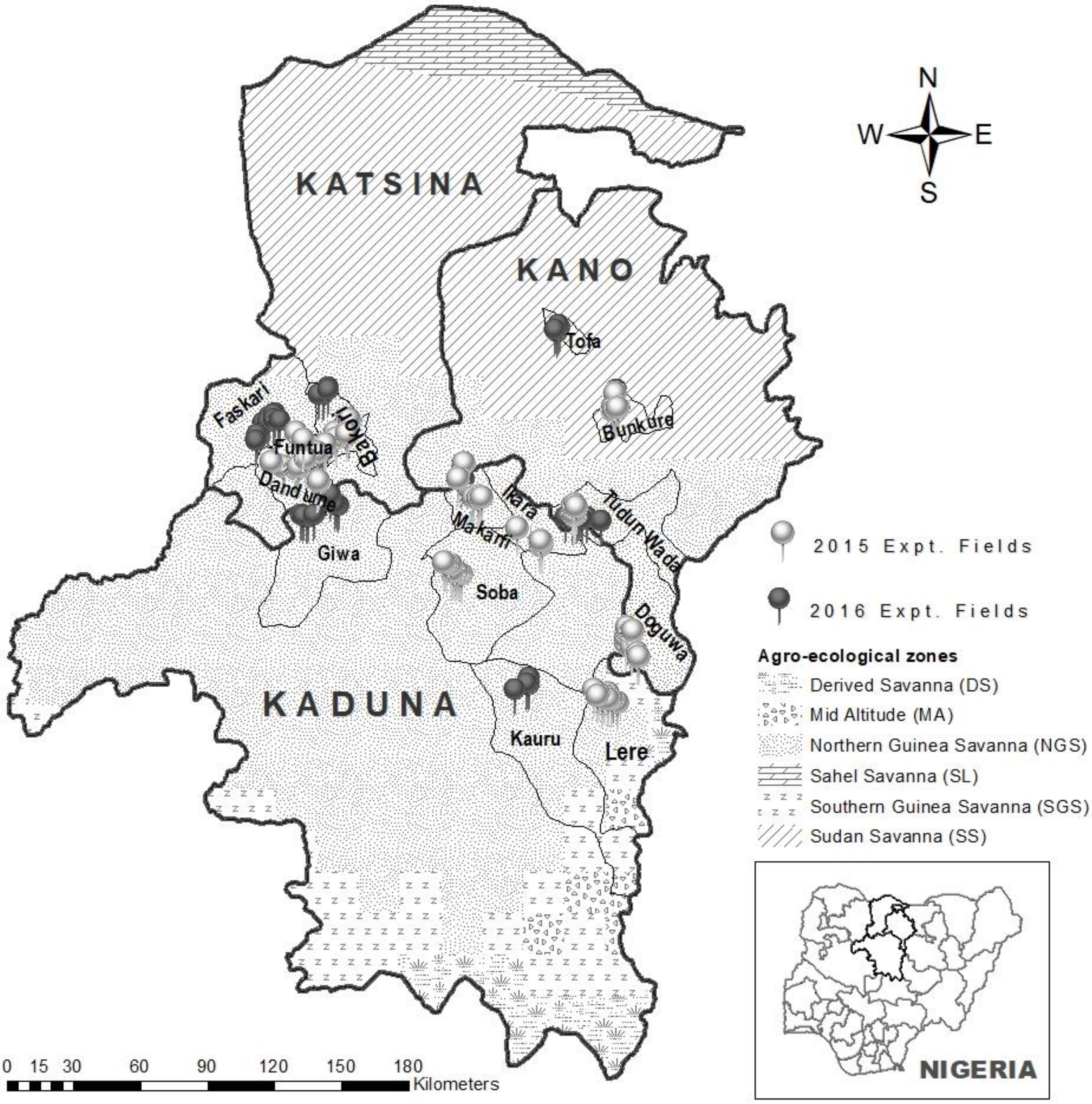


Figure 2.1: A map of Nigeria showing study sites (districts) and experimental fields for on-farm diagnostic nutrient omission trials (NOTs) established in 2015 and 2016 cropping seasons.

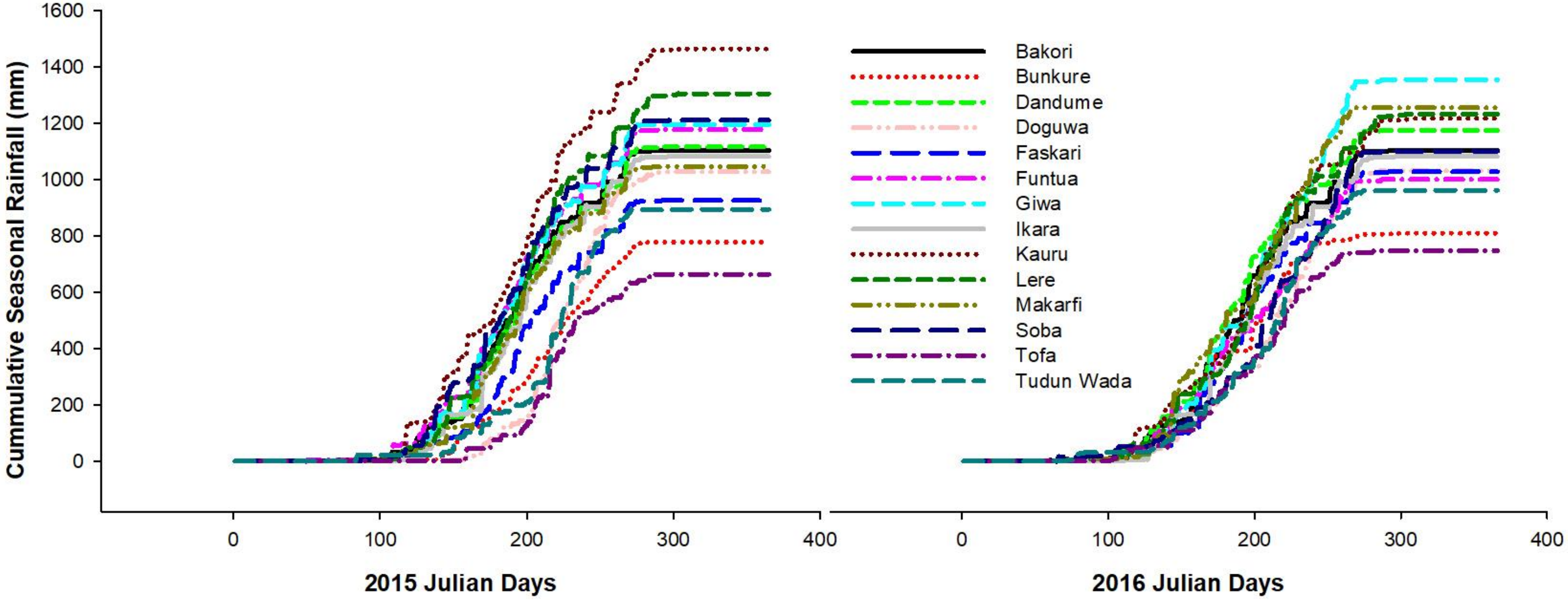


Figure 2.2: Seasonal cumulative rainfall recorded in two cropping seasons, 2015 and 2016, at each on-farm diagnostic nutrient omission trial (NOTs) study site.

establishment before application of fertilizer treatments using a V zig-zag random sampling pattern. The four collected samples were thoroughly mixed and passed through a 2 mm sieve to have one disturbed composite sample per field for laboratory analysis. In addition, one undisturbed core sample was also collected close to each of the four auger points in each field and used for bulk density determination using the thermo-gravimetric core method (Blake and Hartge, 1986); the results were averaged to have one bulk density value per field.

The disturbed composite samples were used to analyse major soil characteristics using wet chemistry. Total soil organic carbon (OC_{tot}) was measured using a modified Walkley & Black chromic acid wet chemical oxidation and spectrophotometric method (Heanes, 1984). Total soil nitrogen (N_{tot}) was determined using a micro-Kjeldahl digestion method (Bremner, 1996). Soil pH in water (S/W ratio of 1:1) was measured using a glass electrode pH meter and the particle size distribution following the hydrometer method (Gee, 2002). The soil texture was categorized according to USDA classification system (USDA, 1993). Soil available phosphorus (P_{av}), available sulphur (S_{av}), exchangeable cations (K, Ca, Mg and Na) and micronutrients (Zn, Fe, Cu, Mn and B) were analysed based on the Mehlich-3 extraction procedure (Mehlich, 1984) preceding inductively coupled plasma optical emission spectroscopy (ICP-OES, Optima 800, Winlab 5.5, PerkinElmer Inc., Waltham, Massachusetts, USA). Exchangeable acidity ($H^+ + Al^{3+}$) was determined by extracting soil with 1M KCl and titration of the supernatant with 0.5M NaOH (Anderson and Ingram, 1993). Effective cation exchange capacity (ECEC) was calculated as the sum of exchangeable cations (K^+, Ca^{2+}, Mg^{2+} and Na^+) and exchangeable acidity ($H^+ + Al^{3+}$). All the laboratory analyses were performed at the IITA laboratories in Ibadan, Nigeria.

Harvesting was carried out at physiological maturity in a net plot of 9 m^2 (i.e. comprising four middle rows of 3 m length). Plants in the net plot were harvested and total fresh weights of cobs and stover were recorded. Ten cobs and five stalks of stover were randomly selected as subsamples to account for grain shelling percentage and moisture content after air-drying. The random selection was carried out by first counting the number of cobs or stalks in the net plot and then randomly arranging them in line; the subsamples were then taken at every interval calculated as the total number of cobs or stalks in the net plot over the number of subsamples to be taken. Finally, grain yield was expressed on a dry weight basis at 15.0% moisture content.

2.2.3 Data analysis

Descriptive statistics were used to check the average and standard deviation values of each of the soil characteristics at each study site using JMP version 13.0 statistical software (SAS Institute Inc., 2017). Inter-field variation in soil properties was assessed using the coefficient of variation (CV) and rated as small (≤15%), moderate (16–35%) and large (>35%) (Wilding, 1985). Analysis of variance on the response of yield to fertilizer treatments was also conducted at each study site using JMP version 13 software, a linear mixed model was used with experimental fields within study sites used as a random factor. The analysis excluded fields where responses to treatments were observed to have been affected by waterlogging, poor weed management and excessive damage by intruders (thieves or livestock). Thus, 174 out of 198 fields were analysed. The analysis of variance was conducted at two levels; (i) comparing the control with NPK treatments across the sites to explore the overall effect of NPK and (ii) comparing the yield difference of the treatments relative to NPK to assess yield gain/loss when a nutrient was omitted or applied across the study sites. The treatment effects were also regressed against the ‘environment’ yield (calculated as the average yield for all treatments at a given study site) to evaluate the most stable nutrient application treatment effect across the study sites (Raun et al., 1993).

To obtain a meaningful and straightforward classification of the different fields, grouping those with similar nutrient response patterns, multivariate K-means cluster analysis was used. This provides an opportunity to design appropriate fertility management interventions that can be recommended. The cluster analysis was conducted on the yield difference of each treatment relative to the control. To select an optimal number of clusters, observations on meaningful distinct cluster response patterns and on the high cubic clustering criterion (CCC) (Sarle, 1983) were used in 2–10 successive K-means clusters using JMP version 13.0 statistical software. Finally, 3 clusters were retained in OPV and 4 clusters in hybrid trials. A multinomial logistic regression model was then used to understand soil characteristics and the associated nutrient management history responsible for the presence of a field in a specific cluster. Due to some outliers in the soil characteristics, a total of 132 fields for OPV and 115 fields for hybrid were used in the multinomial logistic regression. For each identifiable cluster, an average value of each soil characteristic variable was presented to shed more light on its characteristics.

2.3 Results

2.3.1 Soil physicochemical characteristics

Soil particle size distribution showed a moderate inter-field variability with a dominant sand fraction across all the study sites (Table 2.2). Doguwa, Kauru and Lere sites have a clay loam to sandy clay loam texture while Bunkure, Tofa and Tudun Wada have a sandy loam texture. The other sites have a loam texture. All the sites apart from Tofa have an average bulk density below 1.6 g cm^{-3} considered best for root growth and aeration in a soil with a larger sand fraction relative to clay and silt (Arshad et al., 1996). Soil pH showed a small inter-field variability across the sites with a mean value ranging from 5.6 to 6.4 (Table 2.2) and hence soils are categorized as moderately acid (5.6–6.0) to slightly acid (6.1 to 6.5). Soil total organic carbon (OC_{tot}) showed a large variation among the experimental fields, although all the average values fell below 10 g kg^{-1} which is considered low according to the ratings of the National Special Programme on Food Security (NSPFS) (NSPFS, 2005). Soil total nitrogen (N_{tot}) content was also generally low like the OC_{tot} but with a moderate variability among the experimental fields. Soil available phosphorus (P_{av}) differed strongly across the fields with average values of the study sites ranging from 3.1 mg kg^{-1} to 25.0 mg kg^{-1} (Table 2.2). Low values of P_{av} (<7 mg kg^{-1}) were recorded in Funtua, Dandume, Faskari and Bakori and high values (>20 mg kg^{-1}) in Tofa. Other remaining sites had moderate contents (7–20 mg kg^{-1}) according to the same NSPFS (2005) categorization. Available sulphur (S_{av}) showed a moderate variability among the studied fields, with all the mean values across the study sites (districts) occurring within the moderate region (5.1–20 mg kg^{-1}) according to Horneck et al. (2011).

The concentration of exchangeable calcium (Ca) varied moderately across the fields (Table 2.3), with an average content in the study sites between 1.42 and 3.21 $cmol_c$ kg^{-1}. However, most of the study sites have a moderate content (2–5 $cmol_c$ kg^{-1}) except for Lere, Faskari and Bunkure sites with a low content (<2 $cmol_c$ kg^{-1}) as suggested by the classification of ESU (1991). Moderate contents of exchangeable magnesium (Mg) concentration (0.3–1.0 $cmol_c$ kg^{-1}) were also observed in all the study sites (Table 2.3). Exchangeable potassium (K) exhibits large inter-field variability across the study sites with an average content ranging from a moderate (0.16) to high (0.35 $cmol_c$ kg^{-1}) values (Table 2.3). In all the sites (Table 2.3), the

Table 2.2: Selected physical (texture and bulk density) and chemical (pH_{H2O}, OC_{tot} and N_{tot}, P_{av} and S_{av} contents) characteristics of the study sites

Study Sites	Sand	Silt	Clay	Bulk Density	pH_{H2O}	OC_{tot}	N_{tot}	P_{av}	S_{av}
	(%)	(%)	(%)	(g cm^{-3})		(g kg^{-1})	(g kg^{-1})	(mg kg^{-1})	(mg kg^{-1})
Bakori	51 (7)	30 (6)	19 (3)	1.48 (0.11)	6.2 (0.4)	6.40 (2.15)	0.37 (0.07)	3.96 (3.70)	6.41 (1.06)
Bunkure	68 (4)	17 (4)	14 (2)	1.54 (0.13)	6.4 (0.5)	4.74 (2.23)	0.29 (0.06)	10.90 (9.20)	5.21 (0.88)
Dandume	46 (8)	32 (8)	22 (4)	1.60 (0.05)	5.8 (0.4)	7.44 (2.22)	0.46 (0.08)	4.00 (2.35)	7.39 (1.08)
Doguwa	36 (6)	35 (5)	29 (6)	1.51 (0.16)	5.8 (0.5)	8.39 (2.03)	0.55 (0.12)	12.52 (7.66)	8.32 (1.75)
Faskari	46 (7)	29 (6)	25 (3)	1.53 (0.17)	5.6 (0.5)	5.39 (1.07)	0.46 (0.11)	3.08 (3.04)	6.95 (1.50)
Funtua	43 (6)	34 (6)	23 (4)	1.5 (0.07)	5.8 (0.4)	6.87 (2.51)	0.46 (0.12)	4.37 (3.40)	7.10 (1.09)
Giwa	43 (6)	34 (5)	23 (3)	1.47 (0.14)	5.8 (0.6)	6.31 (1.45)	0.53 (0.12)	9.88 (9.22)	7.10 (0.84)
Ikara	48 (8)	30 (5)	22 (6)	1.57 (0.15)	5.6 (0.4)	6.55 (2.43)	0.45 (0.08)	12.73 (8.68)	7.28 (1.64)
Kauru	57 (4)	21 (7)	22 (4)	1.56 (0.09)	5.7 (0.2)	6.34 (0.54)	0.46 (0.05)	18.34 (1.78)	7.66 (1.59)
Lere	54 (8)	24 (4)	22 (6)	1.60 (0.10)	5.7 (0.5)	5.85 (1.71)	0.38 (0.10)	9.22 (6.86)	6.77 (0.97)
Makarfi	45 (8)	33 (5)	22 (6)	1.55 (0.15)	5.7 (0.4)	7.6 (2.66)	0.43 (0.09)	9.56 (9.43)	7.56 (1.44)
Soba	44 (7)	36 (6)	20 (3)	1.59 (0.11)	5.9 (0.4)	8.28 (2.94)	0.51 (0.10)	12.98 (8.55)	7.34 (1.52)
Tofa	70 (7)	15 (4)	15 (4)	1.62 (0.04)	5.7 (0.7)	2.72 (0.72)	0.25 (0.06)	24.98 (2.79)	5.39 (0.64)
Tudun Wada	59 (7)	23 (7)	18 (3)	1.52 (0.08)	6.2 (0.6)	6.21 (1.96)	0.49 (0.10)	17.24 (10.03)	7.77 (1.41)
CV (%)	22.4	27.7	26	8.0	8.4	37.6	28.5	87.7	21.1

CV: coefficient of variation across the study fields; Numbers are mean with standard deviation in brackets. OC_{tot}: total soil organic carbon; N_{tot}: total soil nitrogen; P_{av}: soil available P; S_{av}: soil available sulphur.

Table 2.3: Exchangeable cation concentrations, ECEC and exchangeable acidity of the different soils in the study sites

Study Sites	Ca	Mg	K	Na	Exchange Acidity	ECEC
	(cmol$_c$ kg^{-1})	(cmol$_c$ kg^{-1})	(cmol$_c$ kg^{-1})	(cmol$_c$ kg^{-1})	(cmol$_c$ kg^{-1})	(cmol$_c$ kg^{-1})
Bakori	2.51 (0.52)	0.82 (0.20)	0.23 (0.17)	0.09 (0.01)	0.00 (0.00)	3.64 (0.63)
Bunkure	1.88 (0.88)	0.51 (0.16)	0.23 (0.10)	0.08 (0.03)	0.01 (0.04)	2.69 (0.99)
Dandume	2.16 (0.59)	0.61 (0.19)	0.17 (0.09)	0.08 (0.01)	0.00 (0.00)	3.01 (0.69)
Doguwa	2.82 (0.81)	0.93 (0.30)	0.20 (0.10)	0.09 (0.02)	0.03 (0.08)	4.05 (0.96)
Faskari	1.42 (0.27)	0.73 (0.19)	0.35 (0.21)	0.09 (0.01)	0.07 (0.10)	2.64 (0.40)
Funtua	2.43 (0.75)	0.77 (0.26)	0.20 (0.10)	0.08 (0.02)	0.03 (0.07)	3.48 (0.84)
Giwa	2.24 (0.56)	1.00 (0.30)	0.16 (0.07)	0.09 (0.00)	0.06 (0.09)	3.54 (0.71)
Ikara	2.26 (0.73)	0.49 (0.23)	0.28 (0.15)	0.07 (0.02)	0.10 (0.11)	3.18 (0.89)
Kauru	2.03 (0.27)	0.81 (0.14)	0.16 (0.07)	0.09 (0.00)	0.00 (0.00)	3.07 (0.32)
Lere	1.80 (0.83)	0.48 (0.26)	0.20 (0.05)	0.07 (0.02)	0.02 (0.04)	2.55 (1.04)
Makarfi	2.06 (0.65)	0.68 (0.22)	0.20 (0.16)	0.08 (0.01)	0.15 (0.31)	3.16 (0.94)
Soba	2.13 (0.58)	0.72 (0.17)	0.17 (0.08)	0.08 (0.01)	0.00 (0.00)	3.09 (0.68)
Tofa	2.64 (0.33)	0.42 (0.13)	0.19 (0.07)	0.09 (0.00)	0.09 (0.08)	3.41 (0.39)
Tudun Wada	3.21 (0.92)	0.73 (0.24)	0.27 (0.11)	0.08 (0.02)	0.00 (0.00)	4.27 (1.20)
CV (%)	34.6	39.2	59.8	23.2	3.4	29.0

CV: coefficient of variation across the study fields; Numbers are mean with standard deviation in brackets; ECEC: effective cation exchange capacity of soil.

average values of exchangeable sodium (Na), exchangeable acidity ($H^+ + Al^{3+)}$ and effective cation exchange capacity (ECEC) were low, i.e. <0.1, <1.0 and <6.0 cmol$_c$ kg^{-1}, respectively. Average values of available iron (Fe), zinc (Zn) and manganese (Mn) in the soils (Table 2.4) are indicative of a high fertility class as suggested by Esu (1991) rating (>5.0, >2.0 and >5.0 mg kg^{-1} for Fe, Zn and Mn, respectively). Available copper (Cu) showed a moderate inter-field variability across the sites with average values falling between moderate (0.21–2 mg kg^{-1}) and high (>2.0 mg kg^{-1}) values (Table 2.4). Despite a large inter-field variability of boron (B) concentration across the study sites (Table 2.4), the average values below 0.349 mg kg^{-1} indicated a very low status following NSPFS (2005) classification.

2.3.2 Yield response to fertilizer treatments

Application of NPK significantly increased grain yield in all the study sites (Figure 2.3). Averaged across study sites, the overall yield performance of OPV and hybrid varieties was similar. However, the incremental yield response to NPK application relative to control varied among the various sites. In OPV trials, NPK application produced grain yield that was twice as high as that of the control in all sites, except in Giwa, Bunkure, Bakori, Funtua and Dandume where an increase of 97%, 93%, 90%, 72% and 50% was observed, respectively (Figure 2.3). Similarly, in hybrid trials, application of NPK resulted in grain yield of more than twice that of the control in all study sites except in Dandume where an increase of 53% was observed (Figure 2.3).

There was a wide variation among the study sites and varieties in terms of loss or gain in maize grain yield resulting from the omission of primary macronutrient(s) from the NPK treatment or addition of secondary macro- and micro-nutrients to the NPK treatment (Figure 2.4). In both OPV and hybrid trials, an omission of N (−N) from the NPK resulted in a loss in grain yield of at least 1.5 t ha^{-1} in all sites except at Bunkure where a reduction of less than 1.2 t ha^{-1} was observed (Figure 2.4). Largest reduction in grain yield of more than 3 t ha^{-1} due to −N was found in Lere and Makarfi for the OPV and in Lere, Kauru, Faskari, Bakori and Tofa for the hybrid maize variety. The omission of P (−P) similarly led to a drastic reduction in maize grain yield relative to the NPK treatment in all the sites (Figure 2.4). P is the next most important yield-limiting nutrient after N; except in Giwa and Doguwa where the reductions in yield were larger for −P than for −N. In OPV trials, largest yield reductions of more than 2.5 t ha^{-1} because

Table 2.4: Soil available micronutrients (Zn, Cu, Mn, Fe and B) contents in the study sites

Study Sites	**Zn**	**Cu**	**Mn**	**Fe**	**B**
	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})
Bakori	8.88 (2.38)	2.25 (0.77)	24.2 (13.1)	108.0 (31.1)	0.02 (0.008)
Bunkure	4.77 (2.49)	1.47 (0.49)	34.1 (23.8)	202.9 (17.2)	0.01 (0.004)
Dandume	9.92 (4.87)	2.70 (1.03)	21.5 (5.60)	106.4 (30.4)	0.02 (0.008)
Doguwa	12.60 (9.75)	1.70 (1.02)	40.5 (20.0)	110.0 (44.1)	0.05 (0.020)
Faskari	2.28 (2.12)	2.36 (0.59)	30.9 (17.2)	104.4 (28.6)	0.02 (0.005)
Funtua	4.81 (2.30)	1.76 (0.63)	33.4 (36.3)	217.9 (116.9)	0.03 (0.017)
Giwa	9.72 (5.59)	1.49 (0.56)	36.9 (13.0)	131.4 (117.7)	0.03 (0.011)
Ikara	6.70 (3.48)	1.84 (1.06)	33.4 (22.9)	183.6 (50.1)	0.03 (0.019)
Kauru	15.30 (1.66)	1.13 (0.49)	41.8 (7.9)	133.0 (36.8)	0.07 (0.040)
Lere	4.71 (2.40)	1.58 (0.63)	30.6 (20.2)	203.6 (79.3)	0.04 (0.019)
Makarfi	9.65 (8.37)	2.01 (0.74)	20.8 (9.8)	129.5 (59.7)	0.02 (0.010)
Soba	10.98 (5.37)	2.20 (1.16)	43.0 (20.6)	104.3 (39.0)	0.02 (0.011)
Tofa	6.73 (0.73)	1.49 (0.40)	77.4 (8.4)	158.3 (9.8)	0.01 (0.012)
Tudun Wada	14.78 (8.46)	1.58 (0.66)	45.2 (17.5)	231.0 (78.7)	0.05 (0.030)
CV (%)	72.8	46.5	64	51.6	81.7

CV: coefficient of variation across the study fields; Numbers are mean with standard deviation in brackets.

of −P were obtained in Lere, Kauru, Soba and Doguwa. In hybrid trials at Lere, Kauru, Faskari and Doguwa reductions of more than 2.5 t ha^{-1} were obtained due to −P. The largest decrease in grain yield (0.96 and 0.81 t·ha^{-1}) due to the omission of potassium (−K) was recorded in the trials in Kauru with OPV and in Ikara with hybrid, respectively (Figure 2.4). Contrary to this, average gains in grain yield in the order of 0.27–0.56 t ha^{-1} because of −K were recorded in two sites with OPV trials (Giwa and Tofa) and in two sites with hybrid trials (Soba and Bunkure). The addition of secondary macro- and micro-nutrients resulted in a consistent gain in grain yield of 0.2–1.08 t ha^{-1} compared to NPK treatment in both OPV and Hybrid trials in Soba, Giwa, Faskari and Bunkure.

The stability analysis of all trials (Figure 2.5), allows to draw meaningful conclusions with respect to the overall effectiveness of a given treatment and its resilience against environmental variables. Slope and intercept of the regression lines between treatment means and environment means are crucial in this respect. While the intercept and the general position with respect to the x-axis indicate the yield performance of the different treatments, the slope is indicative of the impact the environment may exert on the variability in yields. Hence, regression lines with small slope values point to a relative insensitivity to environmental factors and consequently to a stable system. Although the slopes values of this

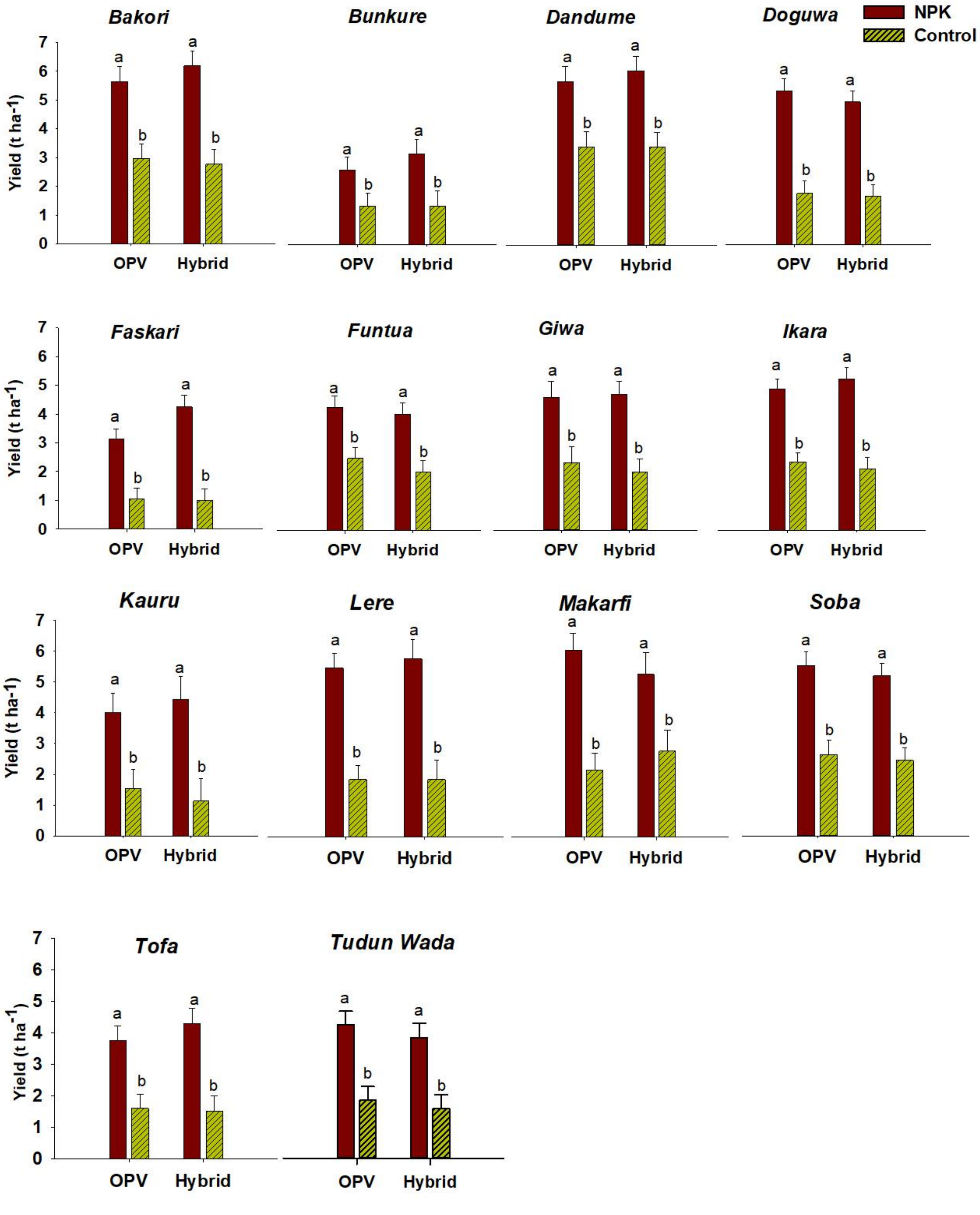


Figure 2.3: Observed maize grain yield in control versus NPK treatment across the study sites. Error bars are standard error of means. Values followed by different letters are significantly different at p-value ≤ 0.05.

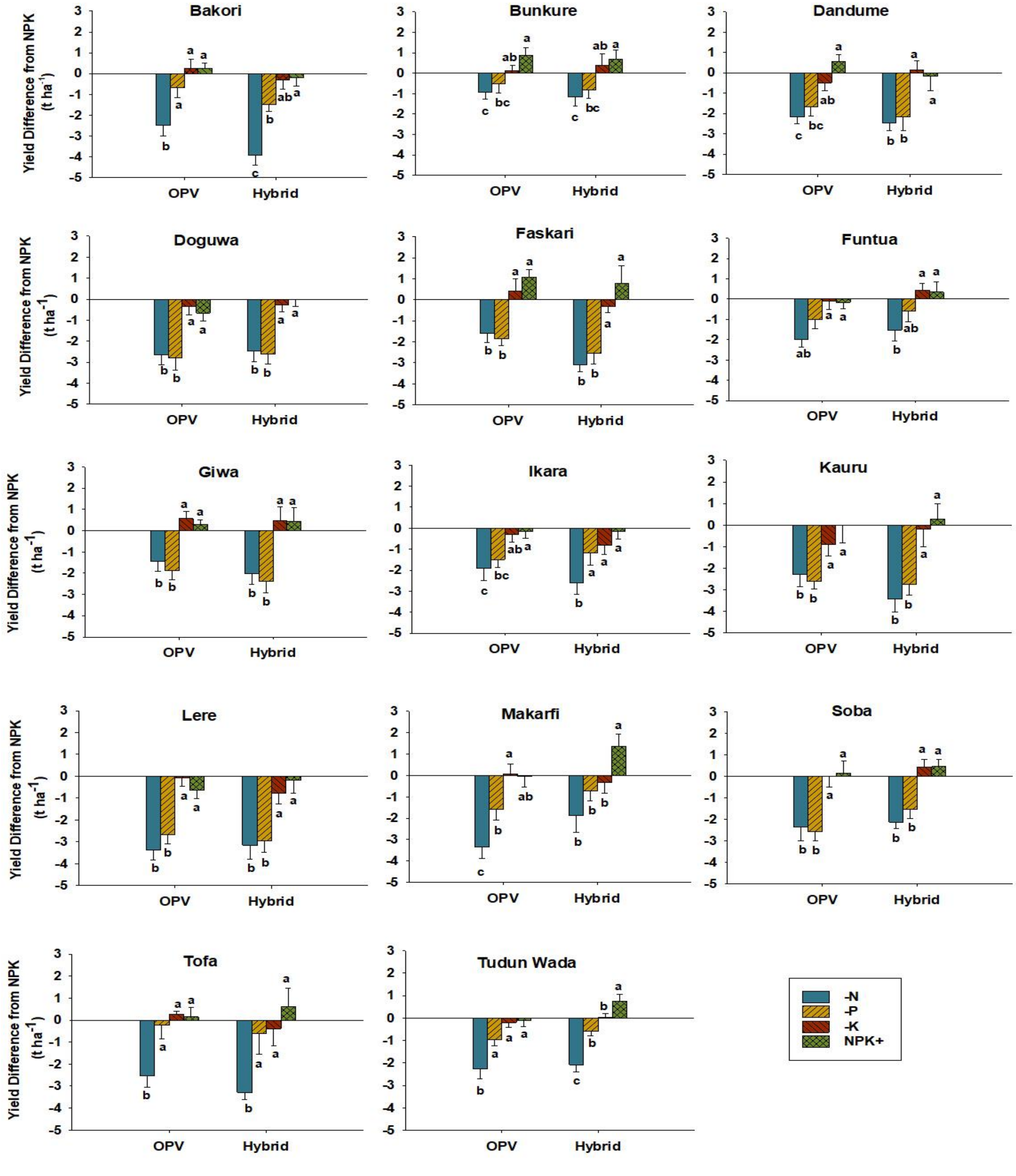


Figure 2.4. Effect of omission of primary macro-nutrients and application of secondary macro- and micro-nutrients on maize grain yield difference relative to NPK across the study sites. Error bars are standard error of means. Values followed by different letters within a group are significantly different at p-value ≤ 0.05.

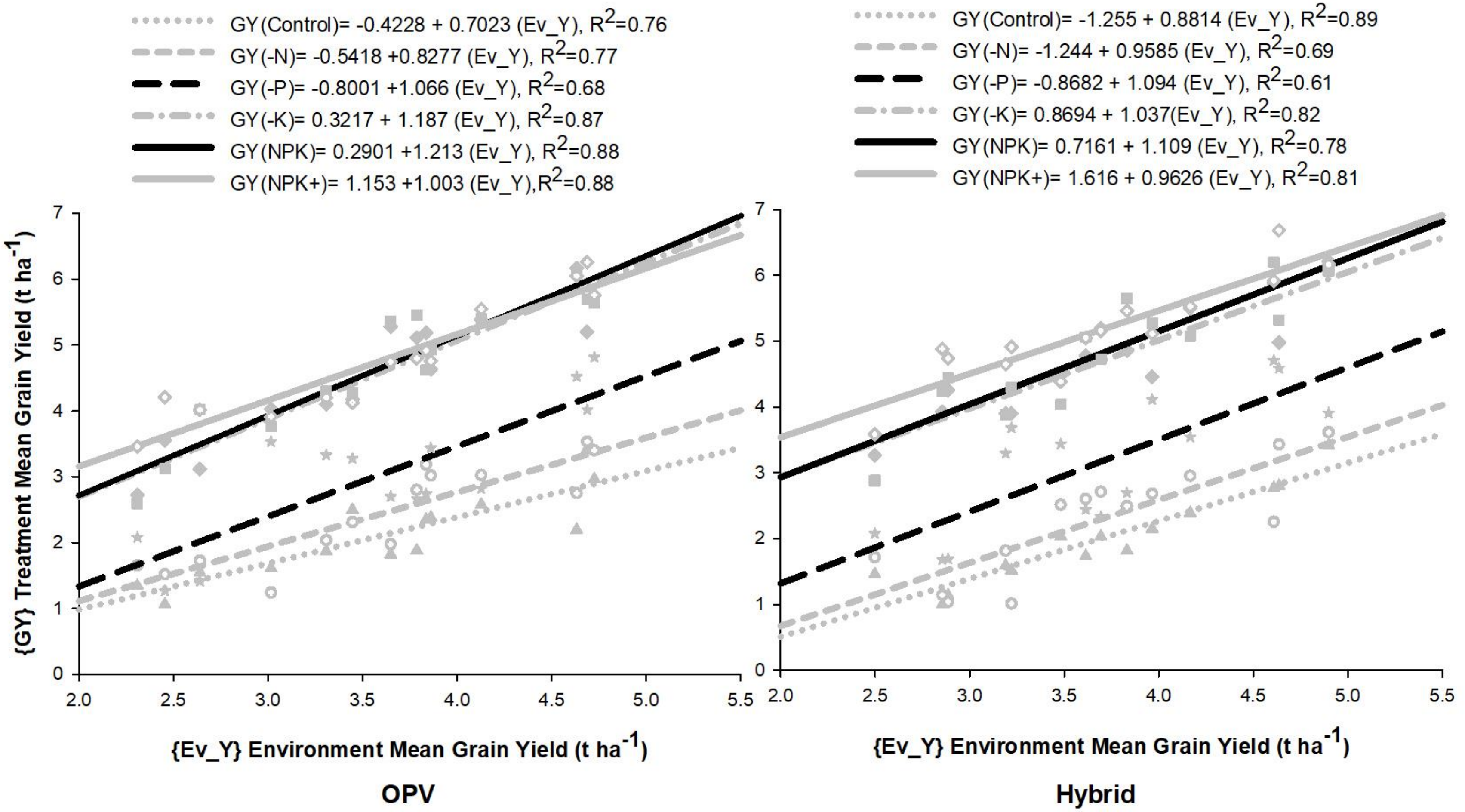


Figure 2.5. Stability analysis of maize grain yields in different nutrient omission treatments for fourteen different environments (sites) in the Northern Nigeria savanna in 2015 and 2016 cropping seasons. OPV: open pollinated maize variety.

study were statistically at par, three relevant observations can be made. First, control (Control) and minus N (−N) treatments demonstrated the smallest intercepts and smallest slopes in comparison to all other treatments implying they were more stable but at a poor level of performance. Secondly, the omission of P (−P) resulted in a larger yield compared to control and −N treatments in both sets of trials with a slightly larger slope value, indicating a slightly reduced resiliency. Finally, the NPK+, NPK and −K treatments responded closely with higher yield performance in all the environment, except that NPK+ had a smaller slope compared to the NPK and -K, portraying NPK+ to be more resilient among the higher yielding nutrient application treatments (i.e. -K, NPK and NPK+).

2.3.3 Yield-nutrients variability response clusters

From the multivariate K-means cluster analysis, three clusters could be identified in the OPV trials and four clusters in the hybrid trials (Figure 2.6). Cluster I to III are common to both varietal trials, while cluster IV is specific to hybrid trials only. Attributes of the response clusters are as follows:

- Cluster I: Fields without yield response to any nutrient application, therefore called “no response fields.” Average yield level in this cluster fell between 3 and 3.7 t ha^{-1} for OPV and 2.7 and 3.8 t ha^{-1} for the hybrid variety, respectively (Figure 2.6). The cluster contains 9% and 16% of the OPV and hybrid study fields, respectively (Table 2.5). Among the four clusters, the fields in this cluster received the largest manure application preceding the trials and the smallest urea fertilizer application (Table 2.6). As a result, the fields in this cluster have the highest soil OC_{tot} content. In addition, fields in this cluster also have the highest available Fe content.
- Cluster II: Fields with a large yield response to N and P, hence known as “N and P response fields.” Average yield levels were 4.6 to 4.8 t ha^{-1} and 4.8 to 5.3 t ha^{-1} for OPV and hybrid variety, respectively (Figure 2.6). It is the largest cluster containing 63% of the study fields in both OPV and hybrid trials (Table 2.5). Using no-response cluster I as the reference category, multinomial logistic regression as indicated by significant odds ratios (Table 2.6), showed that relatively low soil OC_{tot}, small Fe and high available S were the soil properties statistically responsible for allocation of fields into this cluster.
- Cluster III: Fields with a larger yield response to N only and a small response to P, K and

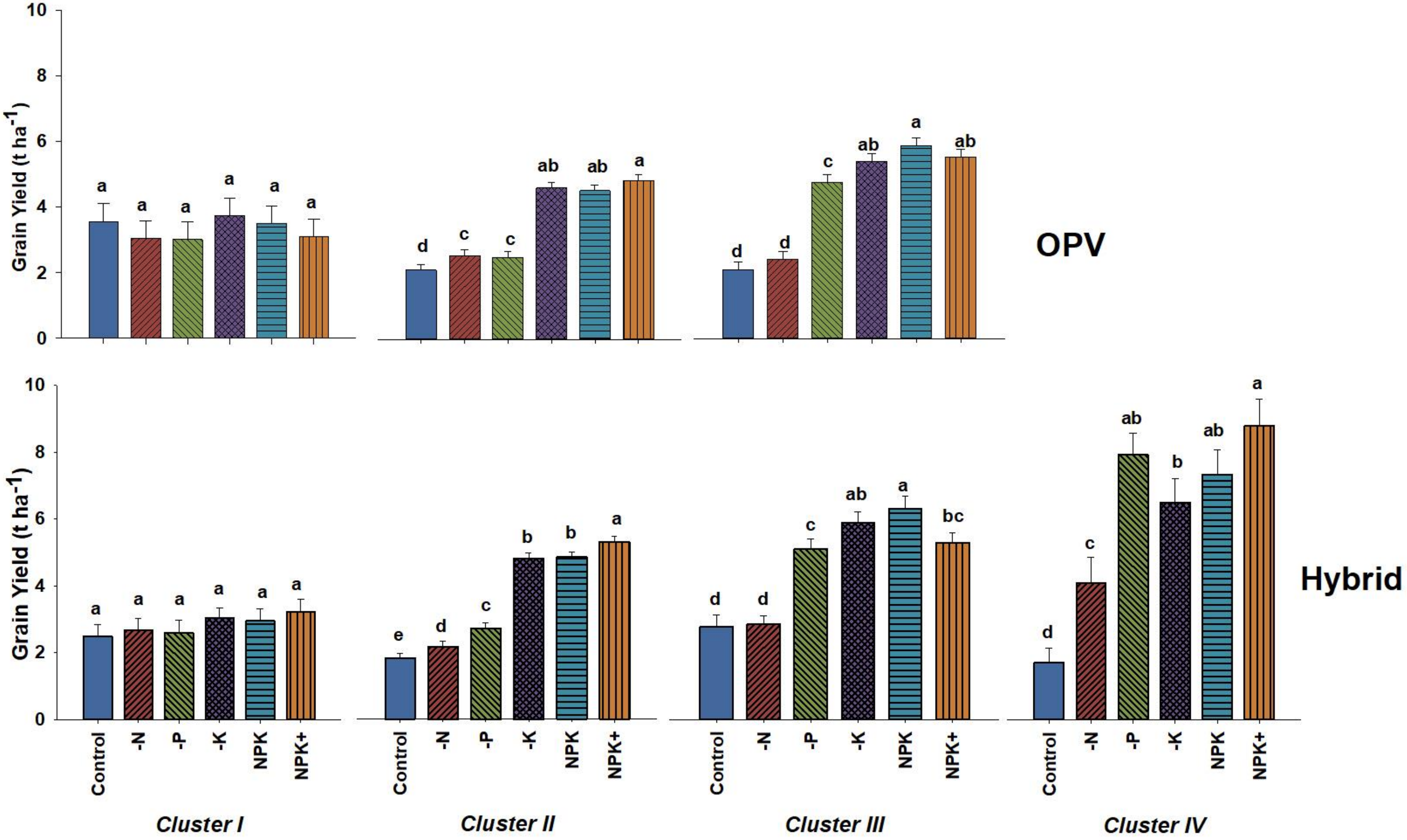


Figure 2.6: Average maize grain yield from fields classified under different clusters following K-means clustering. Error bars are standard error of means. Values followed by different letters within a cluster are significantly different at p-value ≤ 0.05.

Table 2.5: Distribution of fields across study sites in the various OPV and hybrid yield-nutrients response clusters.

Study Sites	**OPV**			**Hybrid**			
	Cluster I	Cluster II	Cluster III	Cluster I	Cluster II	Cluster III	Cluster IV
Bakori	3	7	6	1	11	4	1
Bunkure	1	11	1	7	3	1	1
Dandume	2	8	3	2	8	3	0
Doguwa	1	13	3	2	14	1	0
Faskari	0	7	1	0	7	1	0
Funtua	4	8	5	4	7	6	0
Giwa	0	7	1	0	7	1	0
Ikara	2	8	8	1	10	5	1
Kauru	0	5	0	0	5	0	0
Lere	0	9	5	2	10	2	0
Makarfi	0	6	6	4	5	1	2
Soba	1	13	2	2	11	3	0
Tofa	0	2	3	0	4	1	0
Tudun Wada	1	5	6	3	7	1	2
Total	15 (9.0%)	109 (63.0%)	50 (28.0%)	28 (16.0%)	109 (63.0%)	30 (17.0%)	7 (4.0%)

SMM (secondary macro- and micro-nutrients), therefore called “N response fields.” The average yield in this cluster fell between 4.7 and 5.8 t ha^{-1} for OPV and 5.1 and 5.3 t ha^{-1} for hybrid, respectively (Figure 2.6). Twenty eight percent (28%) and 17% of OPV and hybrid study fields, respectively are assigned to this cluster (Table 2.5). Low soil OC_{tot}, high soil P_{av} and high bulk density relative to the corresponding values in the reference cluster I (Table 2.6) were the significant soil characteristics responsible for the allocation of fields into this cluster.

- Cluster IV: Fields in this cluster have a large yield response to N and secondary macro- and micro-nutrients (SMM), a small response to P and K. Therefore, they are called “N and SMM response fields.” Addition of SMM increased yield by 1.4 t ha^{-1} over the NPK. Cluster IV held only 4.0% of the hybrid fields (Table 2.5) and holds the largest average yield compared to all other clusters of 6.4 to 8.3 t ha^{-1} (Figure 2.6). High soil available P as twice the average content of the reference cluster I and low OC_{tot} and available B contents were the significant soil characteristics of fields for this cluster (Table 2.6). In addition, fields in this cluster received the smallest organic matter input and the largest NPK applications before the trials.

Table 2.6: Multinomial logistic regression showing soil characteristics responsible for the allocation of fields to specific yield-nutrients response clusters.

	# Cluster I	**Cluster II**		**Cluster III**		**Cluster IV**	
	Mean	**Mean**	**Odds Ratio**	**Mean**	**Odds Ratio**	**Mean**	**Odds Ratio**
Soil Characteristics							
pH	6.0	5.8	0.54	5.9	0.66	6.0	0.98
OC$_{tot}$ (g kg^{-1})	7.7	6.97	0.81 *	6.52	0.75 *	5.98	0.45 *
N$_{tot}$ (g kg^{-1})	0.44	0.46	1.52	0.45	3.26	0.49	>1000
P$_{av}$ (mg kg^{-1})	7.76	8.72	1.05	11.21	1.09 **	17.70	1.20 **
Sand (%)	50.94	47.72	el	49.47	el	50.8	el
Silt (%)	28.12	29.71	el	29.89	el	29.09	el
Clay (%)	20.95	22.59	el	20.64	el	20.12	el
Ca (cmol$_c$ kg^{-1})	2.38	2.38	1.13	2.30	1.03	2.96	2.12
Mg (cmol$_c$ kg^{-1})	0.63	0.72	5.08	0.66	6.75	0.61	0.54
K (cmol$_c$ kg^{-1})	0.22	0.23	2.87	0.22	2.50	0.21	3.07
Na (cmol$_c$ kg^{-1})	0.08	0.08	0.59	0.08	<0.001	0.09	>1000
E.A. (cmol$_c$ kg^{-1})	0.02	0.05	el	0.04	el	0.00	el
ECEC (cmol$_c$ kg^{-1})	3.31	3.44	el	3.28	el	3.86	el
Zn (mg kg^{-1})	8.74	8.57	1.00	8.70	1.02	14.21	1.07
Cu (mg kg^{-1})	2.01	1.92	0.90	1.99	1.14	2.14	1.91
Mn (mg kg^{-1})	29.78	33.75	0.98	34.42	0.98	39.83	0.93
Fe (mg kg^{-1})	185.33	144.12	0.99 *	157.22	0.99	165.48	0.99
B.D. (g cm^{-3})	1.55	1.54	2.71	1.60	45.68 *	1.50	9.67
B (mg kg^{-1})	0.04	0.03	<0.001	0.02	<0.001	0.01	<0.001 *
S$_{av}$ (mg kg^{-1})	6.95	7.38	1.42*	6.99	1.34	6.68	1.44
Fertilizer Management History							
Farm Size (ha)	1.29	1.56	el	1.17	el	0.54	el
Organic fertilizer (kg ha^{-1})	6052.67	4035.72	0.99	2129.27	0.98 *	2120	0.99
NPK fertilizer (kg ha^{-1})	223.08	166.82	el	252.75	el	280.4	el
SSP fertilizer (kg ha^{-1})	0.00	4.76	el	9.45	el	9.1	el
UREA fertilizer (kg ha^{-1})	36.17	77.99	el	96.53	el	229.87	el

* and ** indicates differences at $p < 0.05$ and $p < 0.01$, respectively from the reference # cluster I (No response fields). Model p-value = 0.0081 **, el = eliminated in the model, E.A. = exchangeable acidity (Al^{3+} + H^{+}), B.D. = bulk density.

2.4 Discussion

2.4.1 Soil Characteristics

The moderate to high inter-field variability in most soil characteristics can be related to variability in inherent soil forming factors (like parent material, vegetation and local climate) and/or differences in cropping system history and soil management practices influenced by farmers' socio-economic factors. Tittonell et al. (2005) and Giller et al. (2006) found significant variability in soil fertility conditions even among fields within a farm in some parts of SSA. They attributed the variability in soil fertility largely to differences in historic field management intensity and resource productivity allocation affected by the farmer's socio-economic status and/or often distance of the farm from the homesteads. This recommends that soil nutrient management and fertilizer recommendation strategies must consider the existence of this inter-field variability to optimize the overall efficiency of nutrient dynamics in the Northern Nigerian savanna.

But, overall, most of the studied fields do not have potential acidity problems since the exchangeable acidity ($Al^{3+} + H^{+}$) is less than 1 $cmol_c\ kg^{-1}$ and average pH values are within the range of 5.5–7.0. These values are considered ideal for most crops including maize and lead to pH-values entailing an optimal nutrient availability (Brady and Weil, 2002). The large sand fraction in the fields can be attributed to the parent material as most of these soils were developed on deep pre-Cambrian basement complex rocks like granite and sandstone. In addition, sorting of soil materials as a result of clay eluviation and wind erosion has been reported as one of the major reasons for the large sand fraction in the surface soils of Northern Nigeria (Malgwi et al., 2000; Voncir et al., 2008). The overall low soil OC_{tot} (indicative of low organic matter content), N_{tot} and ECEC in the fields can be related to two factors; (i) inherently, the sandy nature of the parent material containing a low weatherable mineral reserve necessary for nutrient recharge and a small capacity for carbon storage, (ii) anthropogenically, through burning or complete removal of crop residues for livestock and other needs (J D Kwari et al., 2011). Many studies have reported low soil OC_{tot}, N_{tot} and ECEC contents within the study area (Manu et al., 1991; Ekeleme et al., 2014; Kamara et al., 2014; Shehu et al., 2015). The overall moderate to high average exchangeable K contents in all the study sites can be linked to the presence of an appreciable amount of K-bearing feldspar minerals in the sand and silt fractions in the study area (Møberg and Esu, 1991) and the residual effect of the historic K application from NPK fertilizer in the fields.

The overall average low exchangeable Ca concentrations in Lere, Faskari and Bunkure indicate the potential development of Ca-deficiency in those areas. The high concentrations of available Fe and Mn in the soils are not surprising given the pH-values as quoted above which are unlikely to lead to Fe- and/or Mn-deficiency. As reported by Sillanpää (1982), only at pH above 7.5 does Mn availability become very small owing to the formation of hydroxides and carbonates. Likewise, Fe is known to be highly soluble under relatively acid and reducing conditions (Shehu et al., 2015). Møberg and Esu (1991) have also documented the predominance of Fe-bearing minerals like haematite and goethite in sand and clay fractions of Nigerian savanna soil. The low B contents in the studied soils are associated with a low organic matter content which is the major reservoir of B and a high leaching potential (B being mobile) due to both high rainfall intensity and coarse-textured soils (Ahmad et al., 2012; Aref, 2011).

2.4.2 Inter-field variability in yield response to nutrient application

A large inter-field variability in maize grain yield response to nutrient applications was observed both within and between study sites. This indicates a substantial effect of soil fertility variability on maize yield nutrient requirements. More than 70% of the study fields (i.e. all except cluster I) showed a larger response to N application and yield was significantly reduced when N was omitted from the NPK in most of the study sites. This asserts that N is the most yield-limiting nutrient. Similarly, other studies have reported a significant response of maize to N application in the Nigerian savannas (Kamara et al., 2005; Kamara et al., 2014; Adnan et al., 2017). Overall, N is recognized as the most limiting nutrient in cereal cropping system over large areas of SSA including Nigeria (Badu-Apraku et al., 2015; Vanlauwe et al., 2011). This suggests that fertilizer practices and technologies that manage N dynamics in the soil are highly required for optimal performance of maize in the Northern Nigerian savannas. Rotation of cereal crops with legumes, appropriate application of inorganic N fertilizer combined with well-managed manure (Badu-Apraku et al., 2015; Vanlauwe et al., 2011; Zingore et al., 2008) can help farmers to improve N status in their fields. Phosphorus is the other most important yield-limiting nutrient after N as 63% of the fields showed a large yield response to P application (cluster II). Ekeleme et al. (2014) and Shehu et al. (2015) have reported the occurrence of small available P contents (<7 mg kg^{-1}) in more than 50% of the fields in some parts of the study area. Average exchangeable K content in most of the study fields is at or above the critical level of 0.16 cmol$_c$ kg^{-1} (Agboola and Ayedele, 1985; FMANR, 1990), which is linked to the small response of K application observed in all the clusters.

The no-response fields (cluster I) have noticeably higher OC$_{tot}$ (7.7 g kg^{-1}) and Fe (185.33 mg kg^{-1}) contents. Although the reason for higher Fe content in this cluster is not clearly understood, the larger historic application of organic resources at 6053 kg ha^{-1} before the start of the trials attributed to the high OC$_{tot}$. The presence of fields that are non-responsive to nutrient applications has been reported elsewhere in SSA (Giller et al., 2011; Zingore et al., 2008; Kihara et al., 2016). Relative to no-response fields, lower Fe (144.12 mg kg^{-1}), lower OC$_{tot}$ (6.97 g kg^{-1}) and higher S$_{av}$ (7.38 mg kg^{-1}) contents were significantly responsible for allocation of fields into cluster II with larger yield responses to N and P. Therefore, this could point towards a high probability that an excess Fe might have substantially reduced mineralization and availability of the applied P in the no-response fields through the formation of insoluble iron phosphates. Meanwhile, the relatively large organic matter content in the no-response fields might have resulted in adequate available N, thus limiting the yield response of fields to the applied N. Soil organic matter, particularly the labile fraction, plays a significant role in N mineralization because it acts as an easily accessible source of energy for microorganisms and in return results in greater N mineralization (Ros et al., 2011). However, there is a need for more research to investigate the effect of the Fe content and other factors accounting for non-responsiveness to fertilizer application in the no-response fields.

Cluster III and IV with a limited yield response to P have the highest average soil Mehlich-3 P$_{av}$ contents of 11.21 and 17.7 mg kg^{-1}, respectively. Both values for available Mehlich-3 P$_{av}$ are above the soil critical levels of 10 mg kg^{-1} for maize as reported by Redi et al. (2016) below which P becomes deficient. The high soil P content in these clusters is likely due to the residual effect of historical P applications, as P applied through fertilizer or manure, not taken up by the crop or temporarily fixed in the soil is released slowly to the succeeding crops (Janssen et al., 1987). Therefore, a larger addition of P to those fields could even reduce yield as excessive levels of P in the soil might become toxic or disrupt the nutrient balance. Similar fields with limited yield response to P application have been reported across SSA under cereal production (Kihara et al., 2016). Although B content in all the clusters was below the critical level as indicated in the literature where it is ranging between 0.15 to 0.5 mg kg^{-1} (Aref, 2011), relatively lower B contents were significantly identified as the major factor for allocation of fields into cluster IV with a large yield response to secondary macro- and micro-nutrients. It follows that there is a need for comparable diagnostic trials where each individual secondary macro- and micro-nutrient is omitted to clearly understand their independent role in yield response before designing improved nutrient addition schemes. Stability analysis also supported this need, as the addition of secondary macro- and micro-nutrients to the NPK treatment resulted in a slightly more stable yield across all the environments. This might indicate a potential future deficiency of secondary macro- and micro-nutrients if the current trend of only using N, P and K based fertilizers with small organic matter additions and complete crop residue removal, as is common among farmers, continues. This may require a reformulation of compound fertilizers for addressing emerging nutrient requirements for balanced nutrition.

2.4.3 Management

A small and statistically non-significant maize yield response to K application was obvious in all the clusters. It follows that only small amounts of K applications are required for maintaining high maize yields at the same time maintaining soil K reserves based on site-specific nutrient management (SSNM) principles. SSNM provide guidelines for maintenance K application in high potential maize production environments to avoid depletion of soil K reserves on the long-term (Witt et al., 1999). The present results of maize response to K however, do not support the current high rate of K (60 kg K_2O ha^{-1}) recommended in many cropping areas in Northern Nigeria savannas. This suggests that farmers who can afford to access K fertilizers to meet the recommended rate are generally applying more K than required for maximizing maize production, resulting in lower profitability.

For the largest cluster displaying N and P yield response (cluster II), the focus should be on optimizing N and P supply, while small applications of K and are recommended for maintenance and for a slight increase in attainable yield since balanced application of N, P, K and secondary macro- and micro-nutrients resulted in a small yield increase of at least 0.3 t ha^{-1} over N and P applications alone. Optimal application of N and a small application of P and K is sufficient for fields in cluster III with large yield response to N only, no addition of secondary macro- and micro-nutrients is required as their application resulted in a slight decrease in yield over the NPK alone. Fields in cluster IV with a large yield response to N and secondary macro- and micro-nutrients requires an optimal application of N and secondary macro- and micro-nutrients and a small maintenance application of P and K. The no-response fields (cluster I) requires specific management once the underlying root causes are clearly understood (Witt et al., 1999). Therefore, for now, the attention should be directed toward understanding the root cause(s) and management option(s) to restore their responsiveness.

2.5 Conclusion

Most soil characteristics of the studied fields reveal large inter-field variability, while in general they are all characterized by low contents of C_{tot}, N_{tot}, ECEC and available B. Consequently, maize showed a large degree of variation in yield response to nutrient applications across the studied fields. It is apparent that nutrient management and fertilizer recommendation strategies must consider these inter-field variabilities to optimize nutrient limited maize yield in the Northern Nigerian savanna. Decision support tools (like QUEFTS or Nutrient Expert), if well calibrated using information from this study may offer a feasible and cheaper alternative for the development of fertilizer recommendations that are tailored toward specific field and farm conditions. Nitrogen and phosphorus were generally the most yield limiting nutrients for maize production in the Northern Nigerian savanna zone. However, in a few study fields, maize yield responded significantly to secondary macro- and micro-nutrients as well. Overall, the maize yield response to K was small across sites suggesting that only small amounts of K are required for maximizing maize production as well as for soil fertility maintenance to avoid K-depletion and sustain maize productivity in the long run. However, to foster a holistic evaluation of all the limiting and unbalanced nutrients in the Northern Nigerian savanna maize cropping system, foliar nutrients compositional diagnosis is strongly recommended. Compositional foliar nutrient diagnosis is a promising approach to improve our understanding of yield response to nutrient applications as it considers all the essential plant nutrients and their interactions in the plant. In addition, fields without any response to fertilizer application are widespread in the Nigerian savanna and there is a need to investigate the underlying causes to restore their responsiveness for efficient maize intensification.

Chapter 3: Diagnosis of nutrient limitations and imbalances in maize in the Northern Nigerian savanna

Summary

Maize (*Zea mays* L.) is an important crop in the savanna of the Northern Nigeria. Despite its importance, nutrient limitations and imbalances limit maize productivity in the region. However, the dearth of information on nutrient limitations and imbalances at a scale preclude the development effective strategies to mitigate such nutrient limitations and imbalances. To address this, foliar (ear leaf) diagnosis of nutrient limitations and imbalances was performed using compositional nutrient diagnosis (CND) method. This was based on the data of on-farm nutrient omission trials (NOTs) conducted in about 198 fields across two savanna zones of Northern Nigeria i.e. Northern Guinea savanna (NGS) and Sudan savanna (SS). Positive correlation was observed between grain yield and ear leaf nutrient concentrations except for Fe in NGS and Mg in SS, respectively. The CND diagnosis result showed yield limitations due to nutrient imbalances in about 40% and 42% of the fields in the NGS and SS, respectively. Although with discrepancies among the nutrient imbalanced fields, the significant limiting nutrients in the decreasing order of importance were: N, P > S > Cu, Mn > B in NGS and N, S > Cu > P > Mn, B in SS. Despite K, was not among the deficient nutrients in the unfertilized control plots of the nutrient imbalanced fields, application of N and P alone resulted to K deficiency in 60-100% in these fields. This implies that application of K is nevertheless required to achieve balanced nutrient supply in the Northern Nigerian savanna. These findings suggest the consideration of S, Cu, B and Mn in addition to the N, P and K in the nutrient and fertilizer management strategies. But we first recommend further field validation and soil bioavailability investigation to document the unique response and requirements of each of these nutrients (i.e. S, Cu, Mn and B) in maize cropping system of the Northern Nigerian savanna.

3.1 Introduction

Plants require an adequate supply of all the essential nutrients to fulfil their potentials. In fact, no nutrient(s) is inferior as they all have a critical role to occupy in optimizing crop productivity and quality. The most frequently cited plant nutrition and production law, Leibig's "law of minimum", asserted that the deficiency of any single nutrient is enough to limit plant yield (Claupein, 1993). However, plants in addition require this supply of nutrients to be balanced, as imbalance supply triggers nutrient interactions which can impede the absorption and utilization of other nutrient(s), thus affecting plants growth and productivity. Therefore, the appraisal of plant nutritional limitation and imbalances are fundamental in nutrient management decisions to improve crop productivity (Magallanes-Quintanar et al., 2006). In this context, nutrients element concentration in plant tissue rather than in soil are widely used as more direct indicator pant nutritional status (Sinclair et al., 1997). Foliar analysis (for example ear leaves in maize at critical initial silking reproductive stage "R1") is the most promising way for this purpose (Roy et al., 2006).

Several approaches are employed to diagnose and interpret results of foliar analysis such as the Critical Value Approach "CVA" (Bates, 1971), the Diagnosis Recommendation and Integrated System "DRIS" (Walworth and Sumner, 1987), and the Compositional Nutrient Diagnosis "CND" (Parent and Dafir, 1992; Parent et al., 1993; Khiari et al., 2001). The Critical value approach (CVA) is a univariate approach that establishes sufficient nutrient concentrations based on a cut-off value at 90-95% of maximum yield (Ware et al., 1982). However, the CVA is biased for not accounting for nutrient interactions (Jones Jr et al., 1991). The Diagnosis recommendation and integrated system (DRIS) is a bivariate method that uses dual nutrient ratios which reflect some level of nutrient interactions (Walworth and Sumner, 1987). But, DRIS indices are empirical without a precise outline of the covariance matrix for conducting multivariate statistical analysis, leading to potential misinterpretations when correlated with yield (Parent et al., 2012; Barłóg, 2016). Parent and Dafir (1992) proposed a multi-ratio compositional nutrient diagnosis (CND) concept based on compositional data analysis (Aitchison, 1986). Compositional nutrient diagnosis (CND) is superior to CVA and DRIS because: (i) it considers multiple and complex interactions among the essential plant nutrients (Fageria, 2001), (ii) it accurately states a covariance matrix enabling multivariate computation of ratios originating from nutrient concentrations that are mutually exclusive (Parent, 2011), thus avoiding potential misinterpretations when correlated with yield.

Northern Nigerian savanna constitutes the largest maize suitability area in Nigeria (Badu-Apraku et al., 2015). However, average maize yield in farmer's fields has been varying around 2 t ha^{-1} over several decades (FAOSTAT, 2018b). This figure is considerably smaller than the attainable yield of about 7 t ha^{-1} in well-managed experimental fields (Fakorede and Akinyemiyu, 2003; Sileshi et al., 2010a), and far below the water limited potential yield of 10.7 t ha^{-1} (GYGA, 2017). Poor soil fertility and inadequate nutrient management are one of the key constraints leading to low maize yields in the region (Ekeleme et al., 2014). To improve maize yield, there is a need for development of nutrient management and fertilizer recommendation strategies that ensure adequate and balanced supply of all limiting nutrients. But, the dearth of information on nutrient imbalances and limitations in maize at scale in the Northern Nigerian savanna preclude the development of such strategies. Given the scarce of such information, this study was conducted to diagnose nutrient limitations and imbalances in maize using foliar compositional nutrient diagnosis (CND). Results of this study offer a holistic evaluation of all the limiting and unbalanced nutrients in the Northern Nigerian savanna maize cropping system, going beyond the use of yield response to the limited number of nutrients application as investigated in Chapter 2. Specifically, this study was conducted to achieve the following aims: (i) to establish foliar nutrient sufficiency ranges for maize in the Northern Nigerian savanna based on CND approach (ii) to evaluate nutrient deficiencies and imbalances in maize in the Northern Nigerian savanna (iii) to identify significant nutrient interactions through principal component analysis (PCA) in maize in the Northern Nigerian savanna.

3.2 Materials and Methods

3.2.1 Site selection, description and experimental design

This study is based on data acquired from a large number of on-farm nutrient omission experiments, conducted over two rainy seasons (2015 and 2016) across fourteen study districts in three administrative states of the Northern Nigerian savanna (Shehu et al. 2018). Details of the study districts have been described in chapter 2. Overall the districts fell within two agro-ecological zones i.e. the Northern Guinea savanna (NGS) and Sudan savanna (SS).

The weather conditions of the two agro-ecological zones during the two years of experimentation are summarized in Figure 3.1. The total annual rainfall in the NGS was 1128 mm in 2015 and 1130 mm in 2016; total annual rainfall in the SS was 717 mm in 2015 and 771 mm in 2016. Field selection procedure and experimental treatments have been comprehensively described in Chapter 2. In each of the experimental field, two sets of the experiment were conducted side by side; one with open pollinated variety (OPV) and the other with a hybrid variety (hybrid).

3.2.2 Field and laboratory measurement

Soil samples were collected from each experimental field and analyzed as described in Chapter 2. For nutrient diagnosis in maize, it is universally accepted that the ear leaf is an organ of greater metabolic activity and that its nutrient concentration relates best to maize yield (Jones Jr, 1998). Therefore, a total of ten maize ear leaves were randomly sampled at the critical initial silking stage (reproductive stage “R1”) from each experimental plot. The ear leaves sampling was performed on the rows next to the net plot (net plot consists four middle rows 3m × 3m for grain harvesting). An ear leaf was removed by plucking downwards (at roughly an adjacent angle of <30°) with moderate force as this allows the leaf to pluck at the collar, leaving behind the leaf base that circles the stem. Next the ear leaf samples were gently washed with distilled water to remove dust and oven-dried at 60°C for 48 hours. Thereafter, the dried ear leaf samples were ground using agate pestle and mortar. The ground samples were digested with nitric acid (HNO_3) and concentrations of P, K, S, Mg, Ca, Zn, Cu, Mn, Fe and B were determined via Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES, iCAP 7000 Series, Thermo Scientific Inc.) while the concentration of N was determined colorometrically using autoanalyzer (Technicon AAII, SEAL Analytical Inc.) following micro-Kjeldahl digestion method (Bremner, 1996).

Plants in the net plot were harvested at physiological maturity, and total fresh weights of cobs and stover were recorded. Ten cobs and five stalks of stover were randomly selected as subsamples for nutrient analysis and to account for grain shelling percentage and moisture content after air-drying. The random selection was carried out by first counting the number of cobs or stalks in the net plot and then arranging them in line at random; the sub samples

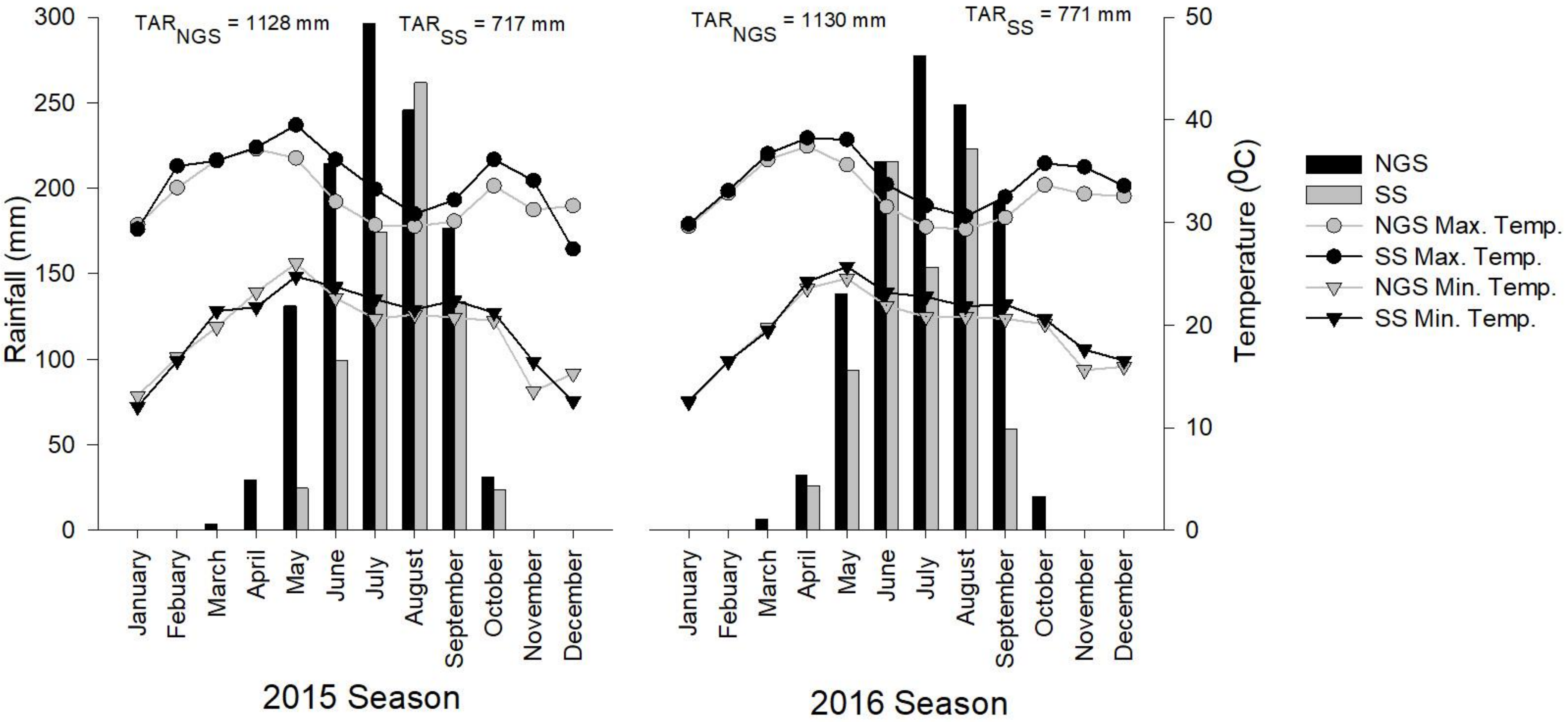


Figure 3.1: Annual rainfall (bar graph), daily minimum and maximum temperatures (line graph) of the two studied agroecological zones recorded in two cropping seasons (2015 and 2016). NGS: Northern Guinea savanna; SS: Sudan savanna; TAR$_{NGS}$: total annual rainfall in NGS; TAR$_{SS}$: total annual rainfall in SS; Min.: minimum; Max.: maximum; Temp.: temperature.

were then subsequently at every interval calculated as the total number of cobs or stalks in the net plot over the number of sub samples to be taken. Finally, grain yield was expressed on a dry weight basis at 15% moisture content.

3.2.3 Data analysis

Soil, yield and ear leaf nutrient characteristics

Descriptive statistics (mean, range and coefficient of variability) and F-test were used to figure out soil properties of the study fields across the two-agroecological zones (NGS and SS). The coefficient of variability (CV) was used to assess variability of soil properties among the study fields and interpreted as small (<15%), moderate (16-35%) and high (>35%) (Wilding, 1985). For the yield and ear leaf nutrient concentration dataset, multivariate outliers (n= 330) were excluded first at p-value <0.05 following Mahalanobis distance in JMP version 14.0 statistical software (SAS Institute Inc., 2018). Thereafter, analysis of variance (ANOVA) was performed on the screened dataset (n=1508) with Nutrient application (NA), agro-ecological zone (AEZ) and variety group (VG) as main factors. Season was not included in the ANOVA because different fields were used between the two seasons of the field experimentation. A linear mixed model was used with fields within agro-ecological zones were used as random factor. Mean values with significant differences were compared using Tukey's HSD (Honestly Significant Difference) test. Spearman correlation was also used to assess the relationship between grain yield and nutrient concentration in the maize ear leaf.

Compositional nutrient diagnosis (CND)

Grain yield and concentrations of eleven different nutrients (N, P, K, Mg, Ca, S, Cu, Fe, Mn, Zn and B) in maize ear leaf plus filling value (Fv) were used for CND as described by Parent & Dafir (1992) and Khiari et al. (2001). In summary, the CND computations were performed in Microsoft Excel software (Microsoft Office, 2016) for the following steps and parameters:

I. The data set (grain yield and corresponding nutrient concentrations in the ear leaf) was arranged in decreasing order of the maize grain yield. Then, the ear leaf nutrient concentrations originally in percentage units were transformed into row-centered log ratios (*clr*) according to Aitchison (1986).

II. The grain yield cut-off separating high yield from the low yield sub-population. This was obtained at the highest inflection point across the nutrient expressions (11 nutrients plus a filling value) from the cubic relationship between yield and cumulative variance ratio function of the nutrient expression. The statistical differences of grain yield and nutrient concentration between high and low grain yielding subpopulations were evaluated using Student’s t-test.

III. The CND norms and indices. The CND norms are the threshold of nutrient’s *clr* and were calculated as means and standard deviations of the nutrient’s *clr* of the high grain yielding sub-population. The CND indices represent deviations from the CND norms. A negative index indicates a small nutrient concentration relative to the norm and suggests a potential deficiency or imbalance (Parent et al., 1994).

IV. The CND imbalance index (CND r^2) was calculated as the sum of the squared CND indices and accounts for the overall nutrient imbalance of the sample. The critical CND r^2 was obtained from assigning the proportion of the low yielding subpopulation as an exact probability of chi-square distribution function with 12 degrees of freedom (i.e. 11 nutrients plus a filling value). The maize grain yield cut-off and critical CND r^2 can be used to categorize and interpret the grain yield and ear leaf nutrient compositional data into four quadrants following Swets (1988). The four quadrants separate the population into (i) a high yielding and nutrient balanced group (HYB), (ii) a high yielding but nutrient imbalanced group (HYI), (iii) a low yielding and nutrient balanced group (LYB) and (iv) a low yielding and nutrient imbalanced group (LYI). Samples in the HYI quadrant suffer from luxury consumption of nutrients whilst the ones in the LYB quadrant have yields limited by other factors than nutrients (Parent et al., 2012).

V. CND nutrient sufficiency ranges define the nutrient adequacy: values below the range indicate nutrient deficiency and above signify nutrient excess. The CND nutrient sufficiency ranges with a lower and upper boundary were derived from means and standard deviations of the individual nutrient concentrations of the subpopulation below the critical CND r^2. The nutrient sufficiency ranges were also compared with the published literature ranges.

VI. The frequency of deficiency of nutrients in the low yield and imbalanced subpopulation (LYI) was evaluated using the CND sufficiency ranges. However, to identify the most important limiting nutrients, the average of the individual nutrient indices in the LYI quadrant were used and tested whether their average is significantly below zero indicating whether the nutrient is significantly limiting or not (De Bauw et al., 2016; Parent et al., 1994). If a normal distribution of the nutrient index was confirmed by 'Shapiro-Wilk W' test in JMP version 14.0 statistical software, the student's t-test was used to test whether the average nutrient index is significantly below zero or not at $p \leq 0.05$. If normality of the nutrient index could not be confirmed, then the 'one-sample Wilcoxon signed rank' test was used to check whether the center of the nutrient index is significantly below zero or not at the same $p \leq 0.05$.

Nutrient interactions

The row-centered log ratios (*clr*) of nutrient concentrations are compatible with principal component analysis (PCA) (Parent and Dafir, 1992). Therefore, to identify significant nutrient interactions, a principal component analysis (PCA) was performed on the *clr* of ear leaf nutrient concentrations using JMP 14.0 statistical software. Only significant principal components (PCs) indicated by an Eigenvalue greater than one were selected. The significant eigenvector loadings within a principal component (PC) were identified using a selection criterion (SC) as described by Collins & Ovalles (1988). Eigenvector loadings greater than the SC value were significant.

$$Selection\ Creterion\ (SC) = \frac{0.5}{\sqrt{PC\ Eigen\ value}} \qquad (1)$$

In addition, to relate soil characteristics with PCA, spearman correlation coefficients were used between the PC scores and the soil parameters. For nutrient application treatments, ANOVA F-values were used, comparing the mean PC score of each treatment.

3.3 Results

3.3.1 Soil, yield and ear leaf nutrient characteristics

Owing to the wide range and high coefficient of variability (CV) values (Table 3.1), a strong variability in most soil physico-chemical properties was observed among the study fields across the two agro-ecological zones (NGS and SS). However, average values of most soil physico-chemical properties were significantly different between the two agro-ecological zones (AEZs). Total organic carbon (OC_{tot}), total nitrogen (N_{tot}), Cu and available sulphur (S_{av}) were larger in the NGS than in the SS. In contrast, pH, available phosphorus (P_{av}), Mn and Fe were larger in the SS than in the NGS. Overall, the study fields have a high sand content with low OC_{tot}, N_{tot}, ECEC and B contents according to the soil fertility ratings of the Nigerian "National Special Program on Food Security" (NSPFS, 2005).

Grain and stover yields were significantly affected by nutrient application (NA) and agro-ecological zone (Table 3.2). Across the AEZ, the yields were significantly larger in NPK+, NPK, and -K treatments, then followed by -P, and smallest in -N and control treatments, respectively (Figure 3.2). When averaged across the NA treatments, grain and stover yield was 17% and 22% larger in NGS than in SS, respectively. Nutrients concentration in the ear leaf was significantly different among the NA treatments (Table 3.2). The concentration of nutrients in the ear leaf was significantly affected by the AEZ, except in S, Fe, Mn and Zn. In addition, the concentration of N, K, Ca, S and Cu and Fe were statistically affected by the variety group (VG) or cultivar. Interaction between NA and AEZ was also significant for the ear leaf concentration of N, P, Ca and B. Therefore, due to a larger variation induced by AEZ than by VG, the CND diagnosis was performed at AEZ level.

Although with variability across the NA, but in overall positive correlation was observed between grain yield and ear leaf nutrient concentrations except for Fe in NGS and Mg in SS, respectively (Table 3.3). In the NGS, stover yield in overall was also positively correlated with nutrients concentration in the ear leaf except K and Fe (Table 3.4). While in the SS only Mg, Ca, S and Mn concentrations in the ear leaf positively correlated with the stover yield (Table 3.4).

Correlation coefficients between concentration of nutrients in the ear leaf and soil characteristics were presented in **Appendix A** for NGS and **Appendix B** for SS. In the NGS, positive but weak correlation was observed between soil and ear leaf concentration of N, P, Ca, Cu and Zn. In the SS, a similar trend was observed for N, with a strong positive correlation between soil and ear leaf P content. Across the AEZs, positive but weak correlation was observed between soil N content and ear leaf S content. Additionally, negative correlation between soil pH and ear leaf Mn concentration was seen across the AEZs.

Table 3.1: Selected physico-chemical properties of topsoil (0-20cm) of the experimental fields between the study agro-ecological zones

Soil Properties	**NGS**		**SS**		**F-Value**
	Mean (Range)	CV (%)	Mean (Range)	CV (%)	
pH$_{H2O}$ (1:1)	5.8 (4.8-7.2)	8	6.2 (5.2-7.2)	9	16.39**
OC$_{tot}$ (g kg^{-1})	7.25 (2.44-15.45)	36	5.01 (2.04-10.12)	36	22.17**
N$_{tot}$ (g kg^{-1})	0.47 (0.25-0.98)	30	0.36 (0.17-0.66)	36	17.18**
P$_{av}$ (mg kg^{-1})	8.43 (0.64-31.77)	82	16.54 (1.44-50.00)	71	22.45**
Ca (cmol$_c$ kg^{-1})	2.31 (0.28-9.78)	43	2.54 (0.38-5.32)	40	1.40
Mg (cmol$_c$ kg^{-1})	0.73 (0.07-1.99)	41	0.59 (0.26-1.35)	38	6.58*
K (cmol$_c$ kg^{-1})	0.22 (0.06-1.35)	78	0.24 (0.07-0.50)	43	0.46
Na (cmol$_c$ kg^{-1})	0.08 (0.04-0.10)	19	0.08(0.04-0.14)	31	0.07
EA (cmol$_c$ kg^{-1})	0.04 (0.00-1.00)	7	0.02 (0.00-0.15)	8	1.05
ECEC (cmol$_c$ kg^{-1})	3.37 (1.23-11.06)	34	3.45 (1.01-7.17)	36	0.14
Zn (mg kg^{-1})	8.66 (0.83-69.06)	87	9.43 (1.73-37.88)	80	0.29
Cu (mg kg^{-1})	2.00 (0.76-5.12)	47	1.52 (0.76-2.55)	35	8.34**
Mn (mg kg^{-1})	30.9 (3.71-158.46)	65	45.76 (7.49-87.50)	53	14.33**
Fe (mg kg^{-1})	142.78 (43.36-327.18)	57	207.22(122.87-439.14)	34	18.47**
B (mg kg^{-1})	0.03 (0.004-0.120)	72	0.02 (0.003-0.100)	112	0.40
S$_{av}$ (mg kg^{-1})	7.29 (4.55-11.70)	20	6.25 (4.09-9.95)	26	14.34**
Sand (%)	45 (23-70)	20	65 (47-77)	11	133.35**
Silt (%)	32 (13-59)	22	19 (9-33)	31	92.27**
Clay (%)	23 (13-42)	24	16 (12-23)	18	48.09**

NGS: Northern Guinea savanna; SS: Sudan savanna; OC$_{tot}$: soil total organic carbon; N$_{tot}$: soil total nitrogen; P$_{av}$: soil available P; S$_{av}$: soil available 52ulphur; EA: soil exchange acidity (Al^{3+} + H^{+}); ECEC: soil effective cation exchange capacity; CV: coefficient of variability. ** ANOVA F-value is significant at 0.01 p-value; * ANOVA F-value is significant at 0.05 p-value.

Table 3.2: F-values for the response of maize grain yield, stover yield and nutrient concentration in the ear-leaf to nutrient application (NA), agro-ecological zones (AEZ) and variety group (VG) of the experimental data

Nutrient Concentration in the Ear-Leaf	**Main Effect**			**Interaction Effect**			
	NA	AEZ	VG	NA x AEZ	NA x VG	AEZ x VG	NA x AEZ x VG
Grain yield (t ha^{-1})	101.95**	2.73*	0.20	2.79**	0.74	0.03	0.24
Stover yield (t ha^{-1})	36.64**	3.58*	23.14**	3.59**	2.06	25.28**	1.03
Macronutrients (%)							
N	64.75**	8.97**	40.89**	3.21**	0.79	3.02	1.90
P	50.42**	24.81**	0.07	4.83**	1.38	0.38	2.17
K	12.21**	4.88**	17.96**	2.22	0.91	0.01	0.40
Mg	12.18**	7.51**	2.59	1.90	2.63*	27.85**	4.13**
Ca	62.84**	17.26**	54.14**	3.63**	1.08	5.07*	1.90
S	43.22**	1.00	12.07**	1.94	2.07	3.05	2.82**
Micronutrients (mg kg^{-1})							
Cu	40.15**	2.37*	118.11**	0.99	1.79	47.24**	1.02
Fe	5.37**	0.72	7.34**	0.84	1.44	9.00**	0.36
Mn	58.48**	0.88	5.10	1.39	0.90	0.89	0.87
Zn	36.43**	2.01	0.57	1.63	0.83	0.82	1.40
B	150.00**	56.23**	0.12	14.28**	0.76	0.08	0.39

** ANOVA F-value is significant at 0.01 p-value; * ANOVA F-value is significant at 0.05 p-value.

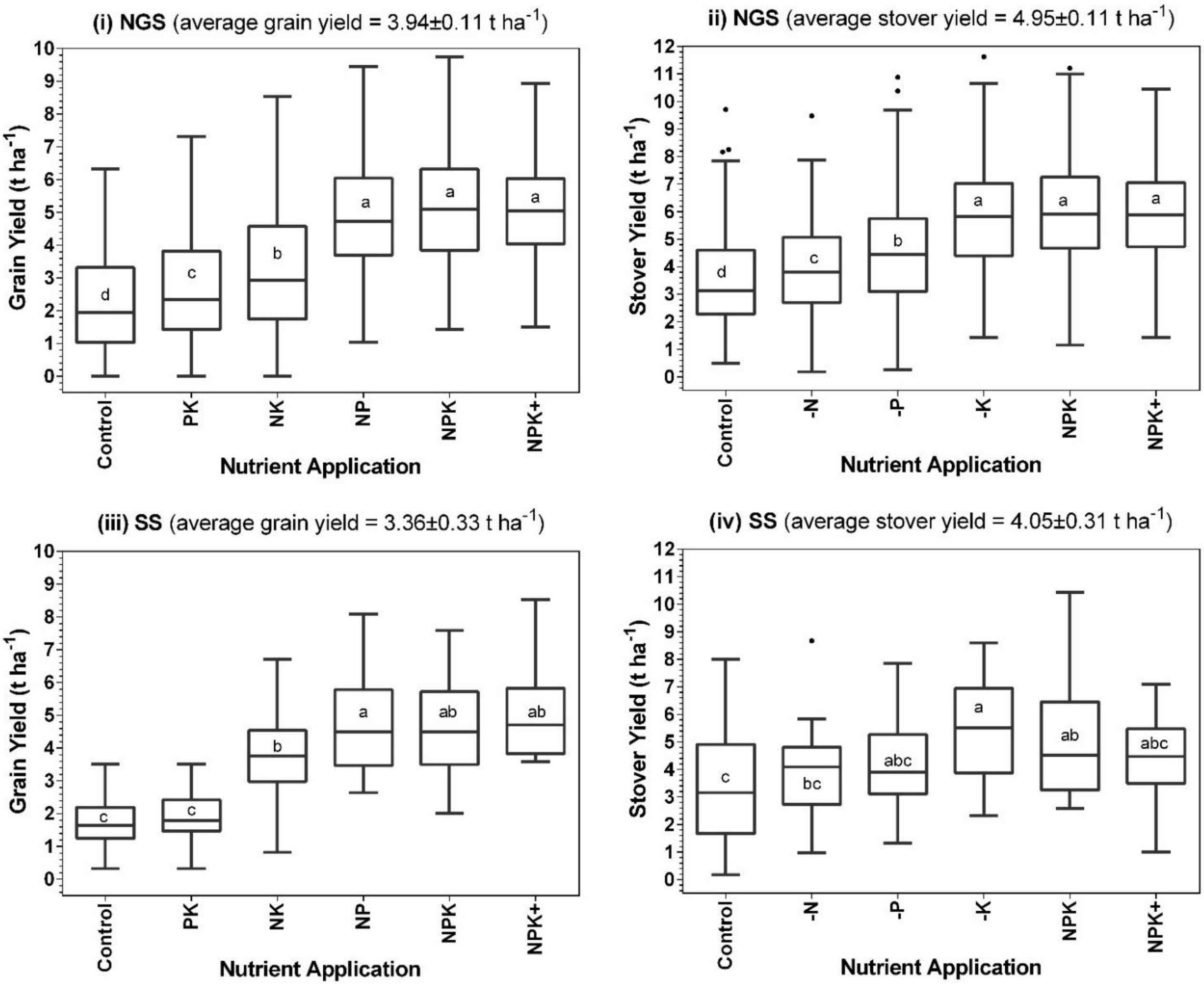


Figure 3.2: A box plot showing the effect of nutrient application on maize grain and stover yield for (i-ii) Northern Guinea savanna “NGS”, and (iii-iv) Sudan savanna “SS”. Values followed by different letters within a graph are significantly different at p-value ≤ 0.05.

Table 3.3: Spearman correlation coefficient between grain yield and nutrient concentration in the ear leaf

Ear Leaf Nutrient Content	Grain Yield (t ha^{-1})													
	Northern Guinea Savanna (NGS)							Sudan Savanna (SS)						
	Control	-N	-P	-K	NPK	NPK+	Overall	Control	-N	-P	-K	NPK	NPK+	Overall
N	0.47**	0.65**	0.42**	0.38**	0.41**	0.36**	0.57**	0.52**	0.71**	0.15	0.54**	0.48**	0.62**	0.62**
P	0.50**	0.22**	0.60**	0.17*	0.27**	0.24**	0.51**	0.26	0.08	0.65**	0.15	0.24	0.21	0.29**
K	0.14*	0.10	0.13	0.33**	0.19**	0.20**	0.13**	0.16	0.23	0.28	0.49**	0.43**	0.10	0.19*
Mg	0.17**	0.31**	< -0.01	0.18*	0.17*	0.07	0.24**	-0.23	-0.24	-0.18	-0.29	-0.21	0.24	-0.09
Ca	0.44**	0.45**	0.44**	0.15*	0.18**	< -0.01	0.45**	0.73**	0.44**	0.49*	-0.04	0.35	0.64**	0.55**
S	0.44**	0.60**	0.36**	0.39**	0.34**	0.19*	0.50**	0.61**	0.78**	0.48*	0.58**	0.76**	0.83**	0.70**
Cu	0.32**	0.45**	0.17*	0.14*	0.15*	0.05	0.33**	0.34	0.66**	0.11	0.05	0.01	0.03	0.32**
Fe	-0.06	0.22**	0.01	< 0.01	-0.15*	-0.15*	0.02	0.29	0.34	0.30	0.27	0.28	0.46*	0.35**
Mn	0.21**	0.22**	-0.06	-0.01	0.05	-0.01	0.29**	0.36	0.40*	-0.01	0.26	0.11	-0.09	0.32**
Zn	0.32**	0.40**	< -0.01	0.34**	0.29**	0.23*	0.28**	-0.19	0.17	-0.19	0.04	-0.22	0.08	0.18*
B	-0.01	-0.01	0.05	0.07	0.08	-0.04	0.20**	0.01	-0.14	0.32	-0.16	0.11	0.34	0.25**

** correlation coefficient is significant at 0.01 p-value; * correlation coefficient is significant at 0.05 p-value.

Table 3.4: Spearman correlation coefficient between stover yield and nutrient concentration in the ear leaf

	Stover Yield (t ha^{-1})													
	Northern Guinea Savanna (NGS)							**Sudan Savanna (SS)**						
Ear leaf Nutrient Content	Control	-N	-P	-K	NPK	NPK+	Overall	Control	-N	-P	-K	NPK	NPK+	Overall
N	0.33**	0.50**	0.32**	0.17**	0.11	0.04	0.41**	-0.02	-0.08	-0.26	-0.02	0.3	-0.06	0.15
P	0.40**	0.08	0.39**	0.06	0.11	0.19**	0.38**	0.04	-0.12	0.33	-0.02	0.18	0.31	0.15
K	0.08	-0.05	0.05	0.04	-0.05	-0.05	-0.02	-0.07	-0.14	-0.01	0.14	0.28	0.13	0.02
Mg	0.19**	0.35**	0.09	0.17*	0.33**	0.04	0.27**	0.33	0.17	0.11	0.40*	0.15	0.19	0.25**
Ca	0.40**	0.42**	0.39**	0.20**	0.30**	0.15*	0.45**	0.51*	0.03	0.29	-0.02	-0.04	-0.12	0.26**
S	0.35**	0.50**	0.39**	0.29**	0.20**	0.16*	0.43**	0.14	-0.03	0.10	0.09	0.51**	0.23	0.26**
Cu	0.31**	0.46**	0.27**	0.21**	0.20**	0.02	0.35**	-0.07	-0.10	-0.16	-0.50**	-0.25	-0.46*	-0.11
Fe	-0.18**	0.08	-0.09	-0.03	-0.14*	-0.07	-0.04	0.08	-0.12	-0.11	0.03	-0.06	-0.07	0.03
Mn	0.07	0.12	-0.04	0.03	0.08	-0.10	0.24**	0.11	-0.09	-0.02	0.32	0.1	0.23	0.21*
Zn	0.24**	0.22**	0.03	0.04	-0.03	0.06	0.15**	-0.12	-0.05	-0.30	-0.06	-0.07	0.25	-0.04
B	-0.01	-0.06	0.03	0.04	0.01	-0.03	0.16**	-0.09	-0.12	0.16	-0.16	0.35	0.21	0.07

** correlation coefficient is significant at 0.01 p-value; * correlation coefficient is significant at 0.05 p-value.

3.3.2 Compositional nutrient diagnosis (CND)

Grain yield cut-off and nutrient concentrations of the *high- and low- grain yield subpopulations*

Based on the recommendation of Parent and Dafir (1992) for accurate CND, the cut-off grain yield between low- and high-yield subpopulations was obtained at the highest inflection point after examining a cubic cumulative-variance ratio functions of 11 nutrients plus a filling value (Fv) versus grain yield. The highest cut-off grain yields in NGS and SS were obtained for P and Zn at values of 3.9 t ha^{-1} and 3.8 t ha^{-1}, respectively (Table 3.5). This was in consideration that the cut-off values for K in NGS, and for B, Fv in SS were out of context (outside the recorded yield range). The respective highest cut-off grain yields defining the high-yield subpopulation included 48% and 51% of observations in NGS and SS, respectively. The NPK+, NPK and NP nutrient application plots constituted the most sizable fraction of high-yield subpopulation by about 72% and 73% in NGS and SS, respectively. Consequently, control, N omitted (PK) and P omitted (NK) were dominant in the low-yield subpopulation contributing to approximately 78% and 73% in NGS and SS, respectively.

Average maize grain yields of the high-yield subpopulations at 5.5 t ha^{-1} for NGS and 5.1 t ha^{-1} for SS were significantly larger than those of the low-yield subpopulations at 2.4 and 2.7 t ha^{-1}, respectively (Table 3.6). Moreover, with an exception of Fe, Mn and B in NGS; and Mn and Zn in SS, the concentration of all nutrients was significantly higher in the high-yield subpopulation compared to the low-yield subpopulation in both agroecological zones (AEZs).

CND norms

The CND norms as means and standard deviations of the row-centered log ratios (clr) for high-grain yield subpopulations are presented in Table 3.7. The norms for each of the AEZ were positive for macronutrients and filling value and negative for micronutrients. Overall, the sum of norm values in each AEZ equals zero indicating that the yield/nutrient response portioning procedure of Nelson (Nelson and Anderson, 1977) has been carried out accurately. The norms for N, Mg, S and Cu were larger in NGS compared to those in SS. In contrary, norms for P, Ca and B were larger in SS compared to NGS.

Table 3.5: Inflection points (-b/3a) of the cubic relation between cumulative variance function of raw row-centered log ratios of each nutrient in the maize ear leaf (V_X) versus grain yield

	NGS		**SS**	
V_x	-b/3a (t ha^{-1})	R^2	-b/3a (t ha^{-1})	R^2
Macronutrients				
V_N	3.1	0.997	2.9	0.998
V_P	**3.9**	0.998	3.2	0.994
V_K	-4.3	0.999	3.4	0.984
V_{Mg}	3.1	0.997	0.5	0.998
V_{Ca}	3.6	0.998	2.9	0.996
V_S	3.2	0.999	3.3	0.994
Micronutrients				
V_{Cu}	3.5	0.998	0.4	0.994
V_{Fe}	3.5	0.997	3.7	0.993
V_{Mn}	2.9	0.997	3.4	0.971
V_{Zn}	2.5	0.997	**3.8**	0.994
V_B	2.7	0.997	43.1	0.925
Filling value				
V_{Fv}	0.7	0.997	-216.9	0.998

V_x: cumulative variance function for nutrient x; -b/3a: Inflection point for each nutrient; NGS = Northern Guinea savanna; SS: Sudan savanna; The highest inflection points of 3.9 and 3.8 t ha^{-1} (values in bold) obtained from P and Zn, respectively, are the selected grain yield cut-off values separating high from low-yield subpopulations.

Critical CND imbalance index (CND r^2) and nutrient imbalance partitioning

The critical imbalance indices (CND r^2) were 11.0 and 11.2 for the NGS and SS, respectively (Figure 3.3). The values less than or equal to the CND r^2 indicate nutritionally balanced, while values above the CND r^2 show nutritionally imbalanced situations. Combining the grain yield cut-off and CND r^2, the experimental data sets were portioned into four quadrants (Figure 3.4). As mentioned earlier in the materials and methods, the four quadrants consisted of observations classified as: high yielding and nutrient balanced (HYB), high yield and nutrient imbalanced (HYI), Low yielding and nutrient balanced (LYB), and low yield and nutrient imbalanced (LYI). Low yield and imbalanced quadrants (LYI) held the most substantial number of observations, constituting 40% and 42% of the data in NGS and SS, respectively. About 81% and 75% of the LYI samples in NGS and SS, respectively, are either from control, or -N or -P plots. This confirms that N and P are the most yield limiting

Table 3.6: Average grain yield and ear leaf nutrient concentrations of the high and low grain yielding sub-populations based on compositional nutrient diagnosis (CND) yield partitioning procedure

	Northern Guinea Savanna (NGS)			**Sudan Savanna (SS)**		
	HY	LY	F-Value	HY	LY	F-Value
Grain yield (t ha^{-1})	5.5	2.4	1684.11**	5.1	2.7	152.51**
Macronutrients (%)						
N	2.42	2.07	164.00**	2.21	1.81	30.29**
P	0.23	0.21	78.85**	0.29	0.26	5.03*
K	2.05	1.93	27.76**	1.93	1.65	12.92**
Mg	0.25	0.23	22.08**	0.19	0.23	11.00**
Ca	0.57	0.50	68.00**	0.71	0.60	16.08**
S	0.17	0.15	141.10**	0.17	0.14	47.56**
Micronutrients (mg kg^{-1})						
Cu	6.72	6.13	26.32**	6.44	5.43	6.67*
Fe	135.12	134.06	0.20	145.30	114.57	22.17**
Mn	52.57	50.00	3.76	58.94	56.33	0.26
Zn	13.79	12.44	39.79**	12.89	12.00	0.15
B	6.82	6.47	29.96	10.77	7.88	5.82*

HY: High grain ielding sub-population; LY: Low grain yielding sub-populations; **: denotes F-value significant at 0.01 probability level; *: denotes F-value significant at 0.05 probability level; the F-Value is for the difference between HY and LY.

Nutrients in both the two agro-ecological zones. The LYB quadrants contained the smallest number of observations holding barely 12% and 7% of the dataset in NGS and SS, respectively. Yield in the LYB samples are limited by other abiotic and biotic constraints than nutrients. The HYI which indicated an excess of some nutrients composing about 25% and 22% of the total observations in NGS and SS, respectively. Finally, HYB held 23% and 29% of the population in NGS and SS, respectively. About 70% of the observations in HYB both in NGS and SS were from NP, NPK and NPK+ plots.

CND ear leaf nutrient sufficiency ranges

The maize nutrient sufficiency ranges obtained for the two AEZs as well as comparison with published literature sufficiency ranges have been shown in Table 3.8. The CND sufficiency ranges for N, K, Mg, Cu and Zn were relatively larger in NGS than those of SS, with an adverse trend observed for P, Ca, Mn and lower boundary limit of Fe. Simultaneously, the sufficiency ranges were comparable between the two AEZs for S, B and upper boundary limit of Fe. Overall, the CND sufficiency ranges in both AEZs were in line with published

Table 3.7: Compositional Nutrient Diagnosis (CND) norms (V_x^*) for the high maize grain yielding subpopulation

	Northern Guinea Savanna (NGS)		**Sudan Savanna (SS)**	
CND norms	Mean	STD	Mean	STD
Macronutrients				
V_N^*	3.39	0.14	3.25	0.14
V_P^*	1.06	0.19	1.23	0.19
V_K^*	3.19	0.23	3.11	0.19
V_{Mg}^*	1.12	0.24	0.83	0.28
V_{Ca}^*	1.95	0.19	2.11	0.19
V_S^*	0.73	0.10	0.68	0.11
Micronutrients				
V_{Cu}^*	-4.82	0.23	-4.95	0.33
V_{Fe}^*	-1.83	0.25	-1.79	0.22
V_{Mn}^*	-2.77	0.40	-2.71	0.44
V_{Zn}^*	-4.11	0.23	-4.25	0.20
V_B^*	-4.96	0.63	-4.54	0.66
Filling value				
V_{Fv}^*	7.05	0.10	7.03	0.10
$\sum V_x^*$	0	-	0	-

CND norms (V_x^*) are means and standard deviations (STD) of raw-centered log ratios in a high yielding sub-population.

Literature, except that the lower boundary limits for Cu and B were relatively smaller. Moreover, the lower boundary limits of Mn and Zn in the two AEZs were smaller than the lower limits published by Njoroge et al. (2017) and Reuters & Robinson (1997), respectively.

3.3.3 Maize nutrient limitations and imbalances

As described above, plots in the low yield and nutrient imbalanced sub-populations (LYI) were used to assess the nutrients in the maize ear leaf that are significantly deficient or – if possible – in excess resulting in nutrient imbalances in the study area. The frequency of significant nutrient deficiencies across the NA for the two AEZ is presented in Table 3.9, while the same for those in excess from the same LYI are presented in Table 3.10. From Table 3.9, significant nutrient deficiencies in the control plots, ranked according to decreasing frequency, were N, P > Ca, S > Cu, Mn > B in NGS and N, S > Ca, Cu > P > Mn, B in SS. Overall, these deficiencies were observed in between 41 to 90% of all control plots in

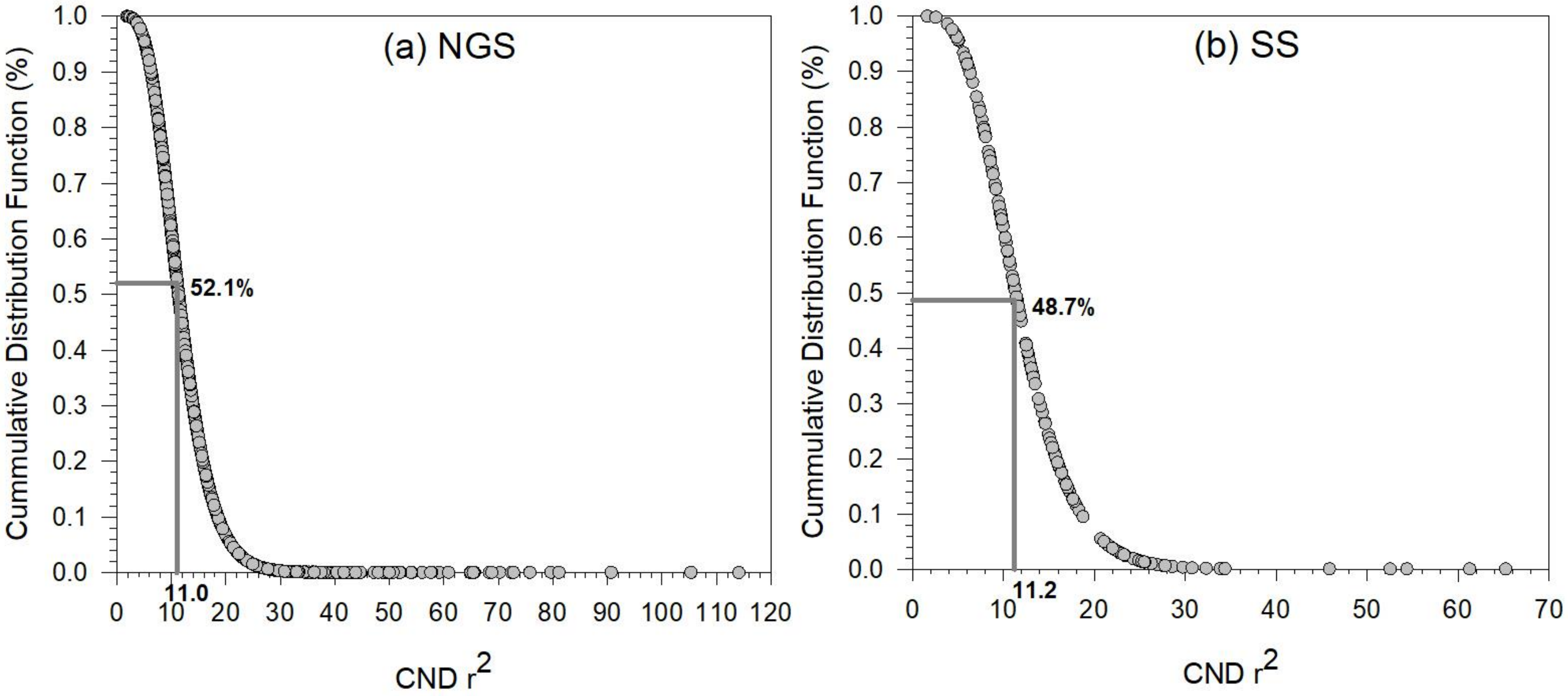


Figure 3.3: The chi-square distribution function with 12 degrees of freedom to obtain the critical threshold value of compositional nutrient diagnosis imbalance index (CND r^2) for a) Northern Guinea savanna (NGS), and b) Sudan savanna (SS).

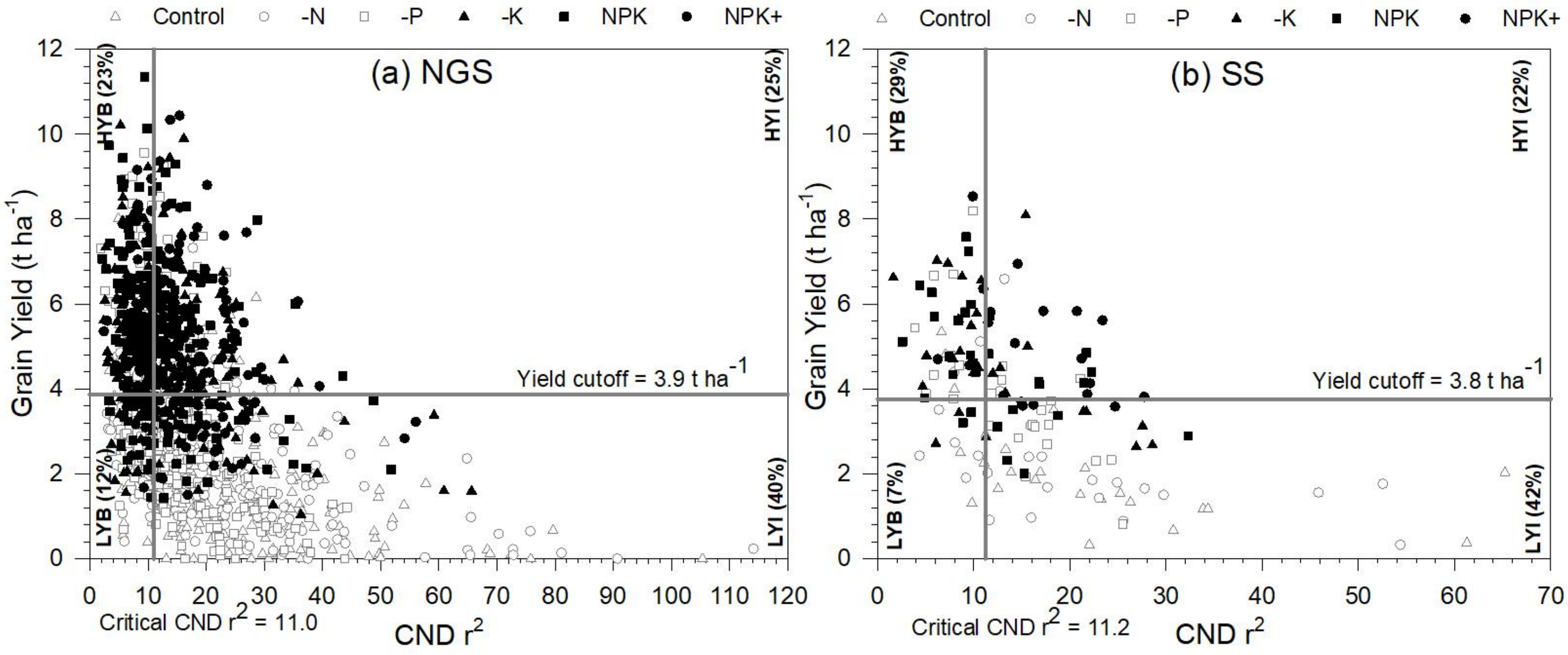


Figure 3.4: Portioning of data into four quadrants based on the relations between the cut-off yield (separating high and low yield subpopulation according to their nutritional balances) and critical CND balance index (CND r^2) for a) Northern Guinea savanna (NGS), and b) Sudan savanna (SS). HYB = high yield and balanced, LYB = low yield and balanced, HYI = high yield and imbalanced, LYI = low yield and imbalanced.

Table 3.8: A comparison of agro-ecological zone maize ear leaf nutrient sufficiency ranges and published references

Nutrient	**NGS**		**SS**		**Published reference (Njoroge et al., 2017)**		**Published reference (Reuters and Robinson, 1997)**	
	LBL	UBL	LBL	UBL	LBL	UBL	LBL	UBL
Macronutrients (%)								
N	2.08	2.87	1.91	2.47	2.09	2.34	2.30	3.30[#]
P	0.19	0.29	0.25	0.35	0.26	0.29	0.17	0.32[#]
K	1.66	2.38	1.68	2.23	1.67	1.87	1.71	2.25[#]
Mg	0.19	0.32	0.15	0.24	0.15	0.17	0.13	0.24[#]
Ca	0.45	0.72	0.57	0.84	0.45	0.51	0.21	1.00[!]
S	0.14	0.20	0.15	0.19	0.15	0.17	0.16	0.22[¶]
Micronutrients (mg kg^{-1})								
Cu	5.13	8.60	4.36	8.24	7.40	8.30	6.00	20.00[!]
Fe	96.68	171.49	113.27	171.53	-	-	30.00	200.00[‡]
Mn	31.35	80.91	34.83	75.72	68.91	77.30	20.00	150.00[#]
Zn	10.26	17.37	10.16	14.39	10.67	11.97	18.00	60.00[‡]
B	3.74	14.74	4.06	14.74	11.10	12.45	5.00	25.00[!]

[#] Cornforth (1982) cited by Reuters and Robinson (1997); [!] Jones et al. (1991) cited by Reuters and Robinson (1997); [¶] Ojeniyi and Kayode (1993) cited by Reuters and Robinson (1997), [‡] Wier and Cresswell (1994) cited by Reuters and Robinson (1997); NGS = Northern Guinea savanna; SS = Sudan savanna; LBL = Lower Boundary Limit; UBL = Upper Boundary Limit.

Table 3.9: Frequency of ear leaf nutrient deficiencies in the low yield and imbalanced maize subpopulation (LYI) based on nutrient sufficiency ranges of this study

NA	**Number of Plots**	**Frequency Intervals (%)**									
		100-91	90-81	80-71	70-61	60-51	50-41	40-31	30-21	20-11	0-10
Northern Guinea Savanna (NGS)											
Control	174			**N**, **P**	**Ca**, **S**	**Cu**, **Mn**	**B**	Mg, Zn	K	Fe	
-N	155		**N**, **S**	**Cu**, **Zn**		Ca, **Mn**, **B**	P, Mg	Fe	K		
-P	105			**P**	**Ca**	**B**		N, **Mg**, S	Cu	Fe, Mn	K, Zn
-K	34			**B**	**N**, **K**	**S**, **Zn**	Cu	Fe	P, Mg, Ca	Mn	
NPK	36				**N**, **Zn**	**S**, **B**	Mg	P, K, Ca	Cu	Fe	Mn
NPK+	31						**N**	**P**, **Cu**	Mg, **S**	K, **Ca**, Zn	Mn, Fe, B
Overall	535				**N**, **S**	**P**, **Ca**, **B**	**Cu**, Zn	Mg, **Mn**	K, Fe		
Sudan Savanna (SS)											
Control	19		**N**, **S**		**Ca**, **Cu**	**P**	Fe, **Mn**, **B**	K		Zn	Mg
-N	17		**N**, **S**		Ca, **Cu**, Zn		P, Fe, **Mn**, **B**	K			Mg
-P	12			**Ca**	**P**		K, **Fe**, **B**	N, S		Mg, Cu	Mn, Zn
-K	6	**K**			**S**		Zn, **B**	N, P		Ca, Fe, Mn	Mg, Cu
NPK	6				**S**		N, K, Ca, Cu, Fe, Mn, **B**	P, Zn			Mg
NPK+	4						**N**, K, Ca, **Fe**		P, **S**, Cu, Zn, B		Mg, Mn
Overall	64				**N**, **S**, **Ca**		P, K, Cu, Fe, **B**	Mn, Zn			Mg

NA: nutrient application treatment; Nutrients in bold are those with indices being significantly below zero (indicating significantly limiting) based on student's t-test (if normality confirmed) or 'one-sample Wilcoxon signed ranked' test (if normality unconfirmed).

Table 3.10: Frequency of excess ear leaf nutrient concentrations in the low yield and imbalanced maize subpopulation (LYI) based on nutrient sufficiency ranges of this study

NA	**Number of Plots**	**Frequency Intervals (%)**							
		80-71	70-61	60-51	50-41	40-31	30-21	20-11	0-10
					Northern Guinea Savanna (NGS)				
Control	174							K, Fe	N, P, Mg, Ca, S, Cu, Mn, Zn, B
-N	155							K	N, P, Mg, Ca, S, Cu, Fe, Mn, Zn, B
-P	105					Zn		K, Cu, Fe, Mn	N, P, Mg, Ca, S, B
-K	34						Mg, Ca, Mn	P, Cu	N, K, S, Fe, ZN, B
NPK	36					Fe		P, K, Mg, Ca, Cu, Mn	N, S, Zn, B
NPK+	31	B				Mn	Fe, Zn	N, K, Mg, Cu	P, Ca, S
Overall	535							K, Fe, Zn	N, P, Mg, Ca, S, Cu, Mn, B
					Sudan Savanna (SS)				
Control	19					Mg		P, K, Fe, Zn	N, Ca, S, Cu, Mn, B
-N	17					P		N, K, Mg, B	Ca, S, Cu, Fe, Mn, Zn
-P	12				Mg, Zn		K, Cu, Mn	N	P, Ca, S, Fe, B
-K	6		Mg					P, Cu, Fe, Mn	N, K, Ca, S, Zn, B
NPK	6					Mg		P, Mn, Zn, B	N, K, Ca, S, Cu, Fe
NPK+	4				Mg, Mn, B		P, Zn		N, K, Ca, S, Cu, Fe
Overall	64					Mg		P, K, Mn, Zn	N, Ca, S, Cu, Fe, B

NA: nutrient application treatment.

Both AEZs. For the N omitted plots (-N), the nutrient deficiency frequencies in decreasing order were N, S > Cu, Zn > Mn, B in NGS and N, S > Cu > Mn, B in SS representing 41 to 90% of the plots. For the P omitted plots (-P) from the same LYI, the significantly limiting nutrients in decreasing order of frequency were P > Ca > B > Mg in NGS and Ca > P > Fe > B in SS. These significant limiting nutrients in the -P plots occurred in 31 to 80% of the plots.

In the K omitted plots (-K), the significant deficient nutrients in descending order were B > N, K > S, Zn in NGS and K > S > B in SS. These deficiencies in the -K plots constitute between 51 to 80% and 41 to 100% of the plots in NGS and SS, respectively. In the NPK plots, the significantly deficient nutrients constituting 41 to 70% of the plots were N, Zn > S, B in NGS and S > B in the SS. For the plots where secondary macro- and micro-nutrients (S, Ca, Mg, Zn and B) were added to the NPK (NPK+) the significantly deficient nutrients from the LYI were N> P, Cu > S in NGS and N > Fe > S in SS. The occurrence of these deficient nutrients in the NPK+ covers 21 to 50% of the plots in NGS and SS, respectively. The detailed result for the test of significance of the nutrient indices indicating whether the nutrient is significantly limiting or not is also shown in the **Appendix C**.

The frequency of excess nutrients is largely below 40% of all the plots in LYI across the AEZs (Table 3.10). The excess nutrients constituting greater than 40% of the plots involves extensively secondary macro- and micro-nutrients from fertilized plots especially NPK+ plots. In -P plots in the SS Mg and Zn is in excess in 50 to 41% of the plots. In the NPK+ in NGS, about 71 to 80% of the samples had excess concentrations of B. While, for the same NPK+ plots in SS, 41 to 50 % of the samples had excessive concentrations of Mg, Mn and B.

3.3.4 Nutrient interactions

The principal component analysis on the row-centered log ratios of ear leaf nutrient concentrations plus a filling value (Fv) showed that the first four principal components (PCs) were significant, based on an eigenvalue ≥ 1.00 in both AEZs (Table 3.11). Cumulatively, these first four significant PCs explained 63.8% and 69.0% of the total variance in NGS and SS, respectively. The first PC explained the largest part of the variance in the data set: i.e. about 22.5% and 26.9% in NGS and SS, respectively (Table 3.11). Therefore, these first four principal components were used to understand the pattern and structure of most important nutrient interactions contributing to much variability in the ear leaf nutrient composition.

Table 3.11: Eigen values, percent explained variance and selection criteria for the selected significant principal components (PCs)

PC	Eigen Values	Explained Variance (%)	Cumulative Explained Variance (%)	Selection Criterion (SC)
		Northern Guinea Savanna (NGS)		
PC1	2.70	22.5	22.5	0.30
PC2	1.94	16.2	38.7	0.36
PC3	1.68	14.0	52.7	0.39
PC4	1.33	11.1	63.8	0.43
		Sudan Savanna (SS)		
PC1	3.23	26.9	26.9	0.28
PC2	2.08	17.3	44.2	0.35
PC3	1.66	13.9	58.1	0.39
PC4	1.31	10.9	69.0	0.44

The biplots of the selected first four PCs are presented in Figure 3.5 (Figure 3.5A and 3.5B for NGS, and 3.5C and 3.5D for SS). Only significant factor loadings, based on the section criteria (SC) (Table 3.11) as suggested by Collins & Ovalles (1988) after varimax rotation were selected and interpreted from the biplots. Principal component 1 (PC1) in NGS was significantly explain by positive scores of N, Ca, S and Cu (group 1) and negative scores of K and Fv (group 2). This reveals a positive interaction among the nutrient elements within a group and negative interactions between the groups. Similar pattern was observed in the same PC1 of SS, except P additionally obtains a significant negative score. In PC2 of the two AEZs, negative scores of B and positive scores of Fv and K constitute the major eigenvector loadings explaining the variance. In PC3 of the two AEZs, synergistic relation between Ca and Mg is the dominant loading explaining the variance, except the two nutrients have positive scores in NGS and negative one in the SS. However, Zn have significant negative interaction with the two nutrients (i.e. Ca and Mg) in the NGS. In Principal component 4 across the AEZs, Fe and Mn are significant factor loadings based on selection criterion, with a synergistic relationship in the NGS and the opposite one in the SS.

All the four selected PCs were significantly influenced by the nutrient application (NA) (Table 3.12). Control and nitrogen omission (-N) lead to significantly negative score in PC1 across the AEZs (Figure 3.6). In PC2 for both the two AEZs, control plots lead to highest positive scores as opposed to NPK+ with the smallest negative score. Omission of P (-P) PC3 lead to significantly negative and positive score in NGS and SS, respectively. In PC4, -N lead to

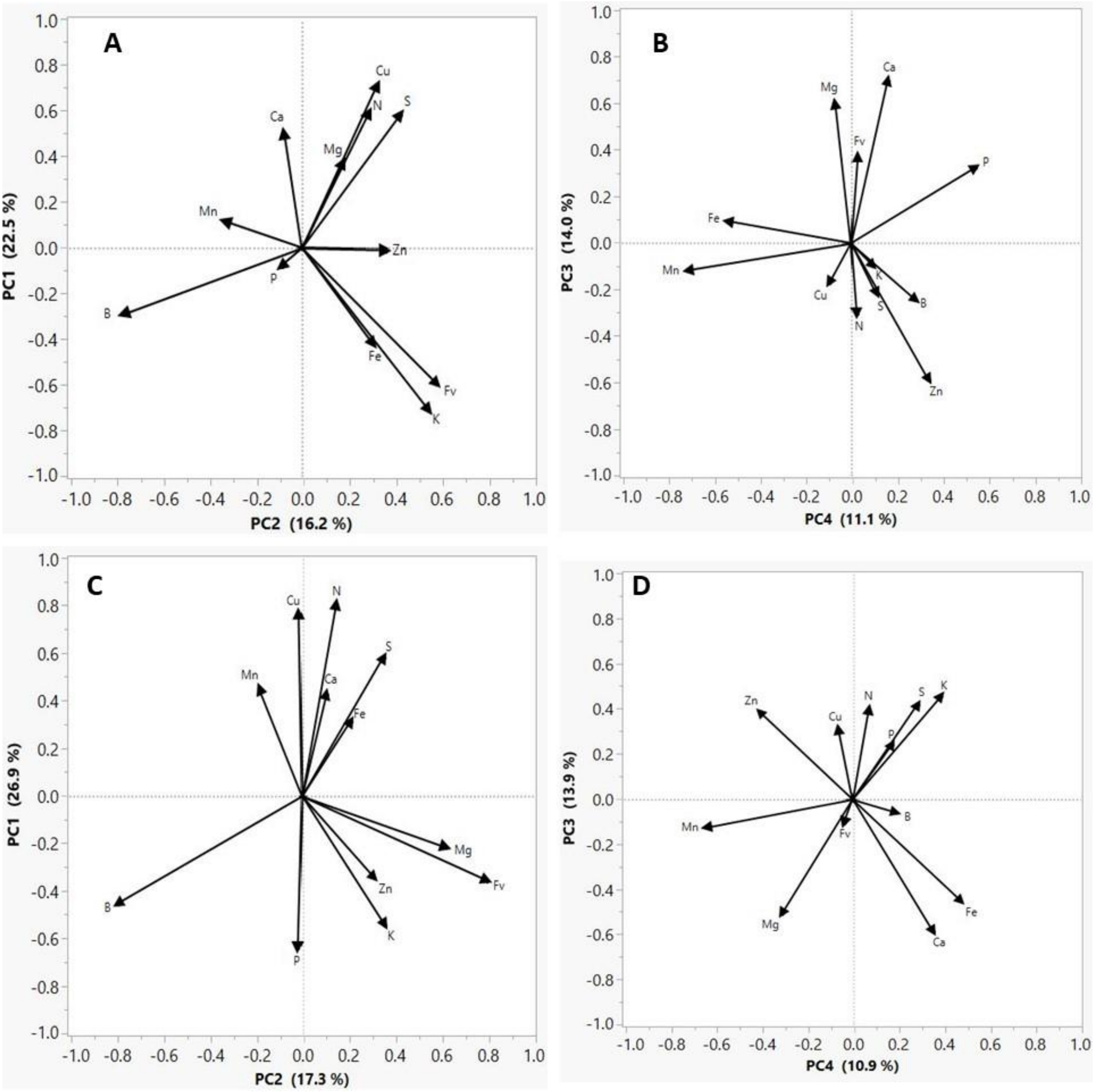


Figure 3.5: Biplot of the eigen vector loadings of the principal component analysis of row-centered log ratios of ear leaf nutrients concentration: A and B for Northern Guinea savanna (NGS); and C and D for Sudan savanna (SS).

Table 3.12: ANOVA F-values (comparing the principal component score of row-centered log ratios of ear leaf nutrients concentration with nutrient application treatments) and Spearman correlation coefficients (relating the principal component score of row-centered log ratios of ear leaf nutrients concentration with the soil characteristics)

		Northern Guinea Savanna				**Sudan Savanna**			
		PC1	PC2	PC3	PC4	PC1	PC2	PC3	PC4
(ANOVA F-value)	NA	77.12**	262.73**	191.03**	32.65**	131.50**	132.30**	130.50**	130.50**
Soil characteristics (Spearman correlation coefficient)	pH	-0.02	0.08**	0.01	0.34**	-0.2*	-0.18*	0.46**	0.44**
	OC_{tot}	0.10**	0.12**	-0.23**	-0.06	0.15	0.14	-0.19*	0.33**
	N_{tot}	0.16**	0.05	-0.15**	-0.04	0.16*	0.16	-0.24**	0.26**
	P_{av}	0.24**	-0.05	0.15**	0.08**	-0.28**	-0.13	0.05	0.44**
	Sand	-0.18**	-0.03	0.09**	0.13**	-0.18*	-0.33**	0.34**	-0.17*
	Silt	0.14**	0.01	-0.01	-0.08*	0.18*	0.32**	-0.36**	0.16
	Clay	0.12**	0.03	-0.12**	-0.11**	0.09	0.23**	-0.17*	0.16*
	Ca	0.14**	0.05	-0.05	0.14**	-0.14	0.13	-0.1	0.42**
	Mg	0.16**	0.09**	0.01	0.05	-0.08	-0.03	0.19*	0.62**
	K	-0.07*	-0.06*	-0.01	-0.10**	-0.19*	-0.02	0.23**	0.33**
	Na	0.33**	-0.01	0.13**	0.12**	0.20*	0.07	-0.09	0.26**
	EA	0.09**	-0.07*	-0.01	-0.22**	0.03	-0.01	-0.13	-0.47**
	ECEC	0.17**	0.05	-0.04	0.10**	-0.15	0.09	0.01	0.49**
	Zn	0.19**	0.08**	-0.02	0.29**	-0.05	0.17*	-0.31**	0.34**
	Cu	0.19**	0.04	-0.16**	-0.08*	0.30**	-0.18*	0.17*	0.21
	Mn	0.21**	-0.11**	0.13**	-0.14**	-0.24**	-0.18*	0.21*	-0.18*
	Fe	-0.22**	-0.02	0.02	-0.06*	0.02	0.27**	-0.46**	0.22**
	B	0.05	-0.07*	-0.04	0.07*	-0.10	-0.06	0.04	0.46**
	S	0.07*	0.03	-0.14**	-0.21**	0.05	0.30**	-0.23**	0.28**

** ANOVA F-value or correlation coefficient is significant at 0.01 p-value; * ANOVA F-value or correlation coefficient is significant at 0.05 p-value; OC_{tot}: soil total organic carbon; N_{tot}: soil total nitrogen; P_{av}: soil available P; S_{av}: soil available 69ulphur; EA: soil exchange acidity ($Al^{3+} + H^{+}$); ECEC: soil effective cation exchange capacity.

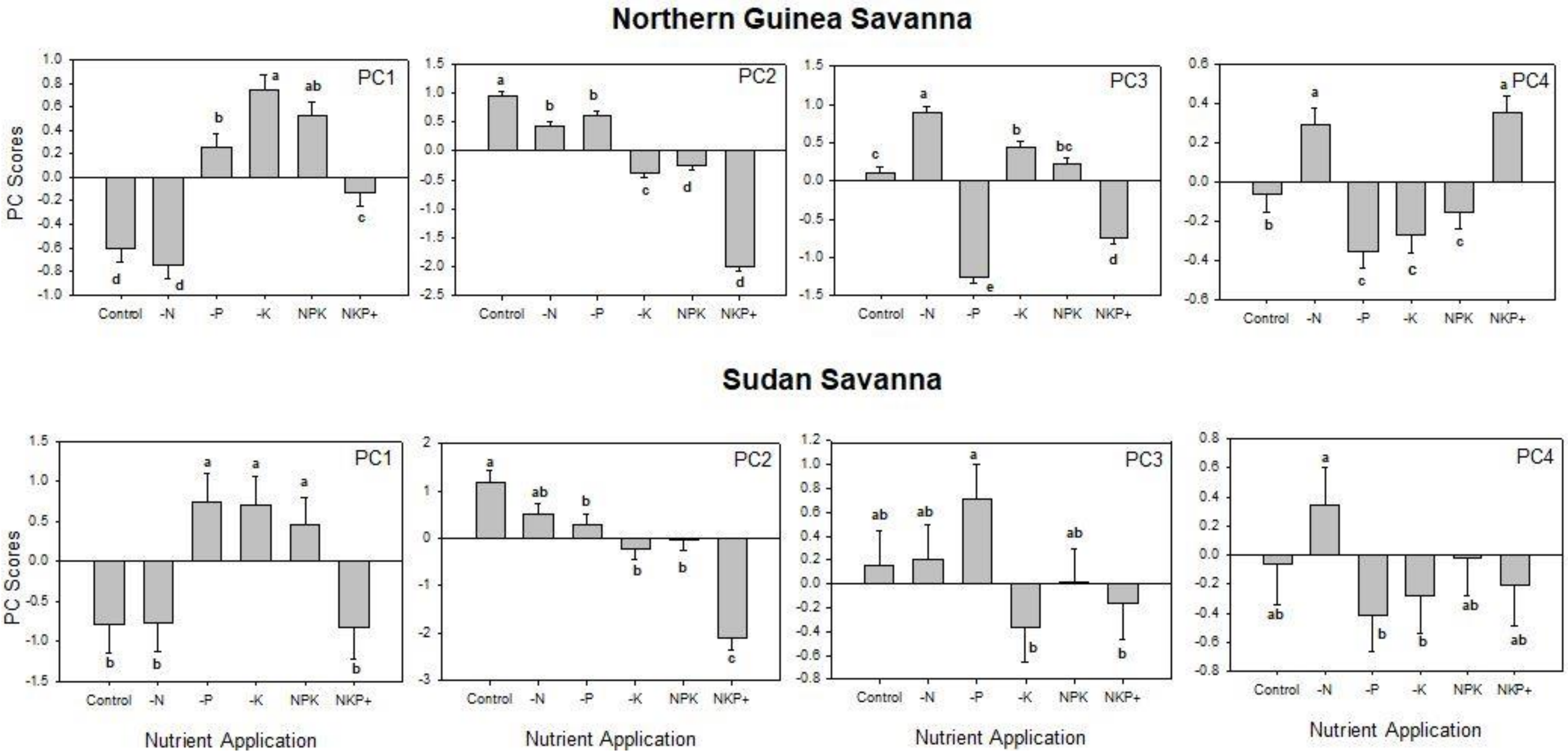


Figure 3.6: Effect of nutrient application (NA) on principal component scores of row-centered log ratios of ear leaf nutrients concentration. Values followed by different letters within a graph are significantly different at p-value ≤ 0.05.

highest positive scores across the two AEZs, except in NGS where -N and NPK+ were comparable. Significant but weak correlation was observed between PCs and most soil characteristics (Table 3.12). Across the two AEZs, PC1 positively correlated with soil N and Cu contents. However, as opposed to NGS, negative correlation was observed between soil P content and the same PC1. Principal component 2 in the SS, have more correlation with soil texture, where silt and clay contents have positive correlation as opposed to the sand content. Soil phosphorus content have a positive correlation with PC3 in the NGS. While soil OC_{tot}, N, Zn, Cu and S have a negative correlation with the same PC3 in the NGS. Principal component 3 (PC3) in the SS positively correlated with soil pH, sand, K, Cu and Mn; and negatively correlated with soil N, silt, Zn, Fe and S. Soil pH positively correlated with PC4 across the two AEZs. However, the same PC4 but in SS have significant positive correlation with soil P, Ca, Mg, ECEC, Fe and B; and negative one with exchangeable acidity and Mn.

3.4 Discussion

4.1.1 Soil, yield and ear leaf nutrient characteristics

The observed variability in most of the physico-chemical properties among the study fields is attributable to both an inherent variability in soil forming factors and management factors. Larger rainfall amount and duration (as presented in Figure 3.1) which naturally favored larger vegetative biomass and litterfall in the NGS compared to the SS can be related to the higher OC_{tot}, N_{tot}, Cu and available S_{av} in the NGS. Alternately, relatively less rainfall in the SS compared to the NGS can be associated with the higher pH and P_{av} in the SS. High rainfall increases the potential for leaching of cations (especially Ca and Mg) which accompanies a decrease in soil pH. In addition, at low or acidic pH level, a rise in soil pH can reduce the fixation potential of P_{av} by aluminum and hydrogen ions, hence increasing soil P_{av}. The soils in the study area have been reported to have formed from aeolian materials and pre-Cambrian basement complex rocks (like granite, schist and sandstone), which led to large sand fractions in the soil profile (Bennett, 1980). The small contents of OC_{tot}, N_{tot}, B and ECEC across the two study agro-ecological zones can be related to two factors: (i) the type of parent material (dominated by low activity clays like kaolinite) and an intensive and long weathering of the soils resulting in small mineral reserves; and (ii) intensive and continuous cultivation of the soils without adequate nutrient replenishment, mostly only relying on burning or complete removal of crop residues (Jones and Wild, 1975; Manu et al., 1991; Smaling et al., 1991; Kwari et al., 2011).

The significant reduction in grain and stover yields due to the omission of P and N across the two agro-ecological zones suggest these nutrients to be the most limiting for maize production. The deficiency of N has been recognized as the most limiting factor for cereal production in vast areas of SSA including in the Nigerian savanna (Vanlauwe et al., 2011). Soil N can be depleted rapidly by maize, especially when yields are high and stover is exported (Kamara, 2017). Additionally, P has been reported to be the second most yield limiting in maize in the highly weathered Nigerian Savannah soils with large P sorption capacity (Osemwotai et al., 2005). The widespread N and P deficiency in the study area can be attributed to small soil organic matter contents (indicated by small OC_{tot}) resulting from inherent poor soil fertility and continuous cropping with inadequate and imbalanced fertilizer or manure applications. Integrated application of balanced fertilizers with manure and rotation of cereal crops with legumes through integrated soil fertility management principles (ISFM) (Vanlauwe et al., 2010) can assist farmers in the study area to improve soil N and P status. The positive correlation observed between the grain yield and ear leaf nutrient concentrations confirms the ear leaf to be an organ of more vital metabolic activity and its nutrient concentration relates best to maize yield as earlier reported by many scientists like Jones (1998) and Kovács & Vyn (2017). It was evident that the correlation between ear leaf nutrient concentrations and the stover yield was less compared to that of the grain yield especially in the SS. Similar trend was observed by Kovács & Vyn (2017) and they attributed this to the more metabolic activity between the maize ear leaf and the ear as a result of their closer proximity compared to the rest of the maize plant parts which constitutes the stover yield. A weak correlation between soil and ear leaf nutrients concentration reflects that apart from the soil nutrient concentration, other soil processes (such as leaching, fixation, immobilization, etc.) and soil physical properties (such as presence of hard pans, drainage, water table, etc.) influences plant nutrient uptake. Therefore, all these factors must be integrated when interpreting plant nutrient content with the soil analysis.

3.4.2 Compositional nutrient diagnosis (CND)

Grain yield cut-off and nutrient concentrations of the high- and low-yield subpopulations

The grain yield cut-offs observed in this study across the two AEZs are comparable to 4.1 t ha^{-1} and 3.1 t ha^{-1} reported by Njoroge et al. (2017) for long and short rain maize in Western Kenya, respectively. The dominance of NPK+, NPK and -K plots in the high- grain yield subpopulation with large concentrations of N and P in the ear leaves indicate these two elements as the most yield limiting for maize production in the study area. The soil N_{tot} and P_{av} values are indeed small in most of the study fields which account for the large yield responses to the addition of N and P. The presence of a substantial number of K omitted (-K) plots in the high- grain yield subpopulation suggests K to be a less important limiting nutrient for maize yield in the study area compared to the N and P. The exchangeable potassium content in the larger number of the study fields is indeed above the soil critical requirement of 0.16 cmol$_c$ kg^{-1} for maize (Agboola, 1985). The small maize grain yield response to the K addition similarly agrees with the work of Adediran & Banjoko (1995) who reported small yield response to K application in some parts of the Nigerian savanna. The lack of significant differences in the concentration of some micronutrients (such as Fe, Mn, Zn and B) in the ear leaves between the high- grain yield and low- grain yield subpopulations suggests these nutrients might not have significant effect on the maize grain yield but rather one other metabolic process enhancing crop quality.

CND norms, Critical CND imbalance index (CND r^2) and nutrient imbalance partitioning

Although slightly different, the values and trend of the CND norms across the AEZs are close to the norms obtained by Gott et al. (2017) and Njoroge et al. (2017). However, the slight differences between the norms could be linked to variations in the prevailing climatic conditions, genotypes and crop management. The larger values of N, Mg, S and Cu norms in the NGS compared to the SS can be explained by the higher supply and demand of these nutrients in the NGS compared to the SS. While a larger demand may stem from the more favorable conditions in the NGS versus the SS, the larger supply can be attributed to the larger soil nutrient contents (Table 3.1) and additionally (specific N) to the larger amounts applied in the NGS compared to the SS. A similar explanation can be made of the larger P, Ca and B norms in the SS compared to the NGS, as larger contents of the three nutrients were observed in the SS soils relative to the NGS. The near identical critical CND r^2 values between the two agro-ecological zones indicate that the values of the minimum CND imbalance index to reach a high maize grain yield are comparable. The most conspicuous pattern in the maize ear leaf nutrient imbalance portioning is that about 40% of the experimental plots across the agro-ecological zones (prominently involving the control, -N and -P plots) ended up in the LYI quadrant. This implies that huge maize yield losses occur due to nutrient imbalances in turn a consequence of the inadequate supply of nutrients (especially N and P). However, the occurrence of some NPK+, NPK and -K (K omitted) plots in the same LYI suggest that additions of these nutrients in specific cases are either inadequate or became unavailable to the plant through various losses like leaching, fixation, among others. There is also a sizable number of fertilized plots in the HYI quadrant, which indicates that a uniform or blanket application of fertilizer in the study area may also result to nutrient imbalances despite good yields due to spatio-temporal variability between the fields. It follows that to achieve a balanced nutrient supply, fertilizer applications in the study area should be tailored toward specific field requirement. In the same vain, occurrence of some fields in the LYB, optimization of the maize yield in the Northern Nigeran Savanna in addition to the nutrients demanded for attention to other limiting factors such as water stress, pest and diseases, agronomic management practices, etc.

CND ear leaf nutrient sufficiency ranges

The differences between the observed and literature published CND ear leaf sufficiency ranges are due to differences in soil, climate and maize cultivars (Agboola 1985; Njoroge et al. 2017). As also explained by Sahrawat (2006), the discrepancies of nutrient sufficiency ranges among diverse areas can largely be attributed to differences in nutrient concentrations which are influenced by crop growing conditions (such as climate and soil), nutrient supply, their interactions and the variety grown.

3.4.3 Maize nutrient limitations and imbalances

Using the unfertilized control plots in the LYI as the ultimate indicator of a present nutrient imbalance, the most important deficient nutrients across the AEZs are N, P, S, Ca, Cu, Mn and

B. As described above, the deficiency of N and P in maize in the Nigerian savanna have been reported before in several research works such as Nziguheba et al. (2009), Ekeleme et al. (2014) and Kamara (2017). Despite the N and P addition in the respective fertilized plots still some deficiencies of the nutrients have been observed in this study. This signifies either that the fertilizer rates were inadequate or their use efficiency low. Sulphur (S) deficiency in maize across West African savanna soils including the Northern Nigerian savanna have been similarly reported by Friesen (1991), Ojeniyi & Kayode (1993), Schulz et al. (2002) and Nziguheba et al. (2009). Application of S in the NPK+ plots substantially reduced the frequency of deficiency of S in the study area. The deficiency of Ca and Mn in the control (unfertilized) plots of the LYI remains mystifying as there is a large content of the nutrients in the study fields. Therefore, it seems better not to over-emphasize these nutrients, also because the lower boundary of the sufficiency ranges of the nutrients across the two agro-ecological zones was almost double than the values reported by Ojeniyi & Kayode (1993) in a similar environment. A substantial number of the study fields across the two agro-ecologies have soil Cu and B contents below the maize critical level of 1.0 mg kg^{-1} and 0.3 mg kg^{-1}, respectively according to Sillanpää (1982). Hence, the deficiencies of Cu and B are no surprise. The deficiency of Cu has been reported in some parts of the Nigerian savanna soils by Ayodele & Omotoso (2008) and Eteng et al. (2014). Similarly, a widespread deficiency of B has been also observed in some parts of the Northern Nigerian savanna soils (Kihara et al., 2016; Oyinlola and Chude, 2010). Cupper (Cu) and B deficiencies are common in many cereal crops and are expressed either as a severe deficiency affecting the vegetative organs or as mild deficiency (hidden hunger) affecting the crop reproductive potentials (Njoroge et al., 2017). Despite the small maize yield response to K application as discussed earlier above, over 60% of the K omitted (NP) plots displays a significant deficiency of K in the LYI. This is reaffirming that addition of K to maize is still required in the northern Nigerian savanna based on site-specific nutrient management (SSNM) principles to ensure balanced nutrient supply and avoid depletion of K reserves in the long-run as recommended in Chapter 2.

3.4.4 Nutrient interactions

The principal component 1 (PC1) across the agroecological zones explaining the highest variance, synergism between N, S and Cu was common. This was also supported by the positive correlation between ear leaf and contents of these nutrients in the soil. Moreover, N remain the most dominant positive contributor in the PC1 across the AEZs as omission of N (-N) lead to significant negative scores in the PC1. Beneficial interaction between N and S have been widely reported (Fageria, 2001). Assimilation of N and S are closely related with a strong synergistic influence on the each other (Hawkesford et al., 1995; Zhao et al., 1997). This is because the central role of both N and S are in the synthesis of proteins in the plant (Jones Jr, 2012). The positive interaction between Cu and N in the ear leaf can equally be related to the associative roles of the two nutrients in photosynthesis. Nitrogen is a critical component of chlorophyll molecule necessary for photosynthesis. And Cu is a part of chloroplast plastocyanin, which participates in photosynthetic electron transport (Yruela, 2005). The positive interaction between K and P observed in the same PC1 but in the SS corroborates with the result obtained by Fageria & Oliveira (2014). Phosphorus and K are required in large quantities and are both essential for photosynthesis, enzyme/energy driven reactions, seed formation and quality, stress tolerance and crop maturity. The positive relations between Ca and Mg in the maize ear leaf in PC3 across the AEZs could be related to their similar ionic properties (valency at least) and hence moved and absorbed synergistically. In PC4, where positive and negative interaction between Mn and Fe in the NGS and SS, respectively was observed, can be related to a statistically different soil Fe contents of the two AEZs. Significantly higher Fe content in the SS than in the NGS (presented in Table 3.1) might have attributed to the negative interaction between Fe and Mn as opposed to the NGS. Plant nutrients uptake inhibition by Fe depends largely on the concentration level of Fe in the soil, with more elevated concentration inhibiting Mn uptake (Fageria and Rabelo, 1987). This can also be supported by a positive and negative correlation between soil Fe and Mn content, respectively with the same PC4 score in the SS.

3.5 Conclusion

This study established maize ear leaf nutrient sufficiency ranges for the Nigerian Northern Guinea savanna (NGS) based on the compositional nutrient diagnosis (CND) of: N = 2.08-2.87%, P = 0.19-0.29%, K = 1.66-2.38%, Mg = 0.19-0.32%, Ca = 0.45-0.72%, S = 0.14-0.20%, Cu = 5.13-8.6 mg kg^{-1}, Fe = 96.68-171.49 mg kg^{-1}, Mn = 31.35-80.91 mg kg^{-1}, Zn = 10.26-17.37 mg kg^{-1} and B = 3.74-14.74 mg kg^{-1}. Correspondingly, the nutrient sufficiency ranges in the Sudan savanna (SS) of the northern Nigeria were: N = 1.91-2.47%, P = 0.25-0.35%, K = 1.68-2.23%, Mg = 0.15-0.24, Ca = 0.47-0.84%, S = 0.15-0.19%, Cu = 4.36-8.24 mg kg^{-1}, Fe = 113.27-171.53 mg kg^{-1}, Mn = 34.83-75.72 mg kg^{-1}, Zn = 10.16-14.39 mg kg^{-1} and B = 4.06-14.74 mg kg^{-1}. Nutrient imbalances were large constituting about 40% and 42% of the study fields in the NGS and SS, respectively. Although with discrepancies among these nutrient imbalanced fields, the most limiting or deficient nutrients apart from N and P as earlier reported in Chapter 2 were S, Cu, Mn and B across the AEZs. Despite, K was not among the significantly limiting nutrients in the unfertilized control plots of the nutrient imbalanced fields, but application of N and P alone resulted in K-deficiency in about 60-100% of the plots. The study equally confirmed the following nutrient interactions in the maize ear leaf across the two AEZs: beneficial among N, S and Cu; and between Ca and Mg. In addition, P and K concentrations in the maize ear leaf were also positively correlated but only in the SS. However, interaction between Mn and Fe in the maize ear leaf was synergistic in the NGS and antagonistic in the SS.

Therefore, in addition to the commonly applied fertilizer nutrients (N, P and K) in maize cropping system in the Northern Nigerian savanna, it is critical to consider inclusion of S, Cu, Mn and B in the fertilizer formulation, but after further field validation investigation of these nutrients. The deficiency of K in the ear leaves due to application of N and P alone in the nutrient imbalanced fields reconfirmed the earlier recommendation in Chapter 2 that application of K is still required but at a more lesser rate. This might demand for the reduction of K content especially in the compound fertilizer formulation (commonly available in the form of 20:10:10 or 15:15:15 N, P and K ratios, respectively) to prevent unavoidable excess application. The discrepancies of nutrient limitations observed among the nutrients imbalanced fields warrants nutrient recommendations to be tailored towards the field or site-specific situation to ensure adequate and balanced nutrients supply. Consequently, the next Chapter of this thesis parameterized and calibrated the model QUEFTS (Quantitative Evaluation of Fertility of Tropical Soils) for a balanced and site or field specific fertilizer recommendations for maize in the Northern Nigerian savanna.

Chapter 4: Balanced nutrient requirements for maize in the Northern Nigerian savanna: Parameterization and validation of QUEFTS model

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Summary

Establishing balanced nutrient requirements for maize (*Zea mays* L.) in the Northern Nigerian savanna is paramount to develop site-specific fertilizer recommendations to increase maize yield, profits of farmers and avoid negative environmental impacts of fertilizer use. The model QUEFTS (Quantitative Evaluation of Fertility of Tropical Soils) was used to estimate balanced nitrogen (N), phosphorus (P) and potassium (K) requirements for maize production in the Northern Nigerian savanna. Data from on-farm nutrient omission trials conducted in 2015 and 2016 rainy seasons in two agro-ecological zones in the Northern Nigerian savanna (i.e. Northern Guinea savanna "NGS" and Sudan savanna "SS") were used to parameterize and validate the QUEFTS model. The relations between indigenous soil N, P, and K supply and soil properties were not well described with the QUEFTS default equations and consequently new and better fitting equations were derived. The parameters of maximum accumulation (*a*) and dilution (*d*) in kg grain per kg nutrient for the QUEFTS model obtained were respectively 35 and 79 for N, 200 and 527 for P and 25 and 117 for K in the NGS zone; 32 and 79 for N, 164 and 528 for P and 24 and 136 for K in the SS zone; and 35 and 79 for N, 199 and 528 for P and 24 and 124 for K when the data of the two zones were combined. There was a close agreement between observed and parameterized QUEFTS predicted yields in each of the agro-ecological zone using data from independent fields from those used in the parameterization (R^2 = 0.69 for the NGS and 0.75 for the SS). Although with a slight reduction in the prediction power, a good fit between the observed and model predicted grain yield was also detected when the data for the two agro-ecological zones were combined (R^2 = 0.67). Therefore, across the two agro-ecological zones, the model predicted a linear relationship between grain yield and above-ground nutrient uptake until yield reached about 50 to 60% of the yield potential. When the yield target reached 60% of the potential yield (i.e. 6.0 t ha^{-1}), the model showed above-ground balanced nutrient uptake of 20.7, 3.4 and 27.1 kg N, P, and K, respectively, per one ton of maize grain. These results suggest an average NPK ratio in

the plant dry matter of about 6.1:1:7.9. We concluded that the QUEFTS model can be used for balanced nutrient requirement estimations and development of site-specific fertilizer recommendations for maize intensification in the Northern Nigerian savanna.

4.2 Introduction

The average number of individuals facing food insecurity in Nigeria has increased from 40.7 million between 2014 and 2016 to 46.1 million between 2015 and 2017 (FAOSTAT, 2018a). Maize (*Zea mays* L.), the most widely grown arable crop (Adesoji et al., 2016) and valuable cereal in Nigeria (FAO, 2016), can play a vital role in achieving food security in the country providing that the current meagre yield of the crop is increased drastically. Grain yield of maize in Nigeria over the last several decades has been hovering at 2 tons per hectare (t ha^{-1}) (FAOSTAT, 2018b), which is far less than the yield of about 7 t ha^{-1} observed in well-managed field experiments (Fakorede, 2003; Sileshi et al., 2010). One of the plausible reasons for the huge maize yield gap in Nigeria, as in other many countries in sub-Saharan Africa (SSA), is poor soil fertility, the result of inherently low soil nutrient reserves as well as continuous cropping with inadequate nutrient replenishment (Manu et al., 1991; Ekeleme et al., 2014).

The Northern Nigerian savanna (especially the Northern Guinea savanna agroecology) is the most suitable zone for maize production in Nigeria due to high incident solar radiation, adequate rainfall, moderate incidences of biotic stresses and natural dryness at the time of harvest. However, soils in the Northern Nigerian savanna are the major limitation for intensification of maize production. They are predominantly sandy Lixisols, Plinthosols, Acrisols, and Cambisols with low activity clays (like kaolinite), small organic matter contents and small nutrient reserves, and prone to water and wind erosion (FDALR, 1999; FFD, 2012; Jones and Wild, 1975). Use of Fertilizer in maize production is necessary in this environment to replenish nutrients removed through the harvested product and exported crop residues (a common practice by most farmers in the area). Fertilizer use for maize production in the Northern Nigerian savanna as the case in other agroecological zones of Nigeria, has been conventionally promoted through blanket recommendations regardless of wide variability in soil, climate and management regimes. The use of blanket fertilizer recommendations, however, is bound to create imbalanced crop nutrition since maize is cultivated in highly heterogeneous fields (Kihara et al., 2016; Shehu et al., 2018). Such imbalances lead to increased nutrient losses and low fertilizer use efficiency (Cassman et al., 2002), which can impede productivity, profitability and sustainability of a farm (Ezui et al., 2016). To reduce the persistent maize yield gaps in the Northern Nigerian savanna, appropriate fertilizer recommendations need to be developed based on establishing balanced nutrient requirements, for specific yield targets and tailored to account for a specific field and/or soil condition.

A balanced requirement of a given nutrient refers to an amount of the nutrient required to meet a plant's needs while maximizing the use efficiency of the nutrient (Ezui et al., 2016). When more than one nutrient is needed, for example, nitrogen (N), phosphorus (P) and potassium (K), balanced requirements refer to optimization of use efficiency of these three nutrients and simultaneously resulting in the largest response to their supplies (Ezui et al., 2016). The Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) is a practical model that can be used to estimate balanced nutrient requirements for a location and for a target yield level while accounting for the interactions among macronutrients (particularly N, P and K) that affect plant's physiological efficiencies (Janssen et al., 1990). The original QUEFTS model was developed for maize using data from Suriname and Kenya (Janssen et al., 1990) and it was later improved by Smaling and Janssen (1993) and Sattari et al. (2014). The QUEFTS model has been successfully tested for other crops like rice, wheat, cassava and sweet potato in different regions (Witt et al., 1999; Pathak et al., 2003; Ezui et al., 2016; Lam et al., 2016). Four major steps are involved in QUEFTS modelling (Sattari et al., 2014); (i) potential supply of the available nutrients (N, P and K) is calculated depending on the indigenous soil supply of the nutrient, plus average fertilizer recovery fraction multiplied by the amount of nutrient input. The indigenous soil nutrient supply is estimated by applying relations between soil chemical properties of the 0-20 cm soil layer and dry matter uptake of the nutrient in plots where this very nutrient is omitted; (ii) actual uptake of each nutrient is calculated based on the potential supply of that nutrient, considering the potential supply of the other two nutrients; (iii) the establishment of yield ranges as a function of uptake of the nutrients for maximum dilution and accumulation of that nutrient, respectively; and (iv) the yield ranges are combined into pairs, and yield estimated for pairs are averaged to obtain an ultimate yield estimate considering the maximum potential yield of the crop.

The most fickle part of QUEFTS model is the relations between soil chemical characteristics and the supply of available nutrients described in step 1 (i) above, as many local environmental factors may interfere (Sattari et al., 2014). In the original version of QUEFTS model the soil supply of available nutrients is calculated from soil chemical characteristics using regression equations primarily requiring datasets of soil organic carbon, available P, exchangeable K and pH (Janssen et al., 1990). The applicability and effectiveness of these default QUEFTS indigenous soil nutrient supply equations in different environments other than those in which the model was developed is uncertain. Tabi et al. (2008) applied the QUEFTS model in maize to quantify potential supply of soil N and P, utilization efficiency and fertilizer recovery fractions in Northern Nigeria. This study was based on experiments conducted in only 27 farmers' fields in two villages, limiting their representativeness for the entire maize producing area in the northern Nigerian savanna. It follows that it remains necessary to parameterize and validate the QUEFTS model to obtain balanced nutrient requirements for maize production at scale in the Northern Nigerian savanna to enable effective implementation of site-specific nutrient management (SSNM) practices. The objectives of this study were to: (1) assess the relation between indigenous soil nutrient supply and soil chemical characteristics in the Northern Nigerian savanna, (2) parametrize standard coefficients of QUEFTS model to determine balanced nutrient requirements for maize in the Northern Nigerian savanna, and (3) validate the performance of the QUEFTS model in predicting maize grain yield in the Northern Nigerian savanna.

4.3 Materials and Methods

4.3.1 Site selection, description and experimental design

To generate datasets for this study, on-farm nutrient omission experiments were conducted over two rainy seasons (2015 and 2016) across fourteen study sites in three administrative states of the Northern Nigerian savanna as described in detail Chapter 2.

4.3.2 Field and laboratory measurement

Four auger soil samples were collected from 0–20 cm depths from each experimental field during trial establishment and analyzed for various physical and chemical properties as described in Chapter 2.

The crop was harvested at physiological maturity in a net plot of 9 m^2 (i.e. comprising four middle rows of 3 m length of the experimental plot). Plants in the net plot were harvested, and total fresh weights of cobs and stover were recorded. Ten cobs and five stalks of stover were randomly selected as subsamples for nutrient analysis and to account for grain shelling percentage and moisture content after air-drying. The random selection was carried out by first counting the number of cobs or stalks in the net plot and then randomly arranging them in line; the sub samples were then taken at every interval calculated as the total number of cobs or stalks in the net plot over the number of sub samples to be taken. Finally, grain yield was expressed on a dry weight basis at 15.0% moisture content and the stover yield was expressed on an oven dried basis (dried at 60°C). The concentration of total nitrogen in the grain and stover was determined using a micro-Kjeldahl digestion method (Bremner, 1996), while P and K were analyzed by digestion with nitric acid (HNO_3) and concentrations measured with inductively coupled plasma optical emission spectroscopy (ICP-OES, Optima 800, Winlab 5.5, PerkinElmer Inc.,Waltham, MA, USA).

4.3.3 Data screening and analysis

The screening of the data was necessitated because some data points were inconsistent and observed to have either soil or plant nutrient concentrations extremely above and below literature range. To address this, multivariate outliers (n=219) from the experimental data were discarded first at p-value < 0.05 using Mahalanobis distance in JMP version 13.0 statistical software (SAS Institute Inc., 2017). Then to understand the characteristics of the screened experimental data (n=1371), analysis of variance was computed using the same JMP 13.0 statistical software. A linear mixed model was used with Nutrient application (NA), agro-ecological zone (AEZ) and variety group (VG) were used as main factors, while fields within AEZ were used as random factor. Season was excluded in the ANOVA because different fields were used between the two seasons of the field experimentation. Mean values with significant differences were compared using Tukey's HSD (Honestly Significant Difference) test. Finally, the screened experimental data was randomly divided into 80% independent fields for parameterization (n=1090) and the remaining 20% (n=281) for validation of the QUEFTS model.

4.3.4 QUEFTS model parameterization and validation

Model parameterization

Step 1 (assessment of the supply of available nutrients): the supply of available nutrients (S) in the QUEFTS model is given as a function of indigenous soil nutrient supply plus the nutrient input supply. The nutrient input supply is a function of the quantity of nutrient input added multiplied by the average fertilizer recovery efficiency. The indigenous nutrient supply was developed using a multiple regression between soil properties (OC_{tot}, N_{total}, pH, P_{av} and K) and uptake of the nutrient in the omitted plots using best subset–selection procedure. The best regression model was chosen based on the highest coefficient of determination value (R^2) and minimum corrected Akaike Information Criterion (AICc) among five distribution systems (linear, polynomial, logarithmic, exponential and Cauchy). The fertilizer recovery efficiency (R_i) is then calculated as:

$$R_i = (U_i - U_i^0)/F_i \tag{1}$$

Where U_i = i^{th} nutrient in the above ground biomass (kg ha^{-1}) in the NPK plot, U_i^0 = i^{th} nutrient in the above ground biomass (kg ha^{-1}) in the omission plot, F_i = amount of i^{th} nutrient applied (kg ha^{-1}).

Step 2 (relation between the supply of available nutrients and actual uptake): The relations between supply of nutrients and actual uptake were calculated using the following conditions and functions (Janssen *et al.*, 1990; Sattari *et al.*, 2014):

$$\text{If} \quad S_i < r_i + (S_j - r_j)\left({}^{a_j}/_{d_i}\right), \text{ then } U_i(j) = S_i \tag{2a}$$

$$\text{If } S_i > r_i + (S_j - r_j)\left(2\left({}^{d_j}/_{a_i}\right)\right) - \left({}^{a_j}/_{d_i}\right), \text{ then } U_i(j) = r_i + (S_j - r_j)(d_j/a_i) \tag{2b}$$

$$\text{Else } U_i(j) = S_i - \frac{0.25\left[S_i - r_i - (S_j - r_j)\left({}^{a_j}/_{d_i}\right)\right]^2}{(S_j - r_j)\left({}^{d_j}/_{a_i} - {}^{a_j}/_{d_i}\right)} \tag{2c}$$

Where $i, j = N, P, K, \quad i \neq j$; $U_i(j)$ = refers to uptake of i^{th} nutrient in relation to *j*, if *i*= N, j may be P or K; S_i = supply of available i^{th} nutrient obtained from step 1; a_i = physiological efficiency (*PhE*) or internal efficiency (*IE*) at maximum accumulation of nutrient *I* (kg grain kg^{-1} nutrient *i*); d_i = physiological efficiency (*PhE*) or internal efficiency (*IE*) at maximum dilution of nutrient *I* (kg grain kg^{-1} nutrient *i*); r_i = minimum nutrient *I* uptake to produce any grain (kg nutrient *I* ha^{-1}).

The physiological efficiency (*PhE*) was calculated as follows (Sattari *et al.*, 2014):

$$PhE_i = \frac{1000 \times GHI}{GHI \times X_{gi} + (1 - GHI) \times X_{si}} \tag{3}$$

Where G*HI* = grain harvest index, X_{gi} = mass fraction (g kg^{-1}) of the nutrient *I* in the grain, X_{si} = mass fraction (g kg^{-1}) of the nutrient *I* in the stover. The GHI <0.40 values were considered as anomalies in the dataset as the crop might have suffered biotic and abiotic stresses other than nutrients (Hay, 1995); to guarantee accuracy they were excluded from this analysis.

The minimum uptake of the *i*th nutrient to produce any grain (r_i) was obtained from the minimum uptake of the *i*th nutrient in the above ground biomass mass (kg ha^{-1}) in the control plots after discarding all control plots with zero grain yield.

Step 3 (relation between actual uptake and yield ranges): The principles used in QUEFTS at this stage are that the yield ranges are calculated between yield (Y_i^a) at maximum accumulation (*a*) and yield (Y_i^d) at maximum dilution (*d*), as functions of the actual uptake (U_i) and the minimum uptake to produce any grain (r_i):

$$Y_i^a = a_i \times (U_i - r_i), i = N, P, K \tag{4}$$

$$Y_i^d = d_i \times (U_i - r_i), i = N, P, K \tag{5}$$

Step 4 (combining yield ranges to ultimate yield estimates): in this final step yield ranges are combined for pairs of nutrients, and then the yields estimated for pairs of nutrients are averaged to obtain an ultimate yield estimate. The following equation was used to calculate yield (Y_{ij}) for the pair of nutrients *I* and *j* (Sattari *et al.*, 2014):

$$Y_{ij} = Y_j^a + \frac{2\left(\min\left(Y_j^d, Y_k^d, Y_{max}\right) - Y_j^a\right)\left(U_i - r_i - \left(Y_j^a / d_i\right)\right)}{\left(\frac{\min\left(Y_j^d, Y_k^d, Y_{max}\right)}{a_i}\right) - {Y_j^a}/{d_i}} - \frac{\left(\min\left(Y_j^d, Y_k^d, Y_{max}\right) - Y_j^a\right)(U_i - r_i - (Y_j^a / d_i))^2}{\left(\left(\frac{\min\left(Y_j^d, Y_k^d, Y_{max}\right)}{a_i}\right) - {Y_j^a}/{d_i}\right)^2} \tag{6}$$

$i, j, k = N, P, K,\ i \neq j \neq k$; Y_{max} = maximum potential yield (where 10,000 kg ha^{-1} was used in the study area).

The final and ultimate yield estimate (Y_U) is calculated as the mean of the yield estimate of the pairs of nutrients:

$$Y_U = \frac{Y_{NP} + Y_{NK} + Y_{PN} + Y_{PK} + Y_{KN} + Y_{KP}}{6} \tag{7}$$

Model validation and sensitivity analysis

The performance of the QUEFTS model was evaluated using four statistical tests i.e. root mean square error (RMSE), coefficient of determination (R^2), index of agreement (d-index) and percent bias (PBIAS) (Equations 8-11 below). The RMSE is an error index where the lower the value indicates better model performance (Moriasi *et al.*, 2007). The coefficient of determination (R^2) estimates the combined dispersion against the single dispersion of the observed and predicted series (Krause and Boyle, 2005); it ranges between 0 and 1, where a value of 0 means no correlation at all and value of 1 means the dispersion of prediction is equal to that of observation. The index of agreement (d-index) represents the ratio of mean square error and the potential error. The d is interpreted like R^2 and it has the capability to overcome the low sensitivity of R^2 to the differences between the observed and predicted means and variances (Legates and McCabe Jr., 1999). The optimal value of PBIAS is 0.00, with low-magnitude values indicating accurate model simulation. Positive values indicate model underestimation bias, and negative values indicate model overestimation bias (Gupta *et al.*, 1999).

The sensitivity analysis was carried out to test the impact of individual parameters and coefficients on model output for each agro-ecological zone and when the data for the two agro-ecological zones were combined to widen the applicability of the model.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{pre}\right)^2}{n}} \tag{8}$$

$$R^2 = \left(\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - \bar{Y}^{obs}\right)\left(Y_i^{pre} - \bar{Y}^{pre}\right)}{\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - \bar{Y}^{obs}\right)^2}\sqrt{\sum_{i=1}^{n}\left(Y_i^{pre} - \bar{Y}^{pre}\right)^2}}\right)^2 \tag{9}$$

$$d - index = \frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{pre}\right)^2}{\sum_{i=1}^{n}\left(|Y_i^{pre} - \bar{Y}^{obs}| + |Y_i^{obs} - \bar{Y}^{obs}|\right)^2} \tag{10}$$

$$PBIAS = \frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right) \times (100)}{\sum_{i=1}^{n} Y_i^{obs}} \tag{11}$$

Where Y_i^{obs} = *i*th grain yield observed, $\bar{Y}^{obs}$ = mean of the observed grain yield, Y_i^{pre} = *i*th grain yield predicted by the QUEFTS model, $\bar{Y}^{pre}$=mean of the predicted grain yield and *n* = number of observations.

4.4 Results

4.4.1 Soil characteristics of the experimental fields

The soil characteristics of the study fields between the two AEZs have been presented and discussed in Chapter 3.

4.4.2 Characteristics of yield and nutrient uptake of the experimental data

Nutrient application (NA) significantly affected all the measured yield and nutrient uptake

Table 4.1: F values for the response of yield and nutrient uptake parameters to nutrient application (NA), agro-ecological zones (AEZ) and variety group (VG) of the experimental data

Parameter	**Main Effect**			**Interaction Effect**			
	NA	AEZ	VG	NA x AEZ	NA x VG	AEZ x VG	NA x AEZ x VG
Grain yield (t ha^{-1})	100.60**	9.43**	0.01	3.17**	0.82	0.01	0.37
Stover yield (t ha^{-1})	42.75**	34.44**	9.24**	2.38*	0.43	7.90**	0.75
Grain harvest index	39.32**	3.71*	22.34**	3.11**	2.47*	15.06**	1.41
Plant N uptake (kg ha^{-1})	105.86**	18.39**	0.16	1.94	0.34	0.75	0.72
Plant P uptake (kg ha^{-1})	70.96**	0.99	1.55	1.86	0.37	2.19	0.79
Plant K uptake (kg ha^{-1})	24.31**	10.44**	0.42	3.15**	0.74	8.46*	1.60
N harvest index	22.38**	3.90*	12.73**	4.22**	1.97	7.70**	2.02
P harvest index	37.18**	0.88	20.72**	1.91	2.19	9.20**	1.37
K harvest index	16.05**	3.86*	0.78	2.12	2.27*	9.02**	1.50

** ANOVA F-value is significant at 0.01 p-value; * ANOVA F-value is significant at 0.05 p-value.

Characteristics (Table 4.1). Maize grain and stover yields, grain harvest index (GHI), K uptake (Figure 4.1) and nutrient harvest indices (NHI, PHI and KHI) (Figure 4.2) were consistently larger in the NPK+, NPK and -K nutrient application treatments than in the -P, -N and control in the NGS. A similar trend was observed in the SS among those parameters, except that -P treatment was comparable with the values for NPK+, NPK and -K (Figures 4.1 and 4.2). However, the plant uptake of N and P across the AEZs were statistically larger in the same NPK+, NPK and -K nutrient compared to the -P, -N and control treatments (Figure 4.1). With an exception of plant P uptake (kg ha^{-1}) and P harvest index (PHI), all the studied parameters for grain yield and nutrient uptake were significantly different between the agro-ecological zones (AEZ) (Table 4.1). Grain yield and stover yield were on average largest in NGS (3.8 and 4.8 t ha^{-1}) and smallest in SS (3.0 and 3.3 t ha^{-1}) (Figure 4.1). Nitrogen (N) and K uptake were equally larger in the NGS (70.1 and 78.0 kg ha^{-1}) than in the SS (50.4 and 57.1 kg ha^{-1}) (Figure 4.1). In contrast, GHI, nitrogen harvest index (NHI) and potassium harvest index (KHI) were larger in the SS than in the NGS (Figure 4.2). There were few differences between the two variety groups (OPV and hybrid) (Table 4.1), with only GHI, NHI and PHI being larger in the OPV than in the hybrid variety group and an opposite trend observed in the stover yield (Figure 4.3). However, significant interaction among variety group (VG) and AEZ on stover yield, GHI, plant K uptake and nutrients harvest indices (NHI, PHI and KHI) were also observed (Table 4.1). Largest stover yield was recorded in the NGS across the two VG, with a smallest stover yield observed in OPV in the SS (Figure 4.3). In contrast, OPV in the SS has the highest GHI, NHI and KHI. The plant uptake of K was highest in OPV in the NGS with all other interaction values being comparable (Figure 4.3). In addition, plant P uptake were larger in OPV than in hybrid variety across the AEZs. Because of a few statistical differences between VG among the measured yield and nutrient uptake characteristics of the two variety groups compared to the AEZ, the datasets from the VG were combined in the parameterization of the QUEFTS model.

4.4.3 QUEFTS model parameterization

Indigenous soil nutrient supply and fertilizer recovery efficiency

The relations between indigenous soil N, P, and K supply (calculated as the uptake of the given

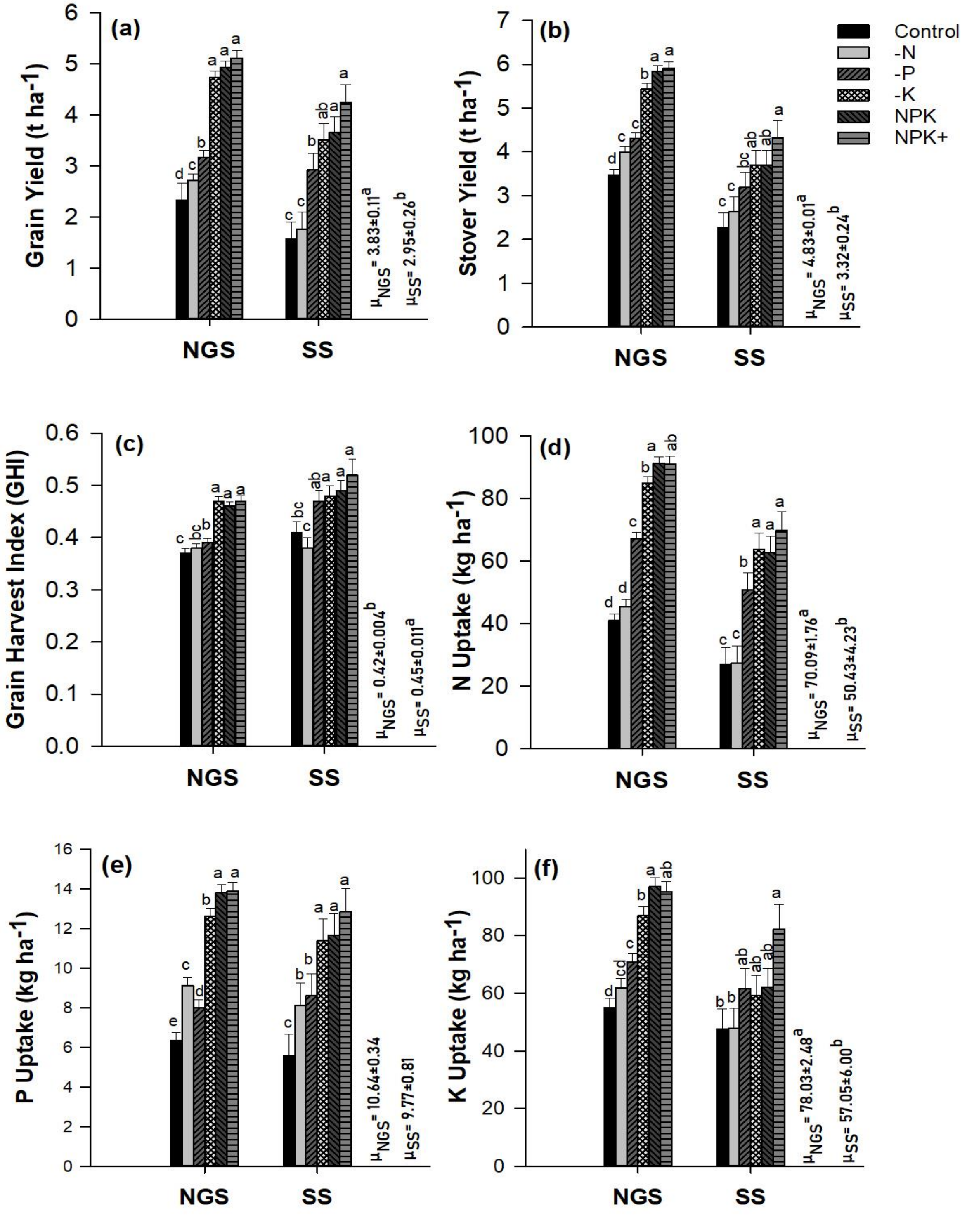

Figure 4.1: Effects of nutrient application (NA) across agro-ecological zones (AEZs) on (a) maize grain yield (b) stover yield (c) grain harvest index (d) plant N uptake I plant P uptake (f) plant K uptake (g). NGS: Northern Guinea savanna; SS: Sudan savanna; μ_{NGS}: mean NGS, μ_{SS} = mean SS. Values followed by different letters within a graph are significantly different at p-value ≤ 0.05.

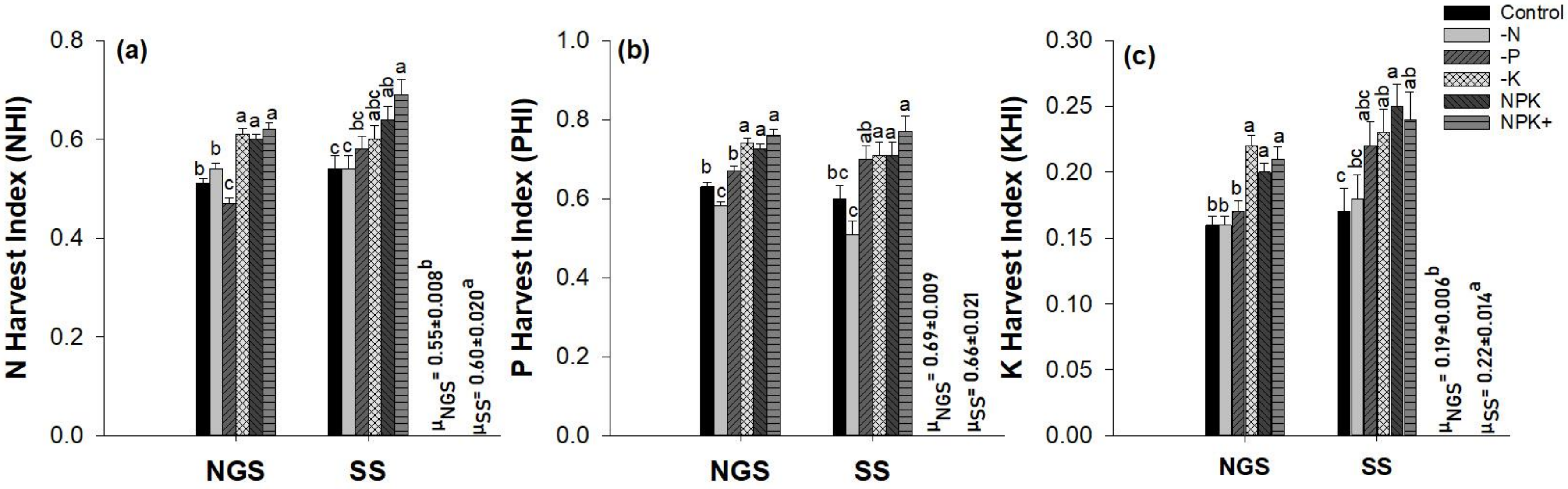

Figure 4.2: Effects of nutrient application (NA) across agro-ecological zones (AEZs) on (a) nitrogen harvest index (b) phosphorus harvest index (c) potassium harvest index. NGS: Northern Guinea savanna; SS: Sudan savanna; μ_{NGS}: mean NGS, μ_{SS} = mean SS. Values followed by different letters within a graph are significantly different at p-value ≤ 0.05.

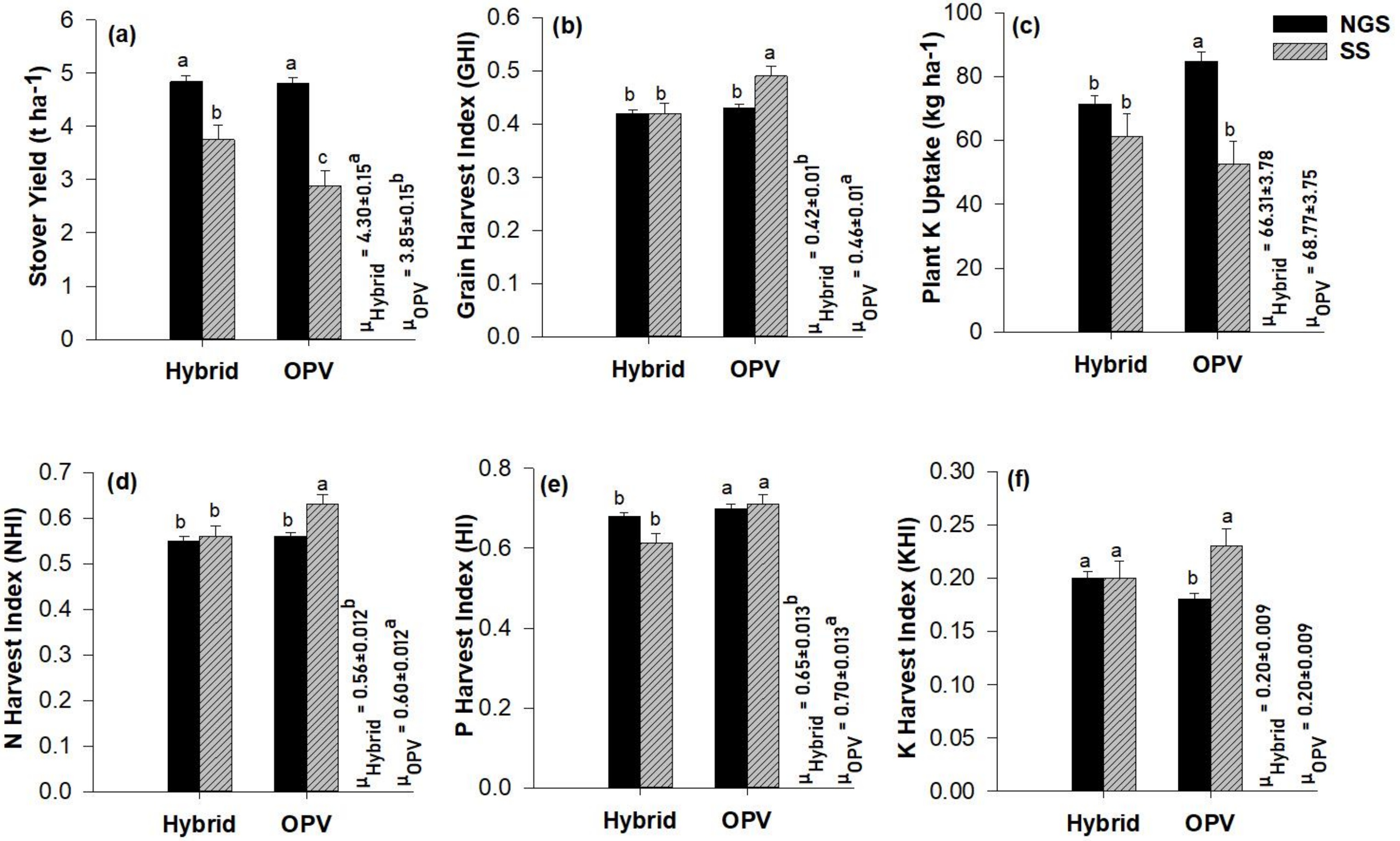

Figure 4.3: Interaction between variety group (VG) and agro-ecological zone (AEZ) on (a) stover yield (b) grain harvest index (c) plant K uptake (d) nitrogen harvest index I phosphorus harvest index (f) potassium harvest index. NGS: Northern Guinea savanna; SS: Sudan savanna; OPV: open pollinated variety; hybrid: hybrid variety; μ_{Hybrid}: mean hybrid, μ_{OPV} = mean OPV**.** Values followed by different letters within a graph are significantly different at p-value ≤ 0.05.

nutrient in the respective omission plots) and soil properties were not effectively described with the QUEFTS' default equations (Table 4.2) in each agro-ecological zone and when the data for the two zones were combined as could be derived from the relatively small R^2 values. Consequently, new and better fitting equations of indigenous soil N, P and K supply were derived for the NGS, SS and the combined zones (Table 4.2). Total organic carbon (OC_{tot}) together with N_{tot} contributed positively as the explaining soil properties for indigenous N soil supply to maize in the NGS. While in the SS and the data of the combined zones only N_{tot} positively explained the indigenous N soil supply. The indigenous soil supply of P in each agro-ecological zone and their combined data were positively explained by pH and P_{av}. The exchangeable potassium (K) was the only soil property positively describing the K indigenous soil supply potential to maize in each agroecological zone and across, except in the SS where pH contributed negatively in addition to exchangeable K. The results revealed that unlike in the default QUEFTS model OC_{tot} did not significantly explained the indigenous potential supply of the three macronutrients except N in the NGS.

Both the newly parameterized and default QUEFTS average fertilizer recovery efficiencies are shown in Table 4.3. The fertilizer recovery fractions of N, P and K were substantially larger in the NGS than in the SS (Table 4.3). In each agro-ecological zone recovery efficiencies of N were smaller than the QUEFTS default value of 0.50. The average P and K recovery efficiencies were larger than the QUEFTS default efficiency values of 0.10 and 0.50, respectively in the NGS and when the data of the two agro-ecological zones were combined. On the contrary, the average P and K recovery efficiencies were smaller than the QUEFTS default values in the SS (Table 4.3).

Physiological nutrient efficiency and minimum nutrient uptake to produce any grain

The relations between grain yield and nutrient uptake showing boundary lines of physiological efficiency (*PhE*) of nutrients at maximum accumulation (*a*) and maximum dilution (*d*) are presented in Figure 4.4. Across the two agro-ecological zones, the coefficients *a* for N, P and K were overall close to the QUEFTS default values (Table 4.3). The sole exception was in the SS where coefficient *a* for P was lower than the QUEFTS standard value. The *d* coefficients for N between the NGS, SS and their combined data were comparable but larger than the QUEFTS default value. In contrast, the *d* coefficients for P between the two agro-ecological zones and

Table 4.2: Parameterized indigenous maize N, P and K supply equations

Nutrient	**Calibrated**	**QUEFTS Default (Janssen et al., 1990)**
	Northern Guinea savanna (NGS)	
N	$S_N = -20.54 + 0.60\ OC_{tot} + 130.92\ N_{tot}$ **(R^2=0.57)**	$S_N = 22.80 + 2.54\ OC_{tot}$ **(R^2=0.11)**
P	$S_P = -12.16 + 2.71\ pH + 0.71\ P_{av}$ **(R^2=0.61)**	$S_P = 5.46 – 0.22\ OC_{tot} + 0.72\ P_{av}$ **(R^2=0.57)**
K	$S_K = 27.10 + 246.22\ K$ **(R^2=0.55)**	$S_K = 37.53 – 1.60\ OC_{tot} + 248.05\ K$ **(R^2=0.46)**
	Sudan savanna (SS)	
N	$S_N = 11.64 + 155.41\ (N_{tot})^3$ **(R^2=0.52)**	$S_N = 24.87 + 0.61\ OC_{tot}$ **(R^2=0.03)**
P	$S_P = -4.11 + 1.40\ pH + 0.0005\ (P_{av})^3$ **(R^2=0.66)**	$S_P = 3.29 – 0.11\ OC_{tot} + 0.31\ P_{av}$ **(R^2=0.56)**
K	$S_K = 228.73 – 35.30\ pH + 275.30\ K$ **(R^2=0.60)**	$S_K = 39.13 – 2.50\ OC_{tot} + 237.21\ K$ **(R^2=0.36)**
	All (combined agroecological zones)	
N	$S_N = 9.56 + 147.28\ (N_{tot})^2$ **(R^2=0.56)**	$S_N = 22.06 + 2.36\ OC_{tot}$ **(R^2=0.10)**
P	$S_P = -8.35 + 2.20\ pH + 0.43\ P_{av}$ **(R^2=0.50)**	$S_P = 4.74 + 0.01\ OC_{tot} + 0.42\ P_{av}$ **(R^2=0.35)**
K	$S_K = 26.35 + 247.97\ K$ **(R^2=0.52)**	$S_K = 36.23 – 1.53\ OC_{tot} + 248.42\ K$ **(R^2=0.43)**

OC_{tot}: soil total organic carbon (g kg^{-1}); N_{tot}: soil total nitrogen (g kg^{-1}); Pav: soil available phosphorus (mg kg^{-1}); K: soil exchangeable potassium ($cmol_c$ kg^{-1}); pH: soil pH in water (1:1); S_N, S_P and S_K are soil indigenous supplies in kg ha^{-1} of maize crop-available N, P, and K, respectively.

Table 4.3: Default and newly parameterized values of average fertilizer recovery efficiency (R_i); physiological efficiency at maximum accumulation of nutrient (a_i) and maximum dilution of nutrient (d_i); and minimum uptake required (r_i) to produce any grain of N, P and K in the above-ground dry matter of maize in the Northern Guinea savanna (NGS), Sudan savanna (SS) and all (combined data of the two agro-ecological zones)

Coefficients	**Nutrients**	**Default QUEFTS Model (Janssen et al.,1990)**	**NGS**	**SS**	**All**
Average fertilizer recovery fraction "R_i"	N	0.50	0.42	0.32	0.40
	P	0.10	0.16	0.08	0.15
	K	0.50	0.54	0.37	0.52
Physiological efficiency at maximum accumulation of the nutrient "a_i" (kg grain kg^{-1} nutrient)	N	30	35	32	35
	P	200	200	164	199
	K	30	25	24	24
Physiological efficiency at maximum dilution of the nutrient "d_i" (kg grain kg^{-1} nutrient)	N	70	79	79	79
	P	600	527	528	528
	K	120	117	136	124
Minimum nutrient uptake to produce any grain "r_i" (kg ha^{-1})	N	5.0	4.0	6.1	4.0
	P	0.4	0.5	0.8	0.5
	K	2.0	4.5	7.3	4.5

their combined data were comparable but lower than the QUEFTS default value. The *d* coefficient for K in the NGS and for the data of the combined zones was close to the QUEFTS default value, but these values were lower than the value observed in the SS. The values for the minimum nutrient uptake coefficient I of N, P and K were 4.0, 0.5 and 4.5 kg ha^{-1} for the NGS and when the data of the two zones were combined; and 6.1, 0.8 and 7.3 kg ha^{-1} for the SS, respectively (Table 4.3). Across the two agro-ecological zones, the *r* coefficient values for all the three nutrients (N, P, and K) were larger than the QUEFTS default values, except *r* coefficient for the N in the NGS, which was slightly smaller than the QUEFTS default coefficient. However, the *r* coefficient values of the three nutrients were smaller in the NGS than in the SS.

4.4.4 Balanced nutrient uptake requirements

The QUEFTS model predicts a linear relationship between grain yield and above-ground nutrient uptake until yield reaches about 50-60% of the yield potential fixed at 10 t ha^{-1} for the NGS and the SS, respectively (Figure 4.4). As the target yield gets closer to the potential

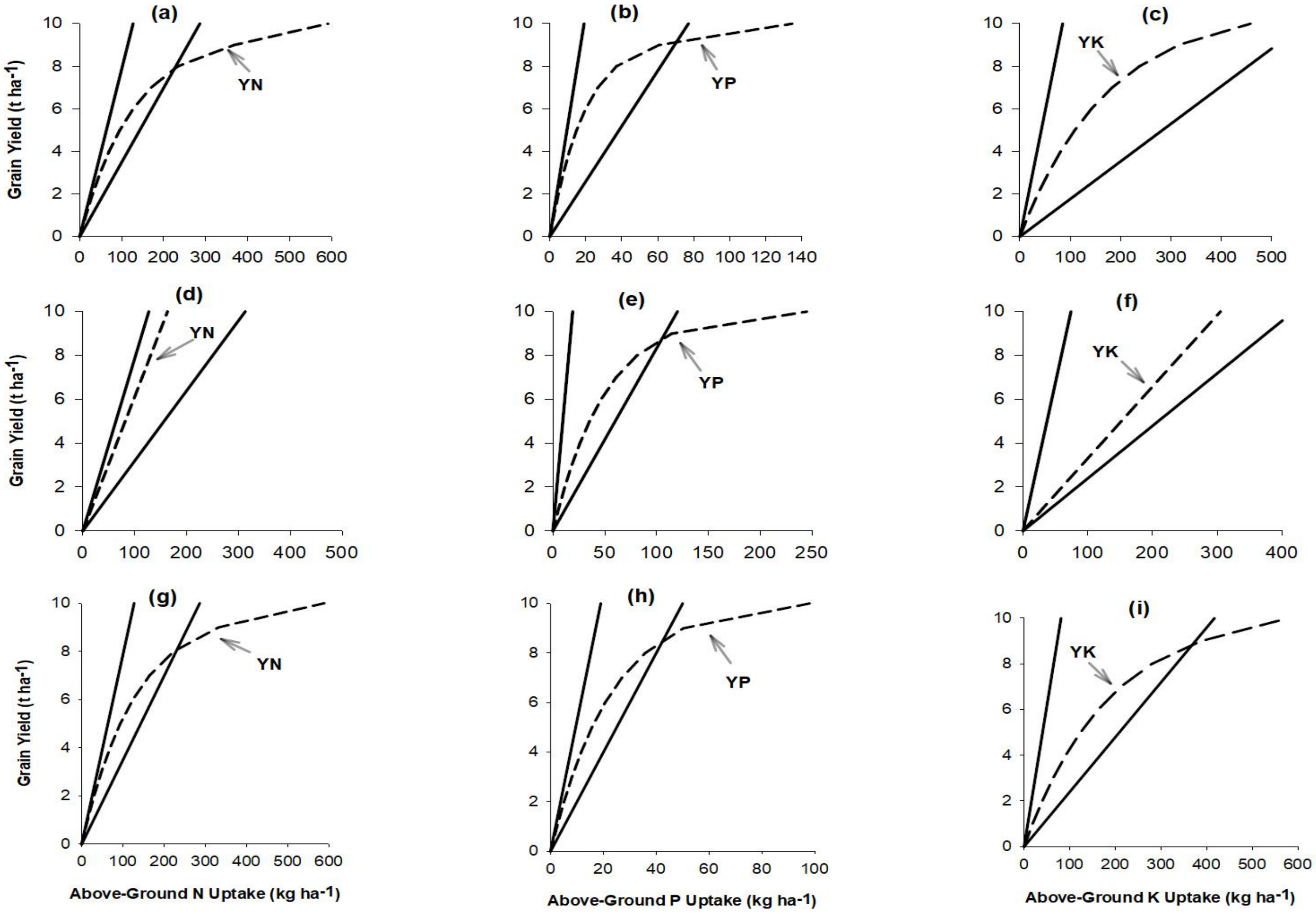

Figure 4.4: The balanced maize N, P and K uptake requirements (YN, YP and YK i.e. the dotted lines) for maximum yield potentials set at 10 t ha^{-1} simulated by the parameterized-QUEFTS model for Northern Guinea savanna (a-c), Sudan savanna (d-f) and all i.e. combined data of the two agro-ecological zones (g-i). The upper and lower lines indicate yields with maximum dilution and maximum nutrient accumulation, respectively.

Yield, *PhE* decreases significantly (**Appendix D**). The parametrized QUEFTS model estimated a balanced uptake of 21.2 kg N, 3.3 kg P and 23.7 kg K in the above-ground parts per ton of maize grain yield when the grain yield reached 60% (6 t ha^{-1}) of the maize potential yield in the NGS (Table 4.4). The corresponding *PhE* was 52.6 kg grain kg^{-1} N, 337.5 kg grain kg^{-1} P and 45.8 kg grain kg^{-1} K. In the SS an uptake of 16.3 kg N, 7.7 kg P and 30.4 kg K was required per ton of grain yield at 60% of the potential yield (Table 4.4); the corresponding *PhE* was 61.5 kg grain kg^{-1} N, 142.4 kg grain kg^{-1} P and 33.0 kg grain kg^{-1} K. Likewise, when the data of the two agro-ecological zones were combined an uptake of 20.7 kg N, 3.4 kg P and 27.1 kg K are required to produce 1 ton of maize grain at 60% of the potential yield; this corresponds to *PhE* of 48.4 kg grain kg^{-1} N, 290.8 kg grain kg^{-1} P and 36.9 kg grain kg^{-1} K. It follows that the optimal N, P & K ratios in the above-ground dry matter at 60% of the maize potential yield are 6.4:1:7.2 for the NGS, 2.1:1:3.9 for the SS and 6.1:1:7.9 when the data of two zones were combined. These results show that the QUEFTS model predicts larger P and K uptake requirements for a balanced nutrition at 60% of the potential yield in the SS than in the NGS, while an opposite trend was observed for N requirements between the two agro-ecological zones.

4.4.5 QUEFTS model validation and sensitivity analysis

Figure 4.5 shows the comparison between observed and parameterized QUEFTS predicted maize grain yields for the NGS, SS and for the combined data of the two agro-ecological zones. There was a satisfactory agreement between grain yields predicted by the parameterized QUEFTS model and those observed from the field experiment in each agro-ecological zone (owing to reasonably high R^2 and d values and relatively small RMSE) (Figure 4.5a and 4.5b). However, the model showed a small overestimation bias in the NGS (PBIAS = -8.5%) and a small underestimation bias in the SS (PBIAS = 12.9%).

The sensitivity analysis shows the performance of the model to be slightly reduced when the data of two agro-eclogical zones were combined (indicated by 2% and 8% reduction in R^2 value over NGS and SS alone, respectively). However, the parameterized model for the data of the combined agro-ecological zones similarly displayed small overestimation bias of 7.6% (Figure 4.5c).

Table 4.4: Maize reciprocal physiological efficiency (*RphE*) of N, P, and K simulated by the QUFETS model to achieve yield targets with maximum yield potential set at 10 t ha^{-1} for the Northern Guinea savanna (NGS), Sudan savanna (SS) and all (combined data of the two agro-ecological zones)

Grain Yield (t ha^{-1})	NGS RphE (kg nutrient t^{-1} grain)			SS RphE (kg nutrient t^{-1} grain)			All RphE (kg nutrient t^{-1} grain)		
	N	P	K	N	P	K	N	P	K
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	14.2	2.2	17.1	16.2	5.4	30.2	14.0	2.4	19.0
2	15.1	2.3	18.0	16.3	5.7	30.2	14.9	2.5	20.1
3	16.1	2.5	19.0	16.3	6.0	30.3	15.9	2.7	21.3
4	17.4	2.7	20.3	16.3	6.5	30.3	17.1	2.9	22.9
5	19.0	3.0	21.8	16.3	7.0	30.3	18.7	3.1	24.7
6	21.2	3.3	23.7	16.3	7.7	30.4	20.7	3.4	27.1
7	24.2	3.8	26.2	16.3	8.7	30.4	23.5	3.9	30.3
8	29.2	4.6	29.6	16.3	10.1	30.4	27.8	4.5	35.0
9	40.8	6.7	35.0	16.3	12.7	30.4	36.9	5.6	43.1
10	59.1	13.5	45.8	16.3	24.5	30.5	58.8	9.8	57.8

4.5 Discussion

4.5.1 Characteristics of grain yield and nutrient uptake of the experimental data

The minimal response of most yield and nutrients uptake characteristics in the control, -N and -P relative to the NPK+, NPK and -K treatments across the NGS indicates N and P as the major nutrients limiting growth and yield response of maize in the region. However, in the SS -P treatment was comparable to the NPK+, NPK and -K treatments especially for the grain and stover yields which can be related to the higher soil available P content in most of the fields in the SS compared the NGS. Nitrogen deficiency has been recognized as the most limiting factor for cereal production in vast areas of SSA including in the Nigerian savanna (Vanlauwe et al., 2011). Soil N can be depleted rapidly by maize, especially when yields are high and stover is exported (Kamara, 2017). The widespread N deficiency in the study area can be attributed to small soil organic matter contents (indicated by small OC_{tot}) resulting from inherent poor soil fertility and continuous cropping with inadequate and imbalanced N fertilizer or manure applications. Adediran and Banjoko (1995) reported P as among the most maize yield limiting nutrients in the Nigerian savanna. Nigerian soils, particularly the highly

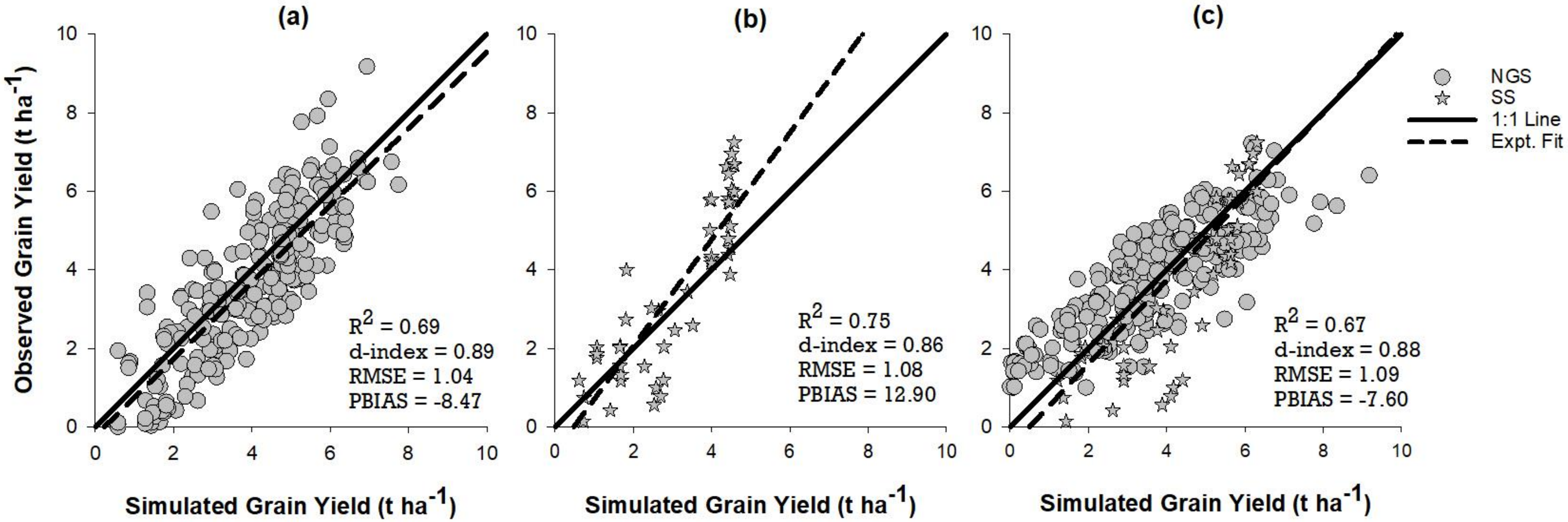

Figure 4.5: Relation between the observed and parameterized QUEFTS simulated maize grain yield for (a) Northern Guinea savanna “NGS”, (b) Sudan savanna “SS” and (c) for the all (combined data of the two agro-ecological zones). R^2: coefficient of determination; d-index = index of agreement; RMSE: root mean square error (t ha^{-1}); PBIAS: percent bias (%).

weathered ones, have small indigenous P contents and often a large P sorption capacity (Osemwotai et al., 2005). Combined application of balanced fertilizers with manure and rotation of cereal crops with legumes through integrated soil fertility management principles (ISFM) (Vanlauwe et al., 2010) can assist farmers in the study area to improve soil N and P status. The lack of a significant increase in grain yield due the addition of secondary macronutrients (S, Ca and Mg) and micronutrients (Zn and B) suggest that these nutrients are not significantly reducing maize yield in the studied area. A significant extra yield increases due to the addition of the secondary macronutrients and micronutrients (SMM) was observed in only 7 fields (Shehu et al., 2018). The lack of large yield response to the addition of the SMM did not support the findings of Wendt and Rijpma (1997) who reported substantial improvement in maize yield in some parts of East Africa due to the addition of the SMM and recommended inclusion of the SMM in NPK fertilizer blends. The larger grain yield and total dry matter in the NGS compared with the SS could be explained by the amount of rainfall, as the larger relative rainfall amount and duration in the NGS favored more maize biomass production than in the SS.

4.4.2 QUEFTS model parameterization

Indigenous soil nutrient supply and fertilizer recovery efficiency

The newly developed supply functions for indigenous soil N, P and K in both agroecological zones explained a minimum of 50% variation in soil characteristics among the studied fields. The unexplained variation can be attributed to the differences in rate of mineralization, in leaching losses and in soil moisture availability, etc. (Barber, 1995). These remain complex factors to integrate into a simple empirical indigenous nutrient supply equation (Tabi et al., 2008). Going beyond the default QUEFTS model, total nitrogen (N_{tot}) represents a more apt explanatory variable for the indigenous soil supply of nitrogen (S_N) rather than the conventional OC_{tot}. Nitrogen mineralization in soil is indeed directly related to microbial activity and organic matter inputs, which are influenced by a combination of several physical, biological and chemical factors in the soil system (He, 2014). Hence, it is no surprise that OC_{tot} does not consistently provide the best proxy for N-availability in the soil. Comparable to this study, Samaké (2003) also reported OC_{tot} did not statistically influence indigenous supply of N, P and K to pearl millet in the similar soil conditions in Mali. The effect of pH on indigenous soil supply of P (S_P) across the agro-ecologies corroborates findings of Janssen et al. (1990). Most of the studied fields have acidic pH values, at this condition a unit decrease in pH level increases the potential of conversion of available phosphorus into a less soluble form through reacting with Al and Fe.

Favorable combinations of adequate rainfall and low night temperatures makes the NGS more suitable for maize production than the SS (Badu-Apraku et al., 2015), this translates into the larger N, P and K fertilizer recovery efficiencies observed in the NGS. Despite in overall N and P recovery efficiency (R_N and R_P) fell below the default QUEFTS values across the two agro-ecologies, but the values in the NGS are close to the result obtained by Saïdou et al. (2003) of 0.40 and 0.14 for N and P, respectively in the Southern Benin. In the same way, the recovery efficiency of K (R_K) in the SS is in agreement with 0.40 reported in the Southern Benin by the same Saïdou et al. (2003). However, the R_P of both NGS and SS is smaller than the value of 0.24 observed by Tabi et al. (2008) in some part of the Northern Nigeria. This suggest that effective results which optimize fertilizer recovery efficiency figures can be obtained exclusively if site-specific nutrient recommendations using balanced nutrient requirements are complemented with the right source, time and placement of fertilizer application, and subject to appropriate agronomic practices.

Boundary line coefficients for physiological efficiency of nutrients and minimum nutrient uptake to produce any grain

The boundary line coefficients *a* and *d* for physiological nutrient efficiency of this study across the two agro-ecological zones are larger than in the analysis of Saïdou et al. (2003) in the Southern Benin (20 and 40 kg grain kg^{-1} N, 110 and 270 kg grain kg^{-1} P, 25 and 90 kg grain kg^{-1} K) except *a* coefficients for K that are comparable. Equally, Tabi et al. (2008) observed smaller *a* and *d* boundary line physiological efficiency for N and P in some part of Northern Nigeria (21 and 71 kg grain kg^{-1} N, 97 and 600 kg grain kg^{-1} P) except *d* coefficient for P that is larger compared with the values of this study. Saïdou et al. (2003) and Tabi et al. (2008) have attributed the smaller physiological efficiencies in their studies to smaller grain harvest indices. Therefore, the larger values of physiological efficiencies in this study proved to be the result of large grain harvest indices. As explained earlier under sub-section 2.4.1, grain harvest indices less than 0.40 were considered as anomalies in the dataset as the crop might have suffered biotic and abiotic stresses other than nutrients (Hay, 1995); to guarantee precision were excluded as similarly performed by Liu et al. (2006), Xu et al. (2013), among others. The significant difference between the minimum uptake requirement to produce any grain *(r)* observed in this study and the QUEFTS default values emphasizes the importance for recalibration of this parameter which has not been considered in most previous QUEFTS parameterization and calibration studies.

4.4.3 Balanced nutrient uptake requirements

Balanced nutrient plant uptake requirement can provide guidance for amount of fertilizer to be applied to achieve a desirable yield and for an efficient maintenance of soil fertility, as at least the nutrients removed or harvested in the above ground plant dry matter must be returned to the soil. The balanced nutrient uptake requirements predicted by QUEFTS in this study with exception of K in the SS are comparable to values of 20.0 kg N, 4.5 kg P, 18.0 kg K reported for a ton of maize grain in similar environmental and soil conditions in Zimbabwe (Piha, 1993). However, the higher balanced K uptake ratio in the above-ground matter relative to N as predicted by the parameterized QUEFTS in this study across the two agro-ecologies does not support the findings of most previous studies which have reported higher N uptake ratio compared to K. This trend was not surprising as most of the study fields have moderate to high K content in addition to the amount K fertilizer applied of 40-50 kg K ha^{-1}. This led to luxury uptake of K especially in the maize stover evidenced by a small K harvest index (KHI). The moderate to high K content of the soils could be linked to an appreciable amount of K-bearing feldspar minerals in the sand and silt particles in the study area (Møberg and Esu, 1991) and the residual effect of previous K fertilizer applications. The supply of available K in soil is strongly dependent upon the type and amount of K-bearing minerals. In the K-feldspars, K is structurally bound in the crystal lattice (structural K) and is only released into the soil solution through weathering (Øgaard and Krogstad, 2005). The larger P uptake requirements in SS relative to the NGS can be attributed to higher soil P content in the SS as confirmed by the low maize yield response to P application observed in the nutrient omission trials.

4.4.4 QUEFTS model validation and sensitivity analysis

The close agreement between the parametrized QUEFTS simulated and observed yields shows that the parameterized QUEFTS model can be used to calculate balanced nutrient requirements and site- or field-specific fertilizer recommendations to optimize maize yield in the Northern Nigerian savanna. The QUEFTS model, however, assumes that other biophysical factors apart from nutrients such as moisture, temperature, pests, diseases and management are non-limiting. As these factors are complex to optimize in on-farm field experiments, this may account for the under- and over-estimation bias obtained with the parameterized QUEFTS model in the SS and the NGS, respectively. To guarantee precision, the under- and over- estimation percent bias in the SS and NGS, respectively should be considered and adjusted at the final and ultimate yield estimate (Y_U) stage in the parameterized QUEFTS model. The good performance of the model when data for the two agro-ecological zones were combined suggests that the parametrized nutrient supply functions and other calibrated parameters can be widely adopted for a larger scale application in similar environmental and soil conditions.

4.5 Conclusion

The present study resulted in the parameterization and validation of the QUEFTS model to arrive at balanced nutrient requirements and site-specific fertilizer recommendations for maize in the Northern Nigerian savanna. This was based on data from on-farm nutrient omission trials conducted across potential maize production sites covering two agro-ecological zones i.e. the Northern Guinea savanna (NGS) and the Sudan savanna (SS). There were considerable differences in soil and nutrient uptake characteristics between the NGS and the SS. The relations between indigenous soil N, P, and K supply and soil properties were not adequately described with the QUEFTS default equations across the agro-ecological zones, consequently new and better fitting equations were derived. The coefficients *a* and *d* of N, P, and K for the QUEFTS model were 35 and 79, 200 and 527, and 25 and 117 kg grain kg^{-1} nutrient for the NGS; 32 and 79, 164 and 528, and 24 and 136 kg grain kg^{-1} nutrient for the SS zone; and 35 and 79, 199 and 528, and 24 and 124 kg grain kg^{-1} nutrient when the data of the two agro-ecological zones were combined. The minimum nutrient uptake coefficients (*r*) of N, P and K were 4.0, 0.5 and 4.5 kg ha^{-1} for the NGS zone and the combined data of the two agro-ecological zones; and 6.1, 0.8 and 7.3 kg ha^{-1} for the SS zone. The parameterized QUEFTS model predicted a linear increase in above-ground dry matter uptake of N, P and K until the grain yield reached about 50-60% of the potential yield. At 60% of the potential yield (6 t ha^{-1}) a balanced uptake in the above-ground part of 21.2 kg N, 3.3 kg P and 23.7 kg K is required to produce a ton of maize grain in the NGS; 16.3 kg N, 7.7 kg P and 30.4 kg K to produce a ton of maize grain in the SS zone; and 20.7 kg N, 3.4 kg P and 27.1 kg K to produce a ton of maize grain when the data of the two agro-ecological zones were combined. Validation results indicated a good correlation between the parameterized QUEFTS estimated and observed grain yields in both agro-ecological zones. The sensitivity analysis revealed that the calibration parameters obtained across the two agro-ecological zones did not substantially reduce the precision of the model when compared with those obtained from the data of the individual agro-ecological zone. This imply that the parametrized QUEFTS model can be a springboard for development of simple and cost-effective decision support tools for nutrient management and fertilizer recommendations in the Northern Nigerian savanna and in similar environments of West and Central Africa. To ensure a greater impact, site-specific fertilizer recommendations developed from the model must be complemented with appropriate agronomic management practices including use of right source, precise time and right placement of the fertilizer.

Chapter 5: Influence of nutrient limitations and rainfall on ^{13}C isotope discrimination of maize in the Northern Nigerian savanna

Summary

Rapid methods, less expensive than conventional nutrient omission and water mass balance experiments, to accurately measure nutrient and water limitations in crops, are paramount to save cost, time and energy. In this study we investigated the influence of nutrient limitations and rainfall abundance on ^{13}C isotope discrimination (Δ) in maize in search for a quick and less expensive alternative tool to diagnose nutrient and water limitations. ^{13}C isotope discrimination (Δ) from the maize ear leaf and yield/rainfall data of the diagnostic on-farm nutrient omission experiments (NOTs) conducted in the Northern Nigerian savanna were used to achieve the aim of the study. The NOTs involved six nutrient application treatments, two agro-ecological zones and two variety groups as described in the preceding Chapters 2-4. A significant effect (p-value < 0.01) of nutrient application on Δ was observed, with N and P limitations (-N and -P) decreasing the Δ. A weak but significant negative correlation was observed between rainfall abundance and Δ at the critical first 25 days of the growing period. In addition, Δ was observed to be significantly (p-value < 0.01) different between the two variety groups, with larger values measured in the OPV than in the hybrid cultivar group. Given these results, we can envisage that Δ-values in maize ear leaves can be used as a proxy for N, P and water limitations in the Northern Nigerian savanna. To quantify the changes in Δ due to N, P and water limitations separately, further studies are needed. These will enable practical application of the Δ values as a proxy for nutrient and water limitations in maize in the Northern Nigerian savanna. Such studies should involve a varying level of N, P and water limitations and involving all commonly grown maize cultivars.

5.1 Introduction

Maize (*Zea mays* L.) is an important arable crop with a C_4 photosynthetic pathway and widely grown in the savanna of Northern Nigeria. Maize production in the savanna of Northern Nigeria is largely done under rainfed conditions by small scale farmers where yields are small and often determined by the limiting factors of the biophysical environment (Kamara et al., 2014). Poor soil fertility and increasing occurrence of drought have been numerously reported to constitute the major biophysical risks for sustainable maize intensification in the region (Sanginga et al., 2003; Kamara et al., 2005; Kamara et al., 2014; Shehu et al., 2018). Therefore, potentials for increasing maize production to meet needs of the fast-growing population of the savanna of Northern Nigeria are constrained by limited soil fertility, climatic unpredictability including inadequate and erratic rainfall, inter- and intra-seasonal droughts and harsh temperatures among others. To develop an effective and sustainable soil fertility management and climate adaptation strategies that would enhance maize productivity in the Northern Nigerian savanna, understanding of how, where, why and when these constraints occur at scale is imperative.

Nutrient omission and water mass balance experiments are conventionally used to quantify nutrient and water limitations and their use efficiencies, respectively. However, nutrient omission and water mass balance experiments are expensive, difficult and time consuming especially when conducted at a large scale. Observations on ^{13}C isotope discrimination (Δ) can be used as a proxy to quantify the net effect of water and nutrient limitations on plant growth at a relatively low cost, short time and low energy (Clay et al., 2001; Clay et al., 2005; Dercon et al., 2006; Yang et al., 2017). The relationships between Δ and water/nitrogen stress have been documented amply for C_3 photosynthetic pathway crops like wheat (Clay et al., 2001; Bachiri et al., 2018), cotton (Saranga et al., 1998), rice (Zhao et al., 2004), peanut (Wright et al., 1988), alfalfa (Moghaddam et al., 2013), among others. A considerably smaller number of studies have done the same for the relations between Δ and water/nitrogen stress for C4 plants, especially maize (Clay et al., 2005; Dercon et al., 2006; Lasa et al., 2011). Based on our information, few if any reports exist on the effect of other nutrient stresses apart from nitrogen (N) on Δ.

In the course of plant photosynthetic CO_2 fixation, plants discriminate (preferential consumption of one isotopologue over another) against the lighter/less abundant, a naturally occurring stable isotope i.e. ^{13}C (which is about 1.1149% in CO_2 in atmospheric air)(Caemmerer et al., 2014). Therefore, ^{13}C isotope discrimination (Δ) is defined as the change that might occur in the $^{13}C/^{12}C$ isotopic composition in the plant relative to the atmosphere (Clay et al., 2005). Such relative changes in the plant's $^{13}C/^{12}C$ isotopic composition occur as a result from a multiplicity of biophysical processes and is an indirect indicator of a plant's physiological response to those biophysical processes.

In C_3 photosynthetic plant species (like rice, wheat, cotton, etc.), Δ during photosynthetic CO_2 fixation is linearly related to the ratio of intercellular and atmospheric concentration of CO_2 and is expressed according to Farquhar et al. (1989) as:

$$\Delta_{C_3} = a + [b - a]\left(\frac{C_i}{C_a}\right) \tag{1}$$

where a (4.4‰) is the discrimination during diffusion of CO_2 in air; b (30‰) is the discrimination associated with carboxylation by ribulose 1,5-bisphosphate carboxylase (Rubisco); and C_i/C_a represent the ratio of intercellular and atmospheric concentrations of CO_2. For example, when plant available soil moisture decreases, plants closes their stomata to reduce water loss and eventually C_i/C_a decreases (Turner et al., 1985). Also, increase in N bioavailability has been reported to enhance the allotment of this nutrient to the photosynthetic enzymes and further decreases the C_i/C_a by stimulating the photosynthetic capacity of the plant (Farquhar et al., 1989; Turner et al., 1985). Therefore, based on equation 1, the most important explaining factor for Δ in C_3 plants is C_i/C_a, where a reduction in C_i/C_a will cause decrease in Δ and vice versa.

In C_4 plant species (like maize, sugarcane, sorghum, etc.), however, the effects on the Δ-values in the leaves are more complex, involving the diffusion of CO_2 through stomata, the dissolution and conversion of CO_2 to HCO_3^-, and the fixation of CO_2 catalyzed by phosphoenolpyruvate carboxylase (PEPC) in mesophyll cells and by Rubisco in the bundle sheath cells (Farquhar et al., 1989; Monneveux et al., 2007) and is expressed as:

$$\Delta_{C_4} = a + [b_2 + \emptyset(b_1 - s)]\left(\frac{C_i}{C_a}\right) \tag{2}$$

where a (4.4‰) is the discrimination during diffusion of CO_2 in air; b_2 (-5.7‰ at 30°C) is the discrimination due to dissolution of CO_2 to HCO_3^- and fixation by phosphoenolpyruvate carboxylase (PEPC); b_1 (30‰) is the discrimination associated with carboxylation by ribulose 1,5-bisphosphate carboxylase (Rubisco); $\emptyset$ is the fraction of CO_2 fixed by PEPC, which is transported to the bundle sheath and subsequently leaks out and s (1.8‰) being the fractionation during this process; and C_i/C_a is the ratio of intercellular and atmospheric concentrations of CO_2. Therefore, relations between Δ and C_i/C_a can be positive or negative in C_4 plants depending on whether $\emptyset$ is larger or smaller than $\frac{(a-b_2)}{(b_1-s)}$ which leads to less unequivocal relationships between Δ and biophysical stresses such as lack of water, light and nutrients (Monneveux et al., 2007). Moreover, variation in ^{13}C isotopic composition is less vulnerable to biophysical stresses among C_4 plant species compared to C_3 plants because the potentially massive effect of discrimination by Rubisco is suppressed in the semi-closed bundle sheath (Bowman et al., 1989 in Dercon et al., 2006). This justifies more intensive investigations to evaluate and quantify relationships between Δ and biophysical stresses in C_4 plants, as a prerequisite to use Δ as a proxy to quantify the effects of biophysical limitations such as limiting water and/or nutrients.

Since information at scale on the influence of the nutrient and water limitations on ^{13}C isotope discrimination (Δ) in maize is rare in Nigeria, we conducted this study to investigate the influence of nutrient limitations and rainfall distribution on Δ in the Northern Nigerian savanna. Results of such would enable the use of the Δ value as a proxy to quantify water and nutrients stresses and their dynamics.

5.2 Materials and Methods

5.2.1 Field experimentation

Data for this study were obtained from on-farm nutrient omission experiments conducted across 14 districts in the savanna of Northern Nigeria over two rainy seasons (2015 and 2016). For this study three fields were selected at random from each district, given a total of 30 and 42 study fields from 2015 and 2016 experimental season, respectively (Figure 5.1). The study districts are situated within two agro-ecological zones (AEZs) i.e. the Northern Guinea savanna (NGS) and the Sudan savanna (SS). The NGS is the wetter zone with an average cumulative annual rainfall of 1129 mm, while the SS is the relatively drier one with an average cumulative annual rainfall of 744 mm. The details of the experimental procedure have been described in Chapter 2 and are summarized as follows. In each field, two sets of experiments were conducted side by side, one with a hybrid variety and the other with an open-pollinated variety (OPV). Six nutrient application and omission treatments (NA) were used in each

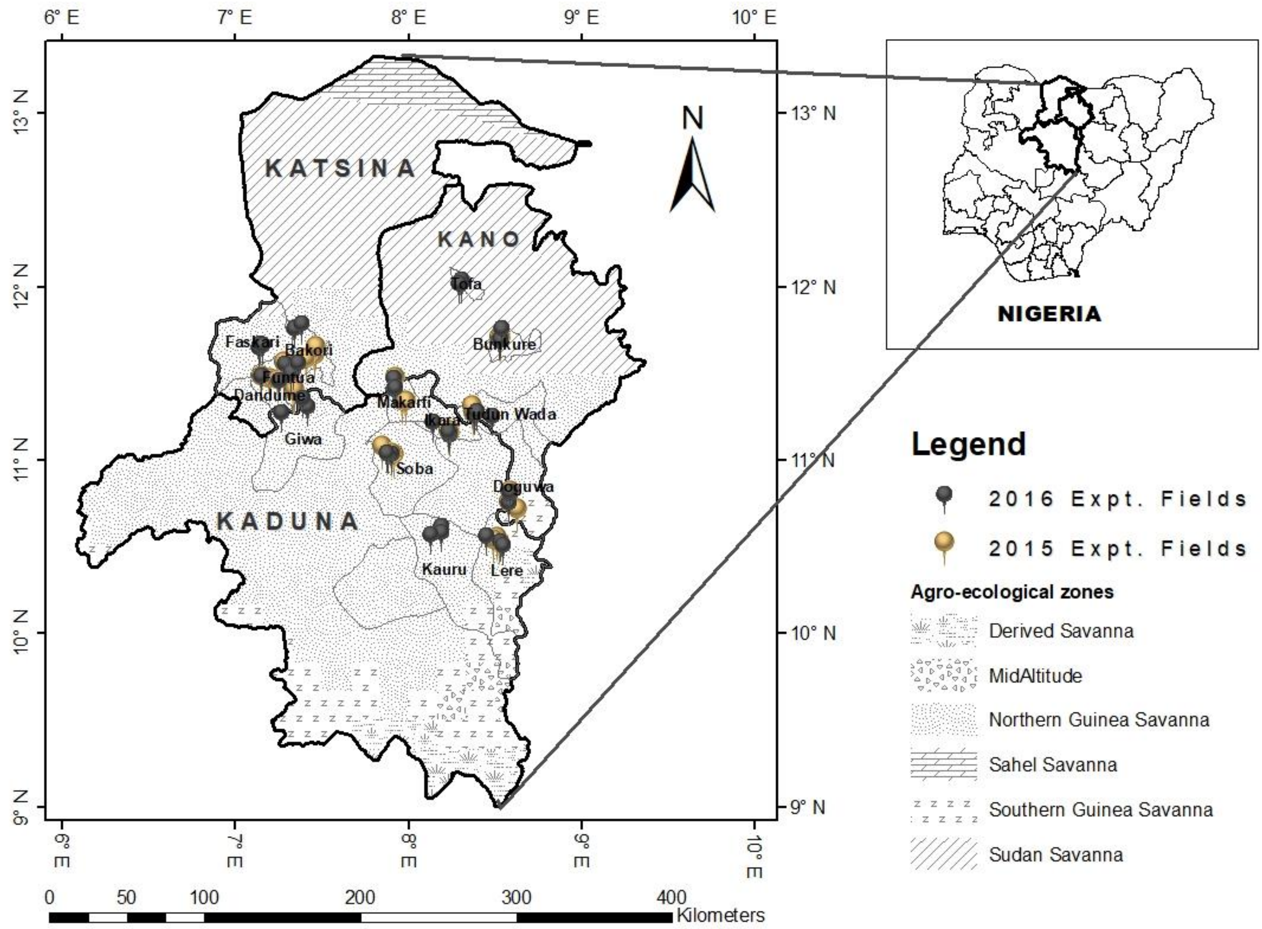

Figure 5.1: A map of Nigeria showing agroecological zones (AEZs), study sites and selected experimental fields from the on-farm diagnostic nutrient omission trials (NOTs) established in 2015 and 2016 cropping seasons.

experimental set i.e. (i) control without applied nutrients (control), (ii) N omitted with P and K applied (-N), (iii) P omitted with N and K applied (-P), (iv) K omitted with N and P applied (-K), (v) treatment with all the three nutrients applied (NPK), and (vi) a treatment where secondary macronutrients (S, Ca and Mg) and micronutrients (Zn and B) were applied in addition to the NPK (NPK+). Primary macronutrients were applied at 140 kg N ha^{-1}, 50 kg P ha^{-1} and 50 kg K ha^{-1} for the NGS sites; and at 120 kg N ha^{-1}, 40 kg P ha^{-1} and 40 kg K ha^{-1} for the SS sites. The secondary macro- and micro-nutrients were applied at 24 kg S ha^{-1}, 10 kg Ca ha^{-1}, 10 kg Mg ha^{-1},5 kg Zn ha^{-1} and 5 kg B ha^{-1} at all sites. Grain yield data were collected from each experimental plot and expressed on a dry weight basis at 15.0% moisture content.

5.2.2 Ear Leaf sampling and laboratory analysis

As the ear leaf is an organ of more intense metabolic activity in maize (Jones Jr, 1998), ten ear leaves were randomly sampled at the critical initial silking stage (reproductive stage “R1”) from each of the experimental plot as described in Chapter 3. An ear leaf was removed by plucking downwards (at roughly an adjacent angle of <30°) with moderate force as this allows the leaf to separate at the collar, leaving behind the leaf base that circles the stem. Next the ear leaf samples were gently washed with distilled water to remove dust and contaminants and oven-dried at 60°C for 48 hours. Thereafter, the dried ear leaf samples were ground using agate pestle and mortar first, and then homogenized to powder by grinding in a ball mill. Carbon isotope compositions (δ^{13}) of the ear leaf samples were measured with elemental analyzer (EA 1110, Thermo Scientific, Massachusetts, USA) coupled to a Delta Advantage Isotope Ratio Mass Spectrometer “IRMS” via a Conflo IV interface (Thermo Scientific, Massachusetts, USA). Concentrations and stable isotope values were calibrated using IAEA-600 (caffeine) and two in-house standards (Leucine and Pacific tuna muscle tissue) that were previously calibrated versus certified standards. Reproducibility of $\delta^{13}C$ measurements was typically better than 0.1 per mil ‘‰’. In many cases it is more appropriate to report $\delta^{13}C$ using ^{13}C discrimination (Δ) calculated using the following equation:

$$\Delta = (\delta^{13}C_a - \delta^{13}C_s)/(1 + \delta^{13}C_s/1000) \qquad (3)$$

Where $\delta^{13}C_a$ is the $\delta^{13}C$ value of air (-8‰) and $\delta^{13}C_s$ is the measured value of $\delta^{13}C$ of maize ear leaf sample.

5.2.3 Data analysis

Analysis of variance (ANOVA) was used to evaluate the differences between treatment factors using JMP statistical software (SAS Institute Inc., 2018). A linear mixed model was used with fields as a random factor; and nutrient application (NA), agro-ecological zone (AEZ) and variety group (VG) as fixed factors. Mean values with significant differences were compared using Tukey's HSD (Honestly Significant Difference) test. Logistic regression modelling was used to diagnose changes in Δ relative to nutrient omission (stress). The logistic regression model predicts the odds for a subject being in one category rather than in another; in this study nutrient omission (stress) or not. Maize ear leaf ^{13}C isotope discrimination (Δ) was used as independent variable and presence of nutrient omission(stress) or not as categorical dependent variable. Spearman correlation was used to assess the relationship between maize ear leaf ^{13}C isotope discrimination (Δ) and grain yield, stover yield and cumulative rainfall (R).

5.3 Results

5.3.1 Rainfall and grain yield

Cumulative rainfall across the growing periods over the two seasons was substantially higher in the NGS than in the SS (Figure 5.2). Although variation among the study districts within each AEZ was not statistically significant, larger variation was observed within the SS compared to the NGS as inferred from the larger standard error of means. Grain and stover yields were statistically different among NA treatments and between AEZs and VG (Table 5.1). Among the NA treatments, the control, the N omitted (-N) and the P omitted (-P) treatments resulted in statistically smaller yields (Figure 5.3). The larger yields were observed in the K omitted (-K), NPK treatments and in a treatment where secondary macro- and micro-nutrients were applied in addition to the NPK (NPK+). Overall, grain and stover yields were higher in NGS than in SS (Figure 5.3) and higher in hybrid variety than in an OPV group (Figure 5.4). However, a significant interaction effect was observed between AEZ and VG (Table 5.1) on the yield parameters, with statistically smaller yields observed in OPV in the SS (Figure 5.4).

5.3.2 ^{13}C isotope discrimination (Δ)

Agro-ecological zone (AEZ), VG and NA significantly influenced Δ (Table 5.1). However, no significant interaction effects were identified among the three factors. Between the AEZs, a significantly larger Δ i.e. more discrimination was recorded in the drier SS zone compared to the more humid NGS zone (Figure 5.5). Likewise, a larger Δ was observed in the OPV compared to the hybrid variety (Figure 5.5). Following the patterns of grain and stover yields, larger Δ values were observed in the -K, NPK and NPK+ NA treatments (Figure 5.5), while significantly smaller and comparable Δ values were observed in control, -N and -P NA treatments.

Logistic regression modelling was used to predict the odds of Δ to be in the NPK treatment relative to -N or -P treatments (taken as reference groups). The -N and -P were selected because they were the only nutrient omission treatments with a significant deviation from the NPK treatment as described above. The overall model fit for both -N and -P was highly significant (p-value <0.01) (Table 5.2). Similarly, the Wald test explaining only the contribution

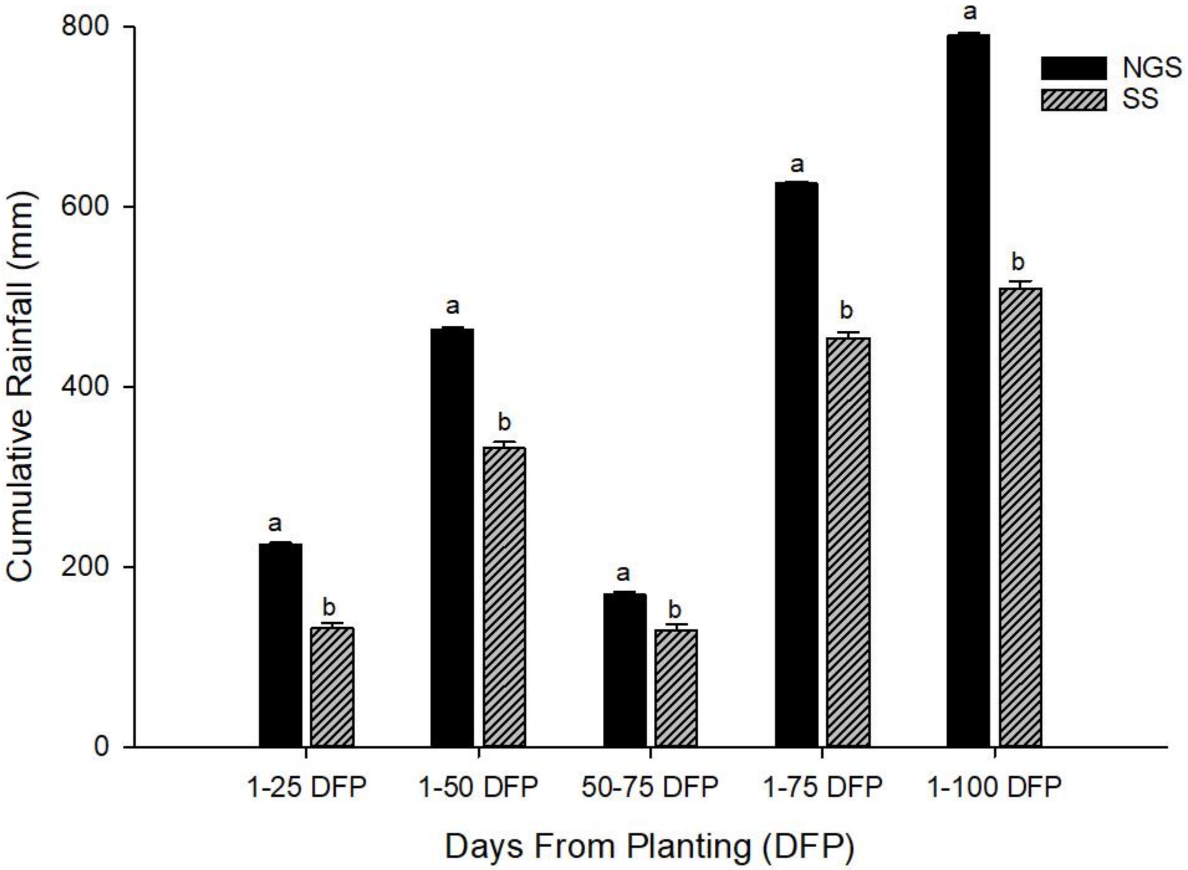

Figure 5.2: Average cumulative rainfall between two study agro-ecological zones (AEZs) across maize growing days. DFP: days from planting; NGS: Northern Guinea savanna; SS: Sudan savanna; Error bars are standard error of means. Values followed by different letters are significantly different at p-value ≤ 0.05.

Table 5.1: F values for the response of maize grain yield, stover yield and maize ear leaf ^{13}C isotope discrimination (Δ) to nutrient application (NA), agro-ecological zone (AEZ) and variety group (VG) of the experimental data

Effect	**Factor**	**Grain Yield (t ha^{-1})**	**Stover Yield (t ha^{-1})**	**Δ (‰)**
Main Effect	NA	58.42**	32.39**	8.17**
	AEZ	3.36*	11.45**	3.04*
	VG	7.96**	6.09*	8.39**
Interaction Effect	NA x AEZ	2.49*	1.52	3.06
	NA x VG	0.57	1.19	0.50
	AEZ x VG	4.65*	8.55**	3.16
	NA x AEZ x VG	0.45	0.69	0.27

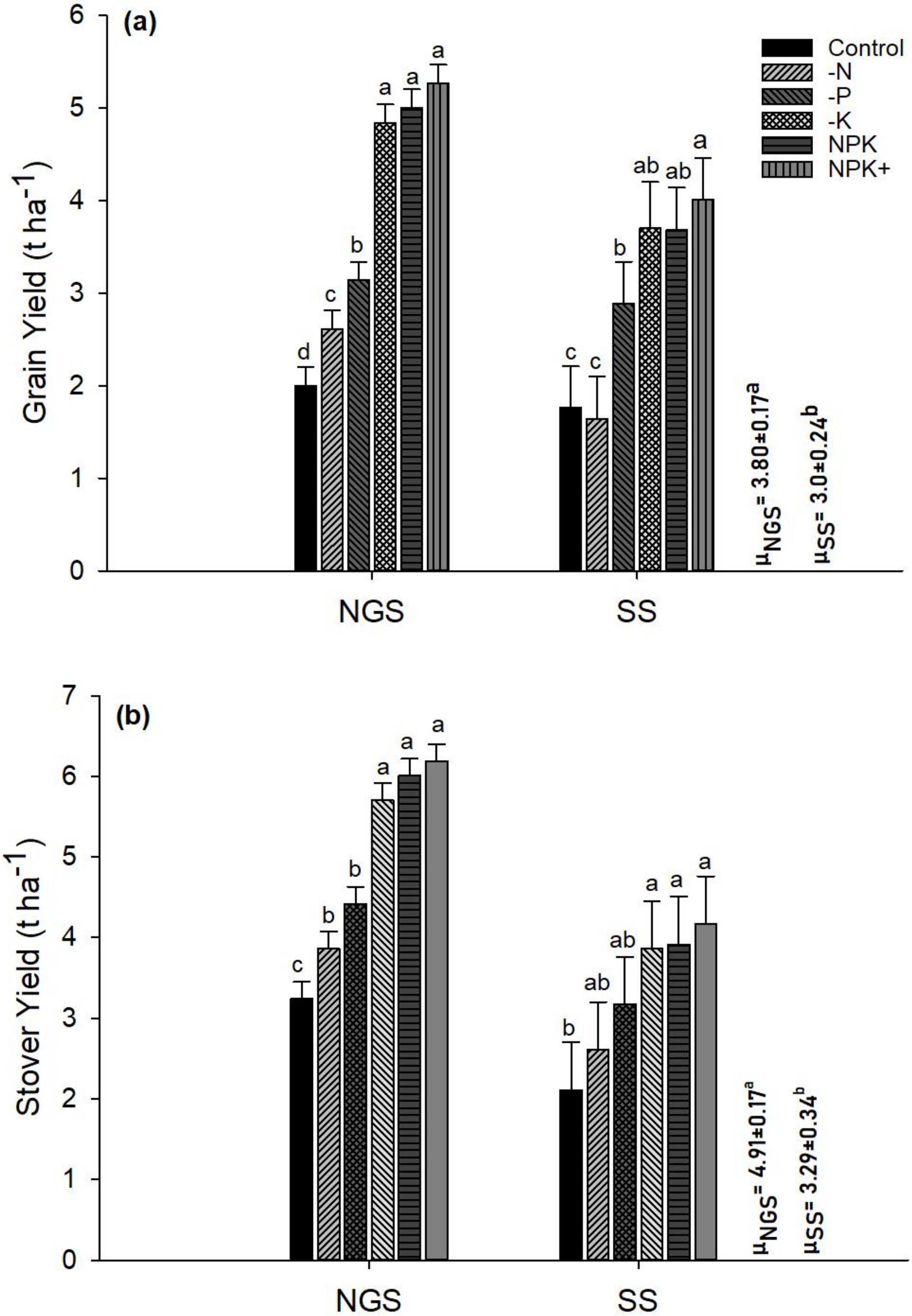

Figure 5.3: Effect of nutrient application (NA) across agro-ecological zones (AEZs) on a) grain yield b) stover yield. NGS: Northern Guinea savanna; SS: Sudan savanna; μ_{NGS}: mean NGS, μ_{SS} = mean SS; Error bars are standard error of means. Values followed by different letters within a group are significantly different at p-value ≤ 0.05.

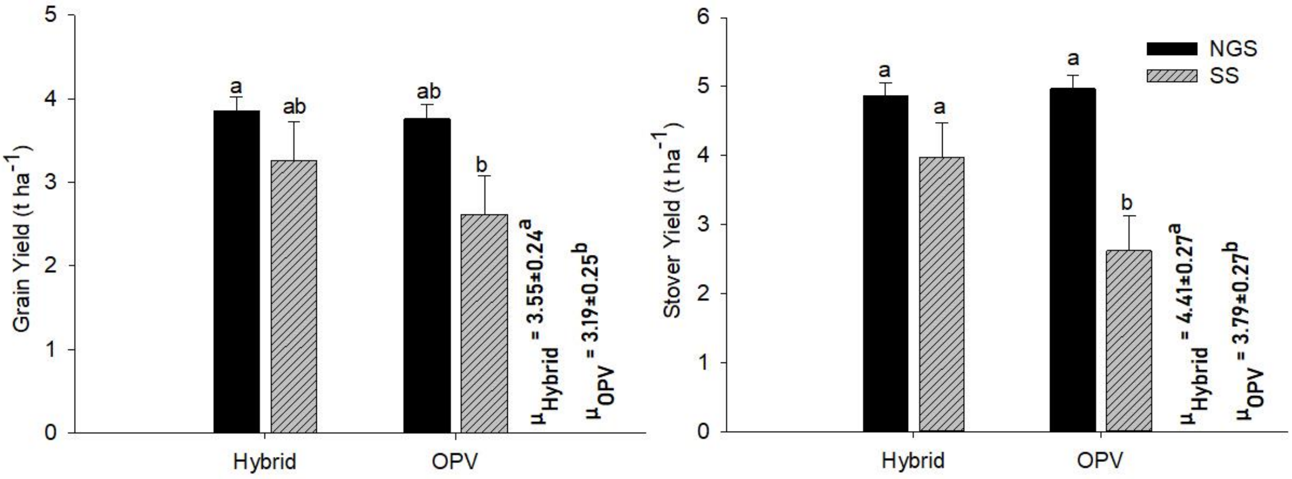

Figure 5.4: Interaction between agro-ecological zone (AEZ) and variety group (VG) on a) grain yield b) stover yield. NGS: Northern Guinea savanna; SS: Sudan savanna; OPV: open pollinated variety; hybrid: hybrid variety; μ_{Hybrid}: mean hybrid; μ_{OPV} = mean OPV; Error bars are standard error of means**.** Values followed by different letters within a graph are significantly different at p-value ≤ 0.05.

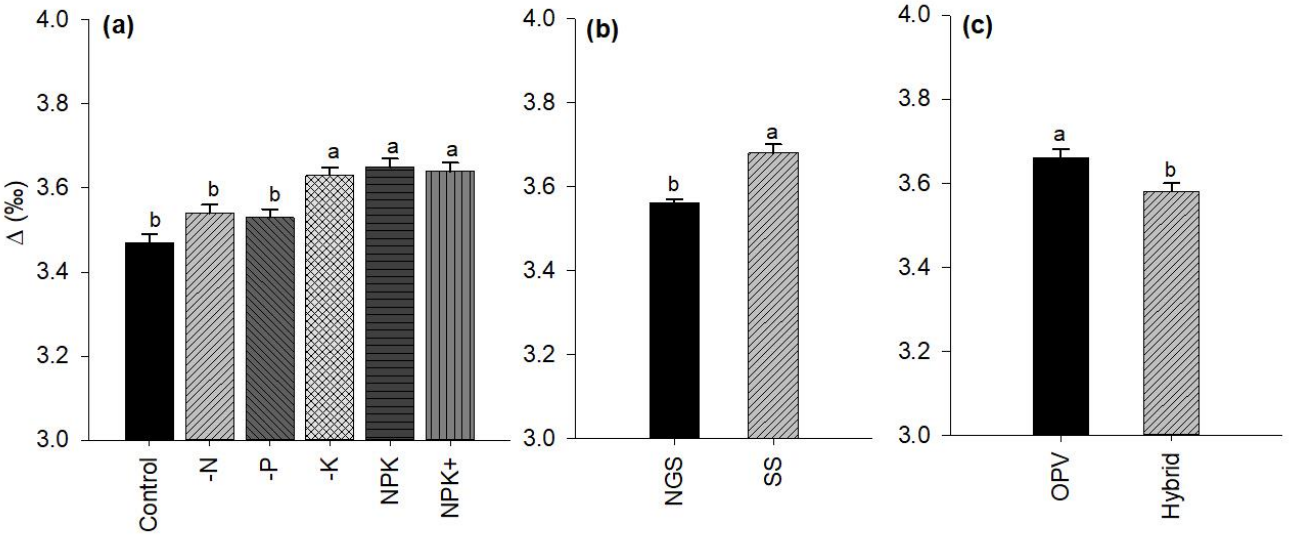

Figure 5.5: Effect of (a) nutrient application (NA) (b) agro-ecological zone (AEZ) (c) variety group (VG) on maize ear leaf ^{13}C isotope discrimination (Δ). NGS: Northern Guinea savanna; SS: Sudan savanna; OPV: open pollinated variety; Error bars are standard error of means. Values followed by different letters within a graph are significantly different at p-value ≤ 0.05.

Table 5.2: Logistic regression showing the change in maize ear leaf ^{13}C isotope discrimination (Δ) in N, P and K nutrient application treatment relative to N and P omission, respectively

Model Parameter	N Omission		P Omission	
	-N$^{\#}$	NPK	-P$^{\#}$	NPK
Mean ± SE	3.54±0.02	3.65±0.02	3.53±0.02	3.65±0.02
Odds Ratio	-	5.01	-	6.36
Model Fit Test	-	<0.001***	-	<0.001***
Model Wald Test	-	<0.001***	-	<0.001***

N: nitrogen; P: phosphorus; K: potassium; $^{\#}$: reference group

of the explanatory variable (i.e. Δ) in the model was also highly significant (p-value <0.01). The odd ratio of Δ in NPK is 5.01 and 6.36 relative to -N and -P (Table 5.2). The interpretation of these odd ratios means that as Δ increases by 1 unit, it increases the probability of the Δ to be in NPK by 5.01 and 6.36 times than to be in -N and -P treatments, respectively.

5.3.3 Relationship between ^{13}C isotope discrimination (Δ) and grain yield, stover yield and cumulative rainfall (CM)

There was a very weak positive but significant relationship between Δ and grain and stover yields when all data, irrespective of the NA, AEZ or VG considered (Table 5.3). Cumulative rainfall in the first 25 days from planting (DFP) across the NA treatments (with an exception of control) shows a weak negative correlation with Δ (Table 5.3). But, across other parts of the growing periods, rainfall did not correlate with Δ, except between 50-75 DFP and then only in NPK+ NA treatment where a weak positive correlation was additionally observed between cumulative rainfall and Δ.

5.4 Discussion

The smaller grain yields in the -N and –P treatments, indicate N and P as the major yield limiting nutrients for maize in the Northern Nigerian savanna. Nitrogen (N) has been reported as the most limiting nutrient in maize production in the savannas of Central and West Africa including Nigeria (Carsky and Iwuafor, 1995; Kamara et al., 2005; Vanlauwe et al., 2011). Shehu et al. (2019) attributed the small yield when N is omitted to the small soil N content in the study area. Osemwotai et al. (2005) observed P to be the second most limiting nutrient in maize after N in highly weathered Nigerian savanna soils. Deficiency of P has been also widely

Table 5.3: Spearman correlation coefficient between maize ear leaf ^{13}C isotope discrimination (Δ) and grain yield, stover yield and cumulative rainfall (CM)

	^{13}C Isotope Discrimination (Δ)						
	Control	-N	-P	-K	NPK	NPK+	All data
Grain Yield	0.05	0.01	0.07	-0.08	-0.01	-0.02	0.15**
Stover Yield	0.02	-0.02	0.06	0.02	0.11	-0.01	0.15**
CM (1-25 DFP)	-0.15	-0.21**	-0.29**	-0.22**	-0.22**	-0.25**	-0.22**
CM (1-50 DFP)	0.03	0.01	-0.22**	-0.06	-0.04	0.01	-0.05
CM (50-75 DFP)	-0.05	0.10	0.15	0.16	0.16	0.24**	0.12
CM (1-75 DFP)	-0.04	0.08	-0.08	0.06	0.10	0.20**	0.05
CM (1-100 DFP)	-0.16	0.01	-0.12	-0.01	0.04	0.15	-0.02

DFP: Days from planting

reported across the Northern Nigerian savanna (Manu et al., 1991; Ekeleme et al., 2014; Shehu et al., 2015). Favorable higher rainfall, low night temperature and reduced biotic pressure make NGS a more suitable zone for maize production than SS (Badu-Apraku et al., 2015), which translated to the higher maize yields in the NGS. Unlike what has been observed in the previous Chapters 3 and 4 when all NOT fields (n=174) were considered, the grain yield was statistically different between hybrid and OPV among the at random selected fields (n=72) for this study. This implies that despite there was no difference in grain yield between the two VGs when analyzed overall, this was not the case in some specific fields. The higher yield in the hybrid varieties than in the OPV, might be attributed to the yield potential of 7-9 t ha^{-1} and tolerance to diseases (streak virus, leaf blight and rust) of the two hybrids used (i.e. *Oba Super 1* and *Oba Super 9*) compared to the OPV cultivars (*EVDT W STR* and *IWD C2 SYN F2*) with a yield potential of 5.5-8 t ha^{-1} but without tolerance to diseases (NACGRAB, 2019; PRS, 2019).

The significant decrease in the Δ due to N and P omissions suggests that the limitations of either-or combination of these two nutrients reduces the Δ. Previous studies have similarly reported a decrease in Δ (less negative $\delta^{13}C$) due to N stress or reduction in N supply in C_4 plants especially maize (Smeltekop et al., 2002; Dercon et al., 2006; Lasa et al., 2011; Yang et al., 2017). This result can be related to the stimulation of photosynthesis when N and P are supplied as this will decrease C_i/C_a either through increasing the amount of Rubisco and phosphoenolpyruvate carboxylase (PEPC) or by increasing photosynthetic organs, hence greater Δ (more negative $\delta^{13}C$) (Farquhar et al., 1989; Turner et al., 1985; Yang et al., 2017). In contrast to this study Ranjith et al. (1995); Meinzer and Zhu, (1998) found an increase in Δ (more negative $\delta^{13}C$) due to increase in N stress in sugarcane (a similar C_4 plant) due to increasing leakiness of CO_2 (∅) fixed by PEPC. The increasing ∅ was attributed to N stress and it reduces Rubisco activity more than PEPC. Generally, variation in Δ in C4 plants results from changes in C_i/C_a and/or variation in ∅ of the bundle sheath. Therefore, we can hypothesize that changes in Δ due to N and P limitations observed in this study are rather due to changes in C_i/C_a than to changes in ∅. Henderson et al. (1992) also found ∅ to be constant under a range of short-term changes in the environmental conditions in a number of C_4 plant species. The opposite relationship between rainfall amount and Δ especially in the first 25 days of the growing period shows that water stress increases Δ especially in the critical early growing period of maize. This can support the larger Δ observed in the drier SS zone compared to the NGS zone with more rainfall. Increase in Δ due to water stress have been consistently reported in previous experiments like Clay et al. (2005); Dercon et al. (2006); Monneveux et al. (2007) and Cabrera-Bosquet et al. (2009). These experiments demonstrated that water stress decreases C_i/C_a which increases Δ in maize (more negative $\delta^{13}C$). This effect has been associated to a decreased stomatal conductance which affects the ^{13}C isotope discrimination (Farquhar et al., 1989). However, the positive relations between rainfall amount and Δ observed in NPK+ between 50-75 days of growing period suggests that the added secondary macro- and micro-nutrients might have also interacted with rainfall to influence the Δ. However, the absolute reason for differences in Δ between the two VGs remained elusive in this study. Yet one might attribute the larger Δ in OPV relative to hybrid variety group to their genotypic differences, as the OPV used were more adapted to the climatic conditions of the study area than the hybrids. Blankenagel et al. (2018) reported different maize lines with different water use efficiency and stomatal conductance, hence different vulnerability of Δ to water limitations. Additionally, Bachiri et al. (2018) found a significant difference in the Δ among different wheat genotypes and asserted the Δ can be used as a physiological marker for selecting drought tolerant wheat cultivars.

5.4 Conclusions

This study investigated the potential use of ^{13}C isotope discrimination (Δ) in maize in the Northern Nigerian savanna as proxy to assess and monitor nutrient and water limitations. ^{13}C isotope discrimination (Δ) significantly decreased with nitrogen (N) and phosphorus (P) limitations, but a significant change in Δ was observed neither with application or omission of potassium (K) nor with addition of secondary macro-/micro-nutrients (in a combined form) i.e. sulphur, calcium, magnesium, zinc and boron. A significant but weak negative relationship was observed between rainfall amount and Δ in the early critical first 25 growing days across all nutrient application and omission treatments. This implies that water stress increases Δ in maize in the Northern Nigerian savanna especially in the early critical growing period. However, genotypic characteristics also influenced the Δ, as a larger Δ was observed in the open-pollinated variety compared to hybrid variety groups used in this study. These findings envisage that observations on Δ can potentially be used as a proxy to assess and monitor the N, P and water limitations in maize in the Northern Nigerian savanna. To further document the changes in Δ due to N, P and water limitations, more studies are needed at scale in the Northern Nigerian savanna. In those, Δ should be evaluated at varying N, P, and water limitation levels and involving commonly grown diverse maize cultivars.

Chapter 6: General conclusions, recommendations and research outlook

This study was conducted to evaluate nutrient related factors limiting maize yield in the Northern Nigerian savanna, where and why they occur and to develop feasible ways to counteract such limitations. In the first place, we tried to understand the status and inter-field variability of soil nutrient contents and quantify the corresponding maize yield response to nutrient addition or omission (Chapter 2). Nutrient limitations and imbalances in maize were explored using foliar compositional nutrient diagnosis (CND) method (Chapter 3). The model QUEFTS (QUantitative Evaluation of Fertility of Tropical Soils) was evaluated for the estimation of balanced nutrient requirements and site-specific fertilizer recommendations to counteract the nutrient limitations and imbalances, and hence optimization of maize nutrient limited yield in the study area (Chapter 4). In the end, owing to the cost and time investment requirements in conducting on-farm nutrient evaluation experiments at scale, we investigated the relationship between foliar ^{13}C isotope discrimination (Δ) and nutrient limitations (Chapter 5). This was based on hypothesis that Δ values can be used as a proxy for nutrient and water limitations in maize (Clay et al., 2005; Dercon et al., 2006). Therefore, this chapter presents overall conclusions drawn from each of the general objectives defined in the introduction section of this thesis (i.e. Chapter 1). Then the conclusions are translated into recommendations, and outlook aspect of future research are discussed.

6.1 General conclusions

Objective 1: Assessment of inter-field variability in soil fertility and maize yield response to nutrient application in the Northern Nigerian savanna.

This study indicates a moderate to high variability in soil nutrient contents among the studied farmer’s fields (CV ≥ 16%). But, in line with other studies (Manu et al., 1991; Ekeleme et al., 2014; Kamara et al., 2014; Shehu et al., 2015), most of these fields have a high sand content and low values for total organic carbon (C_{tot}), total nitrogen (N_{tot}), available boron (B) and effective cation exchange capacity (ECEC), respectively. Correspondingly, the grain yield response to nutrient application significantly varied among the fields. Four distinct clusters of grain yield responses to nutrient application were identified as follows: i) fields with no significant response to nutrient application (constituting 9% and 16% of the OPV and hybrid fields, respectively), ii) fields with significant response to N and P application (containing 63% of the study fields in both OPV and hybrid trials, iii) fields with significant response to N application only (containing 28% and 17% of OPV and hybrid study fields, respectively), and iv) fields with large response to the application of N combined with secondary macro- and micro-nutrients (holding only 4% of hybrid fields). These clusters were largely explained by the inherent soil nutrient status for cluster ii-iv, with low soil status resulting in significant responses and vice versa, as inferred from multinomial logistic regression. While, for the fields without significant response to nutrient application (i.e. cluster i), the reasons for this were not very clear in this study, these fields were nevertheless characterized by significantly higher C_{tot} and Fe contents compared to the other clusters. Additionally, we did not observe a significant yield increase due to the supply of K across all four response clusters. This can be ascertained to the high K contents in most of the fields which could be linked to the presence of an appreciable amount of K-bearing feldspar minerals in the sand and silt fractions in the Northern Nigerian savanna (Møberg and Esu, 1991) and the residual effect of the historic K applications from NPK fertilizer in the fields. The variability in soil nutrient contents and associated classes of maize yield response to nutrient application envisaged the need for the development of nutrient recommendations that consider field or site- specific soil nutrient condition in the Northern Nigerian savanna.

Objective 2: Diagnosis of nutrient limitations and imbalances in maize in the Northern Nigerian savanna

On average, soil nutrient contents, maize yield, and nutrient concentrations in the maize ear leaf were significantly different between the two agro-ecological zones (AEZs) in this study i.e. Northern Guinea savanna (NGS) and Sudan savanna (NGS). No statistical difference in maize grain yield was observed between the two variety groups (VGs) used in the study (i.e. hybrid and open pollinated variety). Also, few significant differences were observed in the ear leaf nutrient concentrations between the VGs compared to the AEZs. Therefore, the diagnosis of nutrient limitations and imbalances was performed separately for the two study AEZs. On average, a significant positive correlation between maize grain yield and concentration of all nutrients in the ear leaf (except Fe in NGS and Mg in SS) was found, which supports earlier findings that the nutrient concentrations in the ear leaf relate best with yield (Reuters and

Robinson, 1997; Jones Jr, 2012). Ear leaf nutrient sufficiency ranges established in this study were different between the two AEZs and different from those in the literature. This emphasizes that the nutrient sufficiency ranges have a local context and are significantly affected by the climate, soil, crop genotype and their interactions (Agboola, 1985; Njoroge et al., 2017; Sahrawat, 2006). The study found that nutrient imbalances in maize are wide-spread in the Northern Nigerian savanna, constituting 40% and 42% of the experimental fields in the NGS and SS, respectively. Despite some discrepancies among the experimental fields, on average, the significantly limiting nutrients ranked according to their decreasing order of frequency of deficiency are N, P > S > Cu, Mn > B in NGS and N, S > Cu > P > Mn, B in SS. Potassium (K) was not among the deficient nutrients in the unfertilized control plots of the nutrient imbalanced fields, but application of N and P alone resulted in K deficiency in 60-100% of these fields. This implies that despite the lack of significant yield increase due to the addition of K, application of K is however required to achieve a balanced nutrient supply and to prevent depletion of the soil reserve in the Northern Nigerian savanna.

Objective 3: Parameterization and validation of QUEFTS model for balanced and site-specific nutrient requirements for maize in the Northern Nigerian savanna

Parametrization and calibration of QUEFTS model involves four variables: i) the indigenous soil supply of available plant nutrients, ii) the average fertilizer recovery efficiency, iii) the minimum uptake to produce any grain, and iv) the physiological or internal efficiency of a nutrient at maximum accumulation and maximum dilution in plants. In this study we were able to parameterize and calibrate these variables for the individual study AEZs and when the data of the AEZs were combined for N, P and K. We limited the analysis to N, P and K because with the data available inclusion of the other identified limiting nutrients (S, Cu, B and Mn) was impossible. The parametrized indigenous soil supply prediction equations for the three nutrients were able to explain 50-66% of the variance between the predicted and observed available soil nutrient supply. The unexplained variance can be attributed to differences in rates of mineralization, leaching losses and soil moisture availability, etc. (Barber, 1995). These factors affect soil nutrient bioavailability and remain too complex to be integrated into simple empirical indigenous nutrient supply functions (Tabi et al., 2008). However, we observed a reasonable agreement between the observed and predicted maize grain yields across the AEZs with the parameterized QUEFTS ($R^2 = 0.69$ for the NGS, 0.75 for the SS, and 0.67 when data for the two AEZs were combined). The model also predicted a linear relationship between grain yield and above-ground nutrient uptake across the AEZs until yield reached about 50 to 60% of the yield potential. When the yield target reached 60% of the potential yield (i.e. 6.0 t ha^{-1}), the model showed above-ground balanced nutrient uptake of 20.7, 3.4 and 27.1 kg N, P, and K, respectively, per one ton of maize grain. These results suggest an average NPK ratio in the plant dry matter of about 6.1:1:7.9. We conclude that the parametrized and calibrated QUEFTS model can be used for balanced nutrient requirement estimations and development of site-specific fertilizer recommendations for maize intensification in the Northern Nigerian savanna.

Objective 4: Assessing the suitability of ^{13}C isotope discrimination (Δ) as a proxy for evaluation of nutrient and water limitations in maize in the Northern Nigerian savanna

In this study, we observed that Δ was significantly influenced (p-value < 0.01) by nutrient application (NA), agro-ecological zone (AEZ) and variety group (VG). The omissions of N (-N) and P (-P) significantly reduced the Δ, implying that N and P stresses decreases the Δ and vice versa. Previous studies have similarly reported a decrease in Δ (less negative δ^{13}C) due to N stress in maize (Smeltekop et al., 2002; Dercon et al., 2006; Lasa et al., 2011). This result can be related to the stimulation of photosynthesis when N and P are supplied, as this have been reported to decrease the C_i/C_a (ratio of intercellular and atmospheric concentrations of CO_2) either through increasing the amount of Rubisco and phosphoenolpyruvate carboxylase (PEPC) or by increasing photosynthetic organs, hence greater Δ (more negative δ^{13}C) (Farquhar et al., 1989; Turner et al., 1985; Yang et al., 2017). Between the two VGs, a larger Δ was observed in the OPV compared to the hybrid variety. The absolute reason for the difference in Δ between the two VGs was not very clear from this study. In the same vein, significantly larger Δ-values were recorded in the drier SS zone compared to the more humid NGS zone. We can relate the differences in Δ between two AEZs to the rainfall abundance, as a weak but significant negative correlation was observed between rainfall abundance and Δ in the early critical first 25 growing days across all the NA treatments and AEZs. Increase in Δ due to water stress in maize has been consistently reported in previous experiments like in Clay et al. (2005); Dercon et al. (2006); Monneveux et al. (2007) and Cabrera-Bosquet et al.

(2009). Therefore, we can conceptualize that the Δ values can be a proxy for nutrient N, P and water limitations in maize Northern Nigerian savanna.

6.2 Recommendations and research outlook

The presence of maize fields without yield response to fertilizer application has been observed in this study in the Northern Nigerian savanna, but further research is required to reconfirm this and understand the underlying cause(s), so that management decision(s) to counteract such non-responsiveness can be developed. Clearly, application of potassium did not cause a significant yield to increase across the study fields owing to the moderate to high content of exchangeable K in the soil. Yet, omission of K resulted in the deficiency of this nutrient as inferred from the foliar CND. Therefore, application of K is required, while in small quantities, to ensure a nutrient balanced supply and maintenance of the soil reserve. In practice, farmers in Northern Nigeria apply K in the form of NPK compound fertilizer commonly in the ratio of 20:10:10 or 15:15:15, respectively. With these fertilizer blends it is very hard to avoid excess application of K while at the same time the requirements for N and P are met. This might call for a reduction of K in the fertilizer blends for maize in the Northern Nigerian savanna to prevent unnecessary excess application. In the same vein, this study demonstrated that apart from N and P, S, Cu, B and Mn are frequently deficient in maize in the Northern Nigeria savanna. This also suggests an inclusion of these nutrients (i.e. S, Cu, B and Mn) in the nutrient and fertilizer management strategies for maize in the Northern Nigerian savanna. However, we first suggest further field validation and soil bioavailability investigations to better document the unique responses and requirements for each of these nutrients (i.e. S, Cu, Mn and B) in maize cropping systems of the Northern Nigerian savanna.

After successful parametrization and validation in this study, we found QUEFTS model to be a suitable and robust decision support tool for a balanced and site-specific N, P and K fertilizer requirement to improve maize yield in the Northern Nigerian savanna. To permit an easy use of the model among agricultural planners, extension agents and farmers, there is a need for the conversion of the current Microsoft-Excel version of the model into a computer and/or android based application. In addition, to use the model in situations when field or site soil data are unavailable, we recommend testing and integrating the model with the emerging geospatial interpolated soil data in Africa like AFSIS (Africa Soil Information Service), among others. Further improvements in the model are also needed which include, i) parameterization and calibration of other identified deficient nutrients (i.e. S, Cu, Mg and B), ii) incorporation of the inputs of other soil physical properties and processes which also effect nutrient bioavailability (such as soil moisture, soil depth, leaching losses, etc.) in the soil nutrient supply prediction equations.

We have indicated that the Δ values can be a proxy for nutrient N, P and water limitations in maize Northern Nigerian savanna from this study. But, to quantify the changes in Δ due to N, P and water limitations that will enable practical application of the Δ values as a proxy for a nutrient and water limitations evaluation in maize in the Northern Nigerian savanna, further studies are needed. Such studies should involve varying levels of N, P and water limitations and involving all commonly grown maize cultivars, as varieties were also observed to have a significant difference in Δ.

Appendices

Appendix A: Spearman correlation coefficient between ear leaf nutrient concentration and soil characteristics in the Northern Guinea savanna (NGS)

		Nutrient Concentration in the Ear Leaf										
		N	P	K	Mg	Ca	S	Cu	Fe	Mn	Zn	B
Soil Characteristic	pH	-0.08	0.11	0.12	0.08	0.06	-0.02	-0.07	-0.01	-0.32**	0.14	0.09
	OC_{tot}	0.20**	0.02	0.40**	-0.08	-0.11	0.08	0.01	0.11	0.15*	0.22**	-0.12
	N_{tot}	0.19**	-0.01	0.03	0.07	0.05	0.19**	0.25**	0.09	0.06	0.14*	-0.03
	P_{av}	0.06	0.10*	-0.29**	0.06	0.13	0.03	0.13	-0.22**	-0.12	-0.18**	0.06
	Sand	-0.25**	0.16*	-0.04	-0.19**	-0.02	-0.18**	-0.17**	-0.15*	-0.01	-0.10	-0.07
	Silt	0.24**	-0.03	0.08	0.12	0.07	0.19**	0.12	0.14*	-0.01	0.04	0.11
	Clay	0.10	-0.23**	-0.04	0.16*	-0.05	0.05	0.12	0.06	0.03	0.10	-0.02
	Ca	0.15*	0.10	0.04	0.13*	0.16*	0.09	0.08	-0.02	-0.09	-0.13*	0.03
	Mg	0.01	-0.17**	-0.07	0.12	-0.08	0.02	0.13*	0.01	-0.21**	0.02	0.06
	K	-0.08	-0.01	0.08	-0.03	-0.05	-0.06	-0.10	0.08	0.05	-0.03	0.18**
	Na	0.03	0.02	-0.47**	0.11	0.11	0.05	0.25**	-0.10	-0.26**	-0.07	0.08
	EA	0.19**	-0.02	0.01	0.02	0.04	0.14*	0.10	0.03	0.32**	-0.13	-0.03
	ECEC	0.15*	0.05	0.02	0.15*	0.12	0.10	0.11	-0.01	-0.09	0.10	0.07
	Zn	0.11	0.29**	-0.02	-0.06	-0.14*	0.03	0.09	-0.19**	-0.15*	0.19**	-0.05
	Cu	-0.06	-0.05	0.18**	-0.20**	-0.18**	-0.11	0.17*	0.12	-0.01	0.11	-0.07
	Mn	0.06	-0.04	-0.32**	0.10	0.03	0.04	0.16*	-0.06	0.07	-0.13*	0.06
	Fe	0.04	0.08	0.15*	-0.15*	0.03	-0.03	-0.09	-0.02	0.17	-0.12	-0.03
	B	0.01	-0.10	-0.05	0.07	-0.12	-0.04	0.08	-0.10	-0.10	0.03	-0.07
	S_{av}	0.18**	-0.21**	0.04	0.03	-0.09	0.07	0.11	0.12	0.09	0.05	-0.15*

OC_{tot}: soil total organic carbon; N_{tot}: soil total nitrogen; P_{av}: soil available P; S_{av}: soil available sulphur; EA: soil exchange acidity ($Al^{3+} + H^{+}$); ECEC: soil effective cation exchange capacity; ** correlation coefficient is significant at 0.01 p-value; * correlation coefficient is significant at 0.05 p-value.

Appendix B: Spearman correlation coefficient between ear leaf nutrient concentration and soil characteristics in the Sudan savanna (SS)

		Nutrient Concentration in the Ear Leaf										
		N	P	K	Mg	Ca	S	Cu	Fe	Mn	Zn	B
Soil Characteristic	pH	0.12	0.48	0.49	0.33	-0.08	-0.04	-0.15	-0.09	-0.53**	0.09	0.25
	OC_{tot}	0.19*	-0.20	-0.05	-0.03	0.26	0.14	-0.03	0.21	-0.04	0.30**	-0.04
	N_{tot}	0.23*	-0.22	0.04	0.09	0.29	0.15*	0.07	0.20	-0.08	0.21*	0.07
	P_{av}	-0.04	0.63**	0.50**	-0.22	0.24	0.16	-0.15	0.03	-0.15	-0.01	0.11
	Sand	0.10	0.55**	0.01	-0.16	0.01	0.19	0.08	-0.06	0.31	0.51*	0.12
	Silt	-0.10	-0.54**	-0.06	0.18	0.01	-0.17	-0.10	0.11	-0.20	-0.50*	-0.07
	Clay	-0.04	-0.40	0.15	0.06	-0.03	-0.17	0.03	-0.11	-0.48*	-0.32	-0.21
	Ca	-0.01	0.22	0.25	0.01	0.08	-0.06	-0.11	-0.04	-0.41*	0.02	-0.11
	Mg	0.24	0.24	0.33	-0.39	0.11	0.09	-0.09	0.17	-0.41*	-0.29	0.17
	K	-0.26	0.33	0.36	-0.28	-0.32	-0.33	-0.31	-0.16	-0.50*	-0.01	0.15
	Na	0.26	-0.25	0.25	-0.05	0.22	0.25	0.23	0.05	0.01	-0.45*	0.12
	EA	-0.07	-0.12	-0.23	0.31	-0.04	0.10	0.21	-0.08	0.46	0.41	-0.19
	ECEC	0.03	0.26	0.36	-0.12	0.05	-0.05	-0.12	-0.01	-0.44*	-0.03	-0.04
	Zn	-0.05	0.05	0.02	0.14	0.23	-0.01	-0.20	0.15	-0.12*	-0.36	-0.02
	Cu	0.05	0.59	0.19	-0.42*	0.09	-0.02	-0.19	0.31	0.04	0.08	0.39
	Mn	-0.13	0.43	0.12	-0.28	-0.06	-0.05	-0.14	-0.17	-0.17	0.17	-0.15
	Fe	-0.26	-0.29	-0.19	0.46*	-0.03	-0.32	-0.22	0.02	-0.18	-0.10	0.04
	B	0.05	0.35	0.33	-0.10	0.32	0.17	-0.06	0.01	-0.13	-0.13	-0.01
	S_{av}	0.17	-0.38	-0.07	0.12	-0.17	-0.23	-0.24	-0.04	-0.29	-0.38	-0.25

OC_{tot}: soil total organic carbon; N_{tot}: soil total nitrogen; P_{av}: soil available P; S_{av}: soil available sulphur; EA: soil exchange acidity ($Al^{3+} + H^{+}$); ECEC: soil effective cation exchange capacity; ** correlation coefficient is significant at 0.01 p-value; * correlation coefficient is significant at 0.05 p-value.

Appendix C: The average ear leaf nutrient CND indices and p-values (indicating indices are significantly below zero) in the low yield and imbalanced subpopulation (LYI)

	Control		**PK**		**NK**		**NP**		**NPK**		**NPK+**		**Overall**	
	Average	p-Value	Average	p-Value	Average	p-Value	Average	p-Value	Average	p-Value	Average	p-Value	Average	p-Value
	Northern Guinea Savanna (NGS)													
I (N)	-0.66	**<0.001**^{t}	-1.26	**<0.001**^{w}	0.06	0.723^{t}	-0.60	**0.010**^{t}	-0.77	**<0.001**^{t}	-1.25	**<0.001**^{t}	-0.73	**<0.001**^{w}
I (P)	-1.09	**<0.001**^{t}	0.64	1.000^{t}	-1.74	**<0.001**^{t}	0.58	0.992^{t}	0.09	0.649^{t}	-0.77	**<0.001**^{t}	-0.52	**<0.001**^{t}
I (K)	0.95	1.000^{t}	1.12	1.000^{w}	0.66	1.000^{t}	-0.41	**0.036**^{t}	0.21	0.854^{t}	-0.27	0.051^{t}	0.73	1.000^{w}
I (Mg)	0.39	1.000^{t}	0.22	0.995^{t}	-0.21	**0.010**^{t}	0.47	0.991^{t}	-0.13	0.333^{t}	-0.59	0.053^{t}	0.14	0.999^{w}
I (Ca)	-0.46	**<0.001**^{t}	-0.15	0.064^{t}	-1.12	**<0.001**^{t}	0.48	0.986^{t}	0.13	0.752^{t}	-0.63	**<0.001**^{t}	-0.41	**<0.001**^{w}
I (S)	-0.15	**0.048**^{t}	-0.55	**<0.001**^{t}	-0.01	0.704^{w}	-1.22	**<0.001**^{w}	-0.93	**<0.001**^{t}	-1.11	**<0.001**^{w}	-0.41	**<0.001**^{w}
I (Cu)	-0.20	**0.031**^{w}	-0.62	**<0.001**^{t}	0.40	1.000^{t}	-0.12	0.300^{t}	0.24	0.921^{t}	-0.80	**<0.001**^{t}	-0.20	**<0.001**^{w}
I (Fe)	0.98	1.000^{w}	0.52	1.000^{w}	0.44	1.000^{t}	0.20	0.850^{t}	0.85	1.000^{t}	0.14	0.767^{t}	0.63	1.000^{w}
I (Mn)	-0.71	**<0.001**^{t}	-0.50	**<0.001**^{t}	0.19	0.981^{t}	0.52	1.000^{t}	0.53	1.000^{w}	0.24	0.930^{t}	-0.26	**<0.001**^{t}
I (Zn)	0.36	1.000^{t}	-0.46	**<0.001**^{t}	1.11	1.000^{t}	-0.47	**0.005**^{t}	-0.72	0.002^{t}	-0.35	0.067^{t}	0.11	0.983
I (B)	-2.70	**<0.001**^{w}	-0.24	**<0.001**^{t}	-0.34	**<0.001**^{w}	-0.48	**0.001**^{t}	-0.47	**<0.001**^{w}	1.50	1.000^{w}	-0.20	**<0.001**^{w}
	Sudan Savanna (SS)													
I (N)	-0.96	**<0.001**^{t}	-1.15	**0.002**^{t}	0.57	0.991^{t}	0.13	0.576^{t}	-0.04	0.474^{t}	-1.37	**<0.001**^{t}	-0.56	**0.003**^{w}
I (P)	-0.39	**0.042**^{t}	0.95	0.982^{t}	-1.39	**0.003**^{t}	-0.70	0.219^{w}	-0.19	0.399^{t}	0.31	0.626^{t}	-0.10	0.335^{t}
I (K)	0.96	0.995^{t}	1.05	0.996^{t}	0.24	0.672^{t}	-2.13	**0.006**^{t}	-0.72	0.110^{t}	-1.11	0.069^{t}	0.27	0.891^{t}
I (Mg)	1.45	1.000^{t}	1.04	1.000^{t}	0.92	0.996^{t}	1.67	0.992^{t}	1.48	0.994^{t}	0.40	0.683^{t}	1.20	1.000^{t}
I (Ca)	-0.61	**0.008**^{t}	-0.38	0.100^{t}	-0.71	**0.040**^{t}	0.73	0.884^{t}	0.25	0.688^{t}	-0.23	0.293^{t}	-0.34	**0.012**^{t}
I (S)	-0.67	**0.045**^{t}	-0.52	**0.048**^{t}	0.29	0.824^{t}	0.96	**0.033**^{t}	-0.76	**0.020**^{t}	-1.56	**0.014**^{t}	-0.36	**0.008**^{t}
I (Cu)	-0.46	**0.021**^{t}	-0.52	**0.027**^{t}	0.45	0.979^{t}	0.53	0.940^{t}	-0.02	0.474^{t}	-0.20	0.234^{t}	-0.16	0.095^{t}
I (Fe)	0.16	0.723^{t}	-0.15	0.292^{t}	-0.29	**0.041**^{t}	0.19	0.628^{t}	-0.46	0.186^{t}	-1.36	**0.007**^{t}	-0.16	0.125^{t}
I (Mn)	-0.54	**0.006**^{t}	-0.53	**0.033**^{t}	0.38	0.885^{t}	0.25	0.778^{t}	-0.28	0.312^{t}	0.92	0.916^{t}	-0.17	0.100^{t}
I (Zn)	1.09	1.000^{t}	-0.01	0.374^{t}	1.30	1.000^{t}	0.03	0.538^{t}	0.73	0.914^{t}	0.05	0.592^{t}	0.62	1.000t
I (B)	-0.63	**<0.001**^{t}	-0.49	**0.012**^{t}	-0.97	**<0.001**^{w}	-0.88	**0.048**^{t}	-0.57	**0.046**^{t}	0.50	0.771^{t}	-0.52	**<0.001**^{w}

^{t} the normality confirmed based on Shapiro-Wilk W' test , therefore p-value were calculated using student's t-test; ^{w} the normality unconfirmed based on Shapiro-Wilk W' test, therefore p-values were calculated using 'one-sample Wilcoxon signed rank' test; the values in bold are significant p-values at ≤ 0.05.

Appendix D: Maize physiological efficiency (*PhE*) of N, P, and K simulated by the QUFETS model to achieve yield targets with maximum yield potential set at 10 t ha^{-1} for the Northern Guinea savanna (NGS), Sudan savanna (SS) and all (combined agro-ecological zones)

Yield (t ha^{-1})	NGS PhE (kg grain kg^{-1} nutrient)			SS PhE (kg grain kg^{-1} nutrient)			All PhE (kg grain kg^{-1} nutrient)		
	N	P	K	N	P	K	N	P	K
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	70.5	454.9	58.6	61.6	186.7	33.1	71.2	418.1	52.7
2	66.3	427.9	55.6	61.5	176.4	33.1	67.1	395.2	49.8
3	62.0	399.6	52.5	61.5	165.7	33.0	62.9	371.3	46.9
4	57.4	369.6	49.3	61.5	154.4	33.0	58.4	346.2	43.7
5	52.6	337.5	45.8	61.5	142.4	33.0	53.6	319.5	40.4
6	47.2	302.6	42.1	61.5	129.5	32.9	48.4	290.8	36.9
7	41.3	263.3	38.2	61.4	115.2	32.9	42.6	259.3	33.0
8	34.3	216.3	33.7	61.4	99.0	32.9	35.9	223.4	28.6
9	24.5	148.6	28.6	61.4	78.7	32.8	27.1	178.9	23.2
10	16.9	74.2	21.8	61.4	40.9	32.8	17.0	101.9	17.3

References

Adediran, J.A., Banjoko, V.A., 1995. Response of maize to nitrogen, phosphorus, and potassium fertilizers in the savanna zones of Nigeria. Commun. Soil Sci. Plant Anal. 26, 593–606. https://doi.org/10.1080/00103629509369320.

Adesoji, A.G., Abubakar, I.U., Labe, D.A., 2016. Economic performance of maize under incorporated legumes and Nitrogen in Northern Guinea savanna zone of Nigeria. Asian J. Agric. Res. 10, 38–46. https://doi.org/10.3923/ajar.2016.38.46.

Adnan, A.A., Jibrin, J.M., Kamara, A.Y., Abdulrahman, B.L., Shaibu, A.S., 2017. Using CERES-Maize model to determine the nitrogen fertilization requirements of early maturing maize in the Sudan Savanna of Nigeria. J. Plant Nutr. 40, 1066–1082. https://doi.org/10.1080/01904167.2016.1263330.

Ado, S., Usman, I., Abdullahi, U., 2007. Recent development in maize research at Institute for Agricultural Research, Samaru, Nigeria. African Crop Sci. Conf. Proc. 8, 1871–1874.

Agboola A.A., Ayedele, O.J., 1985. Prospects and problems of using soil testing for adoption of fertilizer use in Ekiti-Akoko agricultural develepment project area., in: Proceedings of workshops on appropriate technologies for farmers in semi-arid Africa. Purdue University, West Lafeyette. Indiana, USA, pp. 123–136.

Ahmad, W., Zia, M.H., Malhi, S.S., Niaz, A., S., 2012. Boron Deficiency in soils and crops: A Review, in: Goyal, A. (Eds.), Crop Plant. InTech, pp. 77–114.

Ahungwa, G.T., Haruna, U., Muktar, B.G., 2014. Food security challenges in Nigeria: A paradox of rising domestic food production and food import. Int. Lett. Nat. Sci. 18, 38–46. https://doi.org/10.18052/www.scipress.com/ILNS.18.38.

Aitchison, J., 1986. Statistical analysis of compositional data. Chapman and Hall, New York, NY.

Anderson, J.M., Ingram, J.S.I., 1993. Tropical Soil Biology and Fertility (TSBF). A hand book of methods, 2nd Eds. CABI International, Wallingford, UK.

Aref, F., 2011. Concentration and uptake of zinc and boron in corn leaf as affected by zinc sulfate and boric acid fertilizers in a deficient soil. Life Sci. J. 8, 26–32.

Arnon, D.I., Stout, P.R., 1939. The essentiality of certain elements in minute quantity for plants with special reference in copper. Plant Physiol. 14, 371–375.

Arshad M. A., Lowery, B., Grossman, B., 1996. Physical Tests for Monitoring Soil Quality. In: Doran JW, Jones AJ, editors. Methods for assessing soil quality. Madison, WI.

Ayanlade, A., 2009. Seasonal rainfall variability in Guinea Savanna part of Nigeria: A GIS approach. Int. J. Clim. Chang. Strateg. Manag. 1, 282–296.

Ayodele, O.J., Omotoso, S.O., 2008. Nutrient management for maize production in soils of the savanna zones of South-Western Nigeria. Int. J. Soil Sci. 3, 20–27. https://doi.org/10.3923/ijss.2008.20.27.

Bachiri, H., Djebbar, R., Mekliche, A., Djenadi, C., Ghanim, A.M.A., 2018. Carbon isotope discrimination as physiological marker to select tolerant wheat genotypes (*Triticum aestivum* L.) under water limited conditions. Am. J. Plant Physiol. 13, 1–7. https://doi.org/10.3923/ajpp.2018.1.7.

Badu-Apraku, B., Fakorede, M. A. B., Oyekunle, M., Yallou, G.C., Obeng-Antwi, K., Haruna, A., Usman, I.S., Akinwale, R.O., 2015. Gains in grain yield of early maize cultivars developed during three breeding eras under multiple environments. Crop Sci. 55, 527. https://doi.org/10.2135/cropsci2013.11.0783.

Barber, S.A., 1995. Soil nutrient bioavailability: a mechanistic approach, 2nd Eds. John Wiley and Sons, Inc. Canada.

Barłóg, P., 2016. Diagnosis of sugar beet (*Beta vulgaris* L.) nutrient imbalance by DRIS and CND-clr methods at two stages during early growth. J. Plant Nutr. 39, 1–16. https://doi.org/10.1080/01904167.2014.964366.

Bates, T.E., 1971. Factors affecting critical nutrient concentrations in plants and their evaluation: A review. Soil Sci. 112, 116–130. https://doi.org/10.1097/00010694-197108000-00005.

Bennett, J.G., 1980. Aeolian deposition and soil parent materials in Northern Nigeria. Geoderma 24, 241–255. https://doi.org/https://doi.org/10.1016/0016-7061(80)90027-0.

Blake G. R., Hartge, K.H., 1986. Bulk density, methods of soil analysis. In A. Klute (Eds.), Part 1. physical and mineral method. Madison: American Society of Agronomy (ASA) and Soil Science Society of America (SSSA).

Blankenagel, S., Yang, Z., Avramova, V., Schön, C.-C., Grill, E., 2018. Generating plants with improved water use efficiency. Agron. . https://doi.org/10.3390/agronomy8090194.

Bojo, J., 1996. The costs of land degradation in sub-Saharan Africa. Ecol. Econ. 16, 161–173. https://doi.org/10.1016/0921-8009(95)00087-9.

Bowman, W.D., Hubick, K.T., von Caemmerer, S., Farquhar, G.D., 1989. Short-term changes in leaf carbon isotope discrimination in salt- and water-stressed C_4 grasses. Plant Physiol. 90, 162 LP – 166. https://doi.org/10.1104/pp.90.1.162.

Brady N.C., Weil, R.R., 2002. The nature and properties of soils. 13th Eds., Pearson Education, Singapore, ISBN-13: 9780130167637.

Bremner, J.M., 1996. Nitrogen-Total. In: Methods of soil analysis: chemical methods, Sparks D.L. Eds. American Society of Agronomy and Soil Science Society of America, Madison, WI, USA.

Cabrera-Bosquet, L., Sánchez, C., Araus, J.L., 2009. How yield relates to ash content, Δ^{13}C and Δ^{18}O in maize grown under different water regimes. Ann. Bot. 104, 1207–1216. https://doi.org/10.1093/aob/mcp229.

Cadoni, P., Angelucci, F., 2013. Analysis of incentives and disincentives for Maize in Nigeria. Technical notes series, MAFAP, FAO, Rome.

Caemmerer, S.V., Ghannoum, O., Pengelly, J.J.L., Cousins, A.B., 2014. Carbon isotope discrimination as a tool to explore C_4 photosynthesis. J. Exp. Bot. 65, 3459–3470. https://doi.org/10.1093/jxb/eru127.

Carsky, R.J., Iwuafor, E.N.O., 1995. Contribution of soil fertility reserch and maintenance to improved maize production and productivity in sub-Saharan Africa, in: Proceedings of Regional Maize Workshop. IITA, Benin.

Cassman, K.G., Dobermann, A., Walters, D.T., 2002. Agroecosystems, nitrogen-use efficiency, and nitrogen management. Ambio 31, 132–140. https://doi.org/https://doi.org/10.1579/0044-7447-31.2.132.

CBN, 2015. Annual report, Central Bank of Nigeria (CBN) [WWW Document].URL https://www.cbn.gov.ng>RSD (accessed 04.30.2017).

Claupein, W., 1993. Stickstoffdüngung und chemischer Pflanzenschutz in einem Dauerfeldversuch und die Ertragsgesetze von Liebig, L.iebscher, Wollny und Mitscherlich. J. Agron. Crop Sci. 171, 102–113. https://doi.org/10.1111/j.1439-037X.1993.tb00119.x.

Clay, D.E., Clay, S.A., Lyon, D.J., Blumenthal, J.M., 2005. ^{13}C discrimination in corn grain can be used to separate and quantify yield losses due to water and nitrogen stresses. Weed Sci. 53, 23–29. https://doi.org/DOI: 10.1614/WS-04-070R1.

Clay, D.E., Engel, R.E., Long, D.S., Liu, Z., 2001. Nitrogen and water stress interact to influence carbon-13 discrimination in wheat South Dakota State Univ. Experimental Station Journal Series No. 3227. Soil Sci. Soc. Am. J. 65, 1823–1828. https://doi.org/10.2136/sssaj2001.1823.

Collins, M.E., Ovalles, F.A., 1988. Variability of Northwest Florida soils by principal component analysis. Soil Sci. Soc. Am. J. 52, 1430–1435. https://doi.org/10.2136/sssaj1988.03615995005200050042x.

Cornforth, I.S., 1982. Plant analysis, in: Cornforth, I.S., Sinclair, A.G. (Eds.), Fertilizer and lime recommendations for pastures and crops in Newzealand. Ministry of Agriculture and Fisheries, Wellington, Newzealand, Wellington, N.Z., pp. 34–36.

Csathó, P., Magyar, M., Debreczeni, K., Sárdi, K., 2005. Correlation between soil p and wheat shoot p contents in a network of Hungarian long-term field trials. Commun. Soil Sci. Plant Anal. 36, 275–293. https://doi.org/10.1081/CSS-200043081.

De Bauw, P., Van Asten, P., Jassogne, L., Merckx, R., 2016. Soil fertility gradients and production constraints for coffee and banana on volcanic mountain slopes in the East African Rift: A case study of Mt. Elgon. Agric. Ecosyst. Environ. 231, 166–175. https://doi.org/10.1016/J.AGEE.2016.06.036.

Deckers, J., 2002. A systems approach to target balanced nutrient management in soilscapes of sub-saharan Africa. In: Vanlauwe, B., Diels, J., Sanginga, N., Merckx, R. (Eds.), Intergrated Plant Nutrient Management in Sub-Saharan Africa. CAB International, Wallingford, UK.

Dercon, G., Clymans, E., Diels, J., Merckx, R., Deckers, J., 2006. Differential ^{13}C isotopic discrimination in maize at varying water stress and at low to high nitrogen availability. Plant Soil 282, 313–326. https://doi.org/https://doi.org/10.1007/s11104-006-0001-8.

UN DESA, 2019. Probabilistic population projections rev.1 based on the world population prospects 2019 rev. 1., United Nations (UN), Department of Economic and Social Affairs (DESA), Population Division [WWW Document]. URL http://population.un.org/wpp/ (accessed 11.25.19).

UN DESA, 2015. Transforming our world: the sustainable agenda for sustainable development. United Nations (UN), Department of Economic and Social Affairs (DESA) [WWW Document]. URL https://sustainabledevelopment.un.org/post2015/transformingourworld (accessed 11.25.19).

Dewitte, O., Jones, A., Spaargaren, O., Breuning-Madsen, H., Brossard, M., Dampha, A., Deckers, J., Gallali, T., Hallett, S., Jones, R., Kilasara, M., Le Roux, P., Michéli, E., Montanarella, L., Thiombiano, L., Van Ranst, E., Yemefack, M., Zougmore, R., 2013. Harmonisation of the soil map of Africa at the continental scale. Geoderma 211–212, 138–153. https://doi.org/https://doi.org/10.1016/j.geoderma.2013.07.007.

Dugje, I.Y., Kamara, A.Y., Omoigui, L.O., 2006. Infestation of crop fields by Striga species in the savanna zones of Northeast Nigeria. Agric. Ecosyst. Environ. 116, 251–254. https://doi.org/https://doi.org/10.1016/j.agee.2006.02.013.

Eckebil, J.P., 1991. New frontiers for good grains research for the 1990s, in: Progress in food grain research and production in semi-arid Africa. OAU/STRC-SAFGRAD, pp. 3–20.

Edmeades, G.O., Banziger, M., Chapman, S.C., Ribaut, J.M., Bolanos, J., 1995. Recent advances in breeding for drought tolerance in maize, in: West and Central Africa Regional maize and cassava workhop. Cotonou, Benin Republic, p. 28 May to 2 June.

Ejeta, G., 2007. The Striga scourge in Africa: a growing pandemic, in: Intergrating new technologies for striga control: towards ending the witch hunt. World Scientific Publishers, Singapore, pp. 3–16.

Ekeleme, F., Jibrin, J.M., Kamara, A.Y., Oluoch, M., Samndi, A.M., Fagge, A.A., 2014. Assessment of the relationship between soil properties, Striga hermonthica infestation and the on-farm yields of maize in the dry Savannas of Nigeria. Crop Prot. 66, 90–97.

https://doi.org/10.1016/j.cropro.2014.09.001.

ESU, I.E., 1991. Detailed soil survey of NIHORT farm at Bunkure Kano state, Nigeria. Ahmadu Bello University Zaria. Kaduna, Nigeria.

Eteng, U.E., Asawalam, D.O., Ano, O.A., 2014. Effect of Cu and Zn on maize (*Zea mays* L .) yield and nutrient uptake in coastal plain sand derived soils of Southeastern Nigeria. Open J. Soil Sci. 235–245. https://doi.org/10.4236/ojss.2014.47026.

Ezui, K.S., Franke, A.C., Mando, A., Ahiabor, B.D.K., Tetteh, F.M., Sogbedji, J., Janssen, B.H., Giller, K.E., 2016. Fertiliser requirements for balanced nutrition of cassava across eight locations in West Africa. Field Crops Res. 185, 69–78. https://doi.org/10.1016/j.fcr.2015.10.005.

Fageria, N.K., Oliveira, J.P., 2014. Nitrogen, phosphorus and potassium interactions in upland rice. J. Plant Nutr. 37, 1586–600.

Fageria, N.K., Rabelo, N.A., 1987. Tolerance of rice cultivars to iron toxicity. J. Plant Nutr. 10, 653–661. https://doi.org/10.1080/01904168709363598.

Fageria, V.D., 2001. Nutrient interactions in crop plants. J. Plant Nutr. 24, 1269–1290. https://doi.org/10.1081/PLN-100106981.

Fakorede, M.A.B., Akinyemiyu, O.A., 2003. Climatic change: effects on maize production in a tropical rainforest location. In: Badu-Apraku B., Fakorede M.A.B., Ouedraogo M., Carsky R.J., Menkir A., editors. Maize revolution in West and Central Africa., in: Proceedings of regional maize workshop. Cotonou, pp. 272–282.].

Fakorede, M.A.B., Kim, Mareck, S.K., Iken, J.E.,1989. Breeding Strategies and potentials of available varieties in relation to attaining self-sufficiency in maize production in Nigeria., in proceedings: Towards the Attainment of Self-Sufficiency of Maize Production in Nigeria. I.A.R.& T., Ibadan, Nigeria.

FAO, 2016. NIgeria food security and vulnerability survey 2016, report published by the Food and Agriculture Organization of the Unated Nations (FAO) representation in Nigeria.

FAOSTAT, 2018a. Production statistics (prodstat), Rome: Food and Agriculture Organization of the United Nations (FAO) [WWW Document]. URL http://www.fao.org/faostat/en/#country/159 (accessed 4.25.18).

FAOSTAT, 2018b. Production Statistics (prodstat), Rome: Food and Agriculture Organization of the United Nations (FAO), Nigerian maize production data. [WWW Document]. URL http:www.faostat3.fao.org/%0Adownload/Q/QC/E (accessed 4.25.18).

FAOSTAT, 2017a. Food and Agriculture Organization of the United Nations (FAO). Nigerian maize production data [WWW Document]. URL http:www.faostat3.fao.org/%0Adownload/Q/QC/E (accessed 3.3.16).

FAOSTAT, 2017b. Food and Agriculture Organization of the United Nations (FAO), Nigerias agricultural profile [WWW Document]. URL http://www.fao.org/faostat/en/#country/159 (accessed 12.14.17).

Farquhar, G.D., Hubick, K.T., Condon, A.G., Richards, R.A., 1989. Carbon isotope fractionation and plant water-use efficiency BT-stable isotopes in ecological research, in: Rundel, P.W., Ehleringer, J.R., Nagy, K.A. (Eds.), . Springer New York, New York, NY, pp. 21–40.

FDALR, 1999. Assessment of soil degradation in Nigeria. Project report. Federal Department of Agricultural Land Resources (FDALR), Abuja. Abuja, Nigeria.

FDF, 2019. National Forest Reference Emission Level (FREL) for the federal republic of Nigeria. Federal Department of Forestry (FDF), Federal Ministry of Environment, Federal Republic of Nigeria. [WWW Document]. URL https://redd.unfccc.int/files/2019_submission_frel_nigeria.pdf (accessed 21.11.2019.

Fernandes, M.L. V, Indiati, R., Coutinho, J., Buondonno, A., 1999. Soil properties affecting phosphorus extraction from Portuguese soils by conventional and innovative methods. Commun. Soil Sci. Plant Anal. 30, 921–936. https://doi.org/10.1080/00103629909370257.

FFD, 2012. Fertilizer use and management practices for Nigeria. 4th Edition. Federal Fertilizer Department(FFD), Federal Ministry of Agriculture and Rural Development, Abuja. Abuja, Nigeria.

Fisher, M., Abate, T., Lunduka, R.W., Asnake, W., Alemayehu, Y., Madulu, R.B., 2015. Drought tolerant maize for farmer adaptation to drought in sub-Saharan Africa: Determinants of adoption in Eastern and Southern Africa. Clim. Change 133, 283–299. https://doi.org/10.1007/s10584-015-1459-2.

FMANR, 1990. Literature review in soil fertility investigations in Nigeria (in Five Volumes). Federal Ministry of Agriculture and Natural Resources, Lagos.

FMARD, 2011. Agricultural Transfomation Agenda (ATA), Nigeria. Federal Ministry of Agriculture and Rural Dvelopment (FMARD) [WWW Document]. URL https://fmard.gov.ng/ata-nigeria/ (accessed 11.25.19).

Fonseca, A.F. da, Caires, E.F., Barth, G., 2010. Extraction methods and availability of micronutrients for wheat under a no-till system with a surface application of lime. Sci. Agric. 67, 60–70.

Fridgen, J.J., Kitchen, N.R., Sudduth, K. a, Drummond, S.T., Wiebold, W.J., Fraisse, C.W., 2004. Management Zone Analyst (MZA): Software for management zone dileneation Agron. J. 100–108. https://doi.org/http://dx.doi.org/10.2136/sssaj1982.03615995004600030014x.

Friesen, D.K., 1991. Fate and efficiency of sulfur fertilizer applied to food crops in West Africa. Fertil. Res. 29, 35–44.

Garba, Y., Ahmed, B., Katung, M.D., Lawal, A.F., Abubakar, H.N., 2017. Profitability of Striga tolerant maize variety (SAMMAZ 17) amongst smallholder farmers in Lapai, Niger State, Nigeria. South African J. Agric. Ext. 45, 1–9.

García, A., de Iorio, A.F., Barros, M., Bargiela, M., Rendina, A., 1997. Comparison of soil tests to determine micronutrients status in Argentina soils. Commun. Soil Sci. Plant Anal. 28, 1777–1792. https://doi.org/10.1080/00103629709369915.

Gee G.W., Or, D., 2002. Particle-size analysis. In J. H. Dane & G. C. Topp (Eds.) methods of soil analysis. Part 4. Physical methods. Madison, WI: Soil Science Society of America Book Series 5.

Giller, K.E., Rowe, E.C., de Ridder, N., van Keulen, H., 2006. Resource use dynamics and interactions in the tropics: Scaling up in space and time. Agric. Syst. 88, 8–27. https://doi.org/https://doi.org/10.1016/j.agsy.2005.06.016.

Giller, K.E., Tittonell, P., Rufino, M.C., van Wijk, M.T., Zingore, S., Mapfumo, P., Adjei-Nsiah, S., Herrero, M., Chikowo, R., Corbeels, M., Rowe, E.C., Baijukya, F., Mwijage, A., Smith, J., Yeboah, E., van der Burg, W.J., Sanogo, O.M., Misiko, M., de Ridder, N., Karanja, S., Kaizzi, C., K’ungu, J., Mwale, M., Nwaga, D., Pacini, C., Vanlauwe, B., 2011. Communicating complexity: Integrated assessment of trade-offs concerning soil fertility management within African farming systems to support innovation and development. Agric. Syst. 104, 191–203. https://doi.org/10.1016/j.agsy.2010.07.002.

Girei, A.A., Galadima, O.E., 2016. Resource-use efficiency and profitability of maize production in Lafia local government area of Nasarawa state , Nigeria. Eur. J. Acad. Essays 3, 234–238.

Girei, A.A., Saingbe, N.D., Ohen, S.B., Umar, K.O., 2018. Economics of small-scale maize production in Toto local government area, Nasarawa state, Nigeria. Agrosearch 18, 90–104. https://doi.org/https://dx.doi.org/10.4314/agrosh.v18i1.8.

Gott, R.M., Aquino, L.A., Clemente, J.M., Santos, L.P.D. Dos, Carvalho, A.M.X., Xavier, F.O., 2017. Foliar diagnosis indexes for corn by the methods diagnosis and recommendation integrated system (DRIS) and nutritional composition (CND). Commun. Soil Sci. Plant Anal. 48, 11–19. https://doi.org/10.1080/00103624.2016.1253714.

Gressel, J., Hanafi, A., Head, G., Marasas, W., Obilana, A.B., Ochanda, J., Souissi, T., Tzotzos, G., 2004. Major heretofore intractable biotic constraints to African food security that may be amenable to novel biotechnological solutions. Crop Prot. 23, 661–689. https://doi.org/https://doi.org/10.1016/j.cropro.2003.11.014.

Gupta, H.V., Sorooshian, S., Yapo, P.O., 1999. Status of automatic calibration of hydrological models: Comparison with multilevel expert calibration. J. Hydrol. Eng. 4, 135–143. https://doi.org/doi:10.1061/(ASCE)1084-0699(1999)4:2(135).

GYGA, 2017. Global Yield Gap Atlas, Basic data Nigeria [WWW Document]. URL http://www.yieldgap.org/ (accessed 7.24.17).

Hassan A.M., Ogbonnaya, C.S., 2016. Status and distribution of available micronutrient in Udic

Kanhaplustults of Bauchi local government area , Bauchi state. Sch. J. Agric. Vet. Sci. 3, 257–261.

Hawkesford, M.J., Schneider, A., Belcher, A.R., Clarkson, D.T., 1995. Regulation of enzymes involved in the sulphur-assimilatory pathway. Z. Pflanzenernahr. Bodenk. 158, 55–57.

Hay, R.K.M., 1995. Harvest index: a review of its use in plant breeding and crop physiology. Ann. Appl. Biol. 126, 197–216. https://doi.org/10.1111/j.1744-7348.1995.tb05015.x.

He, Z., 2014. Applied manure and nutrient chemistry for sustainable agriculture and environment. Springer Science and business media Dordrecht, New York, U.S.A. https://doi.org/10.1007/978-94-017-8807-6.

Heanes, D.L., 1984. Determination of total organic-C in soils by an improved chromic acid digestion and spectrophotometric procedure. Commun. Soil Sci. Plant Anal. 15, 1191–1213. https://doi.org/10.1080/00103628409367551.

Henao, J., Baanante, C., 2006. Agricultural production and soil nutrient mining in Africa prepared by summary of the paper agricultural production and soil nutrient mining in Africa policy development.

Henao, J., Baanante, C., 1999. Estimating rates of nutrient depletion in soils of agricultural lands of Africa. Alabama. U.S.A. https://doi.org/https://pdf.usaid.gov/pdf_docs/pnacf868.pdf.

Henderson, S.A., Caemmerer, S. V, Farquhar, G.D., 1992. Short-term measurements of carbon isotope discrimination in several C_4 species. Funct. Plant Biol. 19, 263–285.

Hengl, T., Leenaars, J.G.B., Shepherd, K.D., Walsh, M.G., Heuvelink, G.B.M., Mamo, T., Tilahun, H., Berkhout, E., Cooper, M., Fegraus, E., Wheeler, I., Kwabena, N.A., 2017. Soil nutrient maps of sub-Saharan Africa: assessment of soil nutrient content at 250 m spatial resolution using machine learning. Nutr. Cycl. Agroecosystems 109, 77–102. https://doi.org/10.1007/s10705-017-9870-x.

Horneck D.A., Sullivan D.M., Owen J.S., Hart, J.M., 2011. Soil test interpretation guide. https://doi.org/10.1017/CBO9781107415324.004.

Issa, F.O., Kagbu, J.H., Abdulkadir, S.A., 2016. Economic factors influencing farmers adoption of improved maize production practices in Ikara local government area of Kaduna state, Nigeria. Agrosearch 16, 15–24.

Iwuchukwu, J.. C., Igbokwe, E.M., 2012. Lessons from agricultural policies and programmes in nigeria. J. Law, Policy Glob. 12, 2224–3240.

Janssen, B.H., Guiking, F.C.T., Vandereijk, D., Smaling, E.M.A., Wolf, J., Vanreuler, H., 1990. A system for quantative-evaluation of the fertility of tropical soils (QUEFTS). Geoderma 46, 299–318. https://doi.org/10.1016/0016-7061(90)90021-Z.

Janssen, B.H., Lathwell, D.J., Wolf, J., 1987. Modeling long-term crop response to fertilizer phosphorus. II. Comparison with field results1. Agron. J. 79, 452–458. https://doi.org/10.2134/agronj1987.00021962007900030009x.

Jones, J.B.J., Wolf, B., Mills, H.A., 1991. Plant analysis handbook; A practical sampling, preparation, analysis, and interpretation guide. Micro-Macro Inc., Athens, USA.

Jones Jr, J.B., 2012. Plant nutrition and soil fertility manual, Second Eds. Taylor & Francis Group, New York, NY.

Jones Jr, J.B., 1998. Field sampling procedure for conducting plant analysis. CRC Press, Taylor and Fransis Group, LLC, New York, NY.

Jones, M.J., Wild, A., 1975. Soils of West African savanna. Technical communication No.55. Common Wealth Bereau of Soils. Harpenden, England.

Kamara, A.Y., 2017. Good agricultural practices for maize cultivation: the case study of West Africa. In; Watson V. (Eds.), achieving sustainable cultivation of maize, volume : Cultivation techniques, pest and disease control. Burleigh Dodds Science Publishing, Philadelphia, USA.

Kamara, A.Y., Ekeleme, F., Chikoye, D., Omoigui, L.O., 2009. Planting date and cultivar effects on grain yield in dryland corn production. Agron. J. 101, 91–98. https://doi.org/10.2134/agronj2008.0090.

Kamara, Alpha Y., Ekeleme, F., Jibrin, J.M., Tarawali, G., Tofa, I., 2014. Assessment of level, extent and factors influencing Striga infestation of cereals and cowpea in a Sudan savanna ecology of Northern Nigeria. Agric. Ecosyst. Environ. 188, 111–121. https://doi.org/10.1016/j.agee.2014.02.027.

Kamara, Alpha Y, Ewansiha, S.U., Menkir, A., 2014. Assessment of nitrogen uptake and utilization in drought tolerant and Striga resistant tropical maize varieties. Arch. Agron. Soil Sci. 60, 195–207. https://doi.org/10.1080/03650340.2013.783204.

Kamara, A.Y., Menkir, A., Ajala, S.O., Kureh, I., 2005. Performance of diverse maize genotypes under nitrogen deficiency in the Northern Guinea savanna of Nigeria. Exp. Agric. 41, 199–212. https://doi.org/10.1017/S0014479704002479.

Khiari, L., Parent, L.E., Tremblay, N., 2001a. Critical compositional nutrient indexes for sweet corn at early growth stage. Agron. J. 93, 809–814.

Khiari, L., Parent, L.E., Tremblay, N., 2001b. Selecting high-yield subpopulation for diagnosing nutrient imbalance in crops. Agron. J. 93, 802–808.

Kihara, J., Nziguheba, G., Zingore, S., Coulibaly, A., Esilaba, A., Kabambe, V., Njoroge, S., Palm, C., Huising, J., 2016. Understanding variability in crop response to fertilizer and amendments in sub-Saharan Africa. Agric. Ecosyst. Environ. 229, 1–12. https://doi.org/10.1016/j.agee.2016.05.012.

Kim, S.K., 1991. Breeding maize for Striga tolerance and the development of a field technique.

In combating Striga in Africa, in: Proceedings of the International Workshop. IITA, 22-24 August 1991. IITA, Ibadan, Nigeria, pp. 96–108.

Kovács, P., Vyn, T.J., 2017. Relationships between ear-leaf nutrient concentrations at silking and corn biomass and grain yields at maturity. Soil Fertil. Crop Nutr. 109, 1–9. https://doi.org/10.2134/agronj2017.02.0119.

Krause, P., Boyle, D.P., 2005. Comparison of different efficiency criteria for hydrological model assessment. Adv. Geosci. 5, 89–97. https://doi.org/10.5194/adgeo-5-89-2005.

Kwari, J D, Kamara, A.Y., Ekeleme, F., Omoigui, L., 2011. Soil fertility variability in relation to the yields of maize and soybean under intensifying cropping systems in the tropical savannas of Northeastern Nigeria, in: Bationo, A., Waswa, B., Okeyo, J.M., Maina, F., Kihara, J.M. (Eds.), Innovations as Key to the Green Revolution in Africa: Exploring the Scientific Facts. Springer Netherlands, Dordrecht, pp. 457–464. https://doi.org/10.1007/978-90-481-2543-2_47.

Lam, I.L., Kumar, P., Byju, G., Singh, B.P., Minhas, J.S., Dua, V.K., Kumar, P., Byju, G., Singh, B.P., Minhas, J.S., Dua, V.K., Potato, S., 2016. Application of QUEFTS model for site-specific nutrient management of NPK in sweet potato (*Ipomea batatas* L.). Commun. Soil Sci. Plant Anal. 47, 1599–1611. https://doi.org/10.1080/00103624.2016.1194989.

Lasa, B., IraÃ\pmeta, I., Muro, J., Irigoyen, I., Aparicio Tejo, P.M., 2011. Isotopic composition of maize as related to N-fertilization and irrigation in the Mediterranean region. Sci. Agric. 68, 182–190.

Legates, D.R., McCabe Jr., G.J., 1999. Evaluating the use of “goodness-of-fit” measures in hydrologic and hydroclimatic model validation. Water Resour. Res. 35, 233–241.

Liu, M., Yu, Z., Liu, Y., Konijn, N.T., 2006. Fertilizer requirements for wheat and maize in China: The QUEFTS approach. Nutr. Cycl. Agroecosystems 74, 245–258. https://doi.org/10.1007/s10705-006-9002-5.

Lombin, G., 1987. Soil and climatic constraints to crop production in the Nigerian savanna region, in: 15th Annual Conference of Soil Science Society of Nigeria, Kaduna, Nigeria. Soil Science Society of Nigeria, Kaduna, Nigeria.

Magallanes-Quintanar, R., Valdez-Cepeda, R.D., Olivares-Sáenz, E., Pérez-Veyna, O., García-Hernández, J.L., López-Martínez, J.D., 2006. Compositional nutrient diagnosis in maize grown in a calcareous soil. J. Plant Nutr. 29, 2019–2033. https://doi.org/10.1080/01904160600928235.

Malgwi W.B., Ojanuga A.G., Chude V.O., Kparmwang T., R.B.A., 2000. Morphological and physical properties of some soils at Samaru, Zaria, Nigeria. Niger. J. Soil Reseorces 1, 58–64.

Manu, A., Bationo, A., Geiger, S.C., 1991. Fertility status of selected millet producing soils of West Africa with emphasis on phosphorus. Soil Sci. 152, 315–320.

Mehlich, A., 1984. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15, 1409–1416. https://doi.org/10.1080/00103628409367568.

Meinzer, F.C., Zhu, J., 1998. Nitrogen stress reduces the efficiency of the C_4 CO_2 concentrating system , and therefore quantum yield, in *Saccharum* (sugarcane) species. J. Exp. Bot. 49, 1227–1234.

Møberg, J.P., Esu, I.E., 1991. Characteristics and composition of some savanna soils in Nigeria. Geoderma 48, 113–129.

Moghaddam, A., Raza, A., Vollmann, J., Ardakani, M.R., Wanek, W., Gollner, G., Friedel, J.K., 2013. Carbon isotope discrimination and water use efficiency relationships of alfalfa genotypes under irrigated and rain-fed organic farming. Eur. J. Agron. 50, 82–89. https://doi.org/https://doi.org/10.1016/j.eja.2013.05.010.

Monneveux, P., Sheshshayee, M.S., Akhter, J., Ribaut, J.-M., 2007. Using carbon isotope discrimination to select maize (*Zea mays* L.) inbred lines and hybrids for drought tolerance. Plant Sci. 173, 390–396. https://doi.org/https://doi.org/10.1016/j.plantsci.2007.06.003.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Binger, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans. ASABE 50, 885–900. https://doi.org/10.13031/2013.23153.

Morris, M., Kelly, V.A., Kopicki, R.J., Byerlee, D., 2007. Fertilizer use in African agriculture lessons learned and good practice guidelines, World Bank. http://documents.worldbank.org/curated/en/498591468204546593/pdf/390370AFR0Fert101OFFICIAL0USE0ONLY1.pdf.

NACGRAB, 2019. Released crop varieties in Nigeria. National Centre for Genetic Resources and Biotechnology (NACGRAB) [WWW Document]. URL https://nacgrab.gov.ng/index.php/2016-07-25-08-55-11/seed (accessed 11.21.19).

NBS, 2017. Nigerian National Bureau of Statistics (NBS), Q3 GDP report. [WWW Document]. URL. htttps://nigerianstat.gov.ng (accessed 26/03/2019).

Nelson, L.A., Anderson, R.L., 1977. Partitioning of soil test-crop response probability, in: Soil Testing: Correlating and interpreting the analytical results. ASA Spec. Publ., Madison, WI, pp. 19–38.

Njoroge, R., Otinga, A.N., Okalebo, J.R., Pepela, M., Merckx, R., 2017. Occurrence of poorly responsive soils in Western Kenya and associated nutrient imbalances in maize (Zea mays L.). Field Crops Res. 210, 162–174. https://doi.org/https://doi.org/10.1016/j.fcr.2017.05.015

NSPFS, 2005. Nigerian soil fertility rating and thematic maps. National Special Programme for Food Security (NSPFS). Abuja, Nigeria.

Nziguheba, G., Tossah, B.K., Diels, J., Franke, A.C., Aihou, K., Iwuafor, E.N.O., Nwoke, C., Merckx, R., 2009. Assessment of nutrient deficiencies in maize in nutrient omission trials and long-term field experiments in the West African Savanna. Plant Soil 314, 143–157. https://doi.org/10.1007/s11104-008-9714-1

Øgaard, A.F., Krogstad, T., 2005. Release of interlayer potassium in Norwegian grassland soils. J. Plant Nutr. Soil Sci. 168, 80–88. https://doi.org/10.1002/jpln.200421454

Ojeniyi, S.O., Kayode, G.O., 1993. Response of maize to copper and sulfur in tropical regions. J. Agric. Sci. Cambridge 120, 295–299.

Omobolanle, L., Ewuola, S.O.L.U., Daramola, A.G., 2005. Socio-economic impact assessment of maize production technology on farmers ’ welfare in southwest , Nigeria. J. Cent. Eur. Agric. 6, 15–26.

Osemwotai, O., Ogboghodo, I.A., Aghimien, E.A., 2005. Phosphorus retention in soils of Nigeria - A review. Agric. Rev. 26, 148–152.

Oyinlola, E.Y., Chude, V.O., 2010. Status of available micronutrients of the basement complex rock – derived Alfisols in Northern Nigeria savanna. Trop. Subtrop. Agroecosystems 12, 229–237.

Parent, L.-É., 2011. Diagnosis of the nutrient compositional space of fruit crops . Rev. Bras. Frutic, 33:321-334.

Parent, L.E., Cambouris, A.N., Muhawenimana, A., 1994. Multivariate diagnosis of nutrient imbalance in potato crop. Soil Sci. Soc. Am. J. 58, 1432–1438.

Parent, L.E., Dafir, M., 1992. A theoretical concept of compositional nutrient diagnosis. J. Am. Soc. Hortic. Sci. 117, 239–242.

Parent, L.E., Karam, A., Visser, S.A., 1993. Compositional nutrient diagnosis of the greenhouse tomato. Hortic. Sci. 28, 1041–1042.

Parent, S.-É., L.E., P., Rozane, D.E., Hernandes, A., Natale, W., 2012. Nutrient balance as paradigmof plant and soil chemometrics, in: Issaka, R.N. (Ed.), Soil Fertility. InTech, pp. 83–114. https://doi.org/http://dx.doi.org/10.5772/53343.

Pathak, H., Aggarwal, P.K., Roetter, R., Kalra, N., Bandyopadhaya, S.K., Prasad, S., Van Keulen, H., 2003. Modelling the quantitative evaluation of soil nutrient supply, nutrient use efficiency, and fertilizer requirements of wheat in India. Nutr. Cycl. Agroecosystems 65, 105–113. https://doi.org/10.1023/A:1022177231332.

Perez-Quezada, J FPettygrove, G.S., Plant, R.E., 2003. Spatial – temporal analysis of yield and soil factors in two four-crop – rotation fields in the Sacramento valley, California. Agron. J. 95, 676–687. https://doi.org/10.2134/agronj2003.0676

Phillip, D., Nkonya, E., J., P., Oni, O.A., 2009. Constraints to increasing agricultural productivity in Nigeria: A Review. Washington, DC, U.S.A.

https://doi.org/http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.225.4572&rep=rep1&type=pdf.

Piha, M.I., 1993. Optimizing fertilizer use and practical rainfall capture in a semi-arid environment with variable rainfall. Exp. Agric. 29, 405–415. https://doi.org/DOI: 10.1017/S0014479700021128.

Plessis, J., 2003. Maize production. Pretoria, 0001 South Africa. Department of Agriculture and obtainable from Resource Centre Directorate Agricultural Information Services, Private Bag X144. [WWW Document].URL www.arc.agric.za/arc-gci/Fact%20Sheets%20Library/Maize%20Production.pdf (accessed 28/11/2019).

PRS, 2019. Characteristics of available crop varieties. Premier Seeds Limited, Nigeria [WWW Document]. URL https://premierseed.org/product/ (accessed 11.21.19).

Ranjith, S.A., Meinzer, F.C., Perry, M.H., Thom, M., 1995. Partitioning of carboxylase activity in nitrogen-stressed sugarcane and its relationship to bundle sheath leakiness to CO2, photosynthesis and carbon isotope discrimination. Aust. J. Plant Physiol. 22, 903–911.

Raun W.R., Barreto H.J., W.R.L., 1993. Use of stability analysis for long -term soil fertility experiments. Agron. J. 85, 159–167.

Redi, M., Gebremedhin, W., Merkeb, F., 2016. Critical level of extractable phosphorus for maize (*Zea mays* L.) at Metekel Zone , Northwestern Ethiopia. World Sci. News 54, 14–26.

Reuters, D.J., Robinson, J.B., 1997. Plant analysis: An interpretation manual. CSIRO, Collinwood, Australia. pp. 110-125.

Ros, G.H., Hanegraaf, M.C., Hoffland, E., van Riemsdijk, W.H., 2011. Predicting soil N mineralization: Relevance of organic matter fractions and soil properties. Soil Biol. Biochem. 43, 1714–1722. https://doi.org/10.1016/j.soilbio.2011.04.017

Roy, R.N., Finck, A., Blair, G.J., TaNdon, H.L.S., 2006. Plant nutrition for food security, FAO fertilizer and plant nutrition bulletin 6. Food and Agriculture Organization (FAO) of the United Nations, Rome, Italy.

Sahrawat, K.L., 2006. Plant nutrients: Sufficiency and requirements. Encyclopedia of Soil Sci., 1306-1310.

Saïdou, A., Janssen, B.H., Temminghoff, E.J.M., 2003. Effects of soil properties, mulch and NPK fertilizer on maize yields and nutrient budgets on ferralitic soils in Southern Benin. Agric. Ecosyst. Environ. 100, 265–273. https://doi.org/https://doi.org/10.1016/S0167-8809(03)00184-1.

Samaké, O., 2003. Integrated crop management strategies in Sahelian land use systems to improve agricultural productivity and sustainability: A case study in Mali. Wageningen University.

Sanginga, N., Dashiell, K.E., Diels, J., Vanlauwe, B., Lyasse, O., Carsky, R.J., Tarawali, S., Asafo-Adjei, B., Menkir, A., Schulz, S., Singh, B.B., Chikoye, D., Keatinge, D., Ortiz, R., 2003. Sustainable resource management coupled to resilient germplasm to provide new intensive cereal–grain–legume–livestock systems in the dry savanna. Agric. Ecosyst. Environ. 100, 305–314. https://doi.org/https://doi.org/10.1016/S0167-8809(03)00188-9.

Saranga, Y., Flash, I., Yakir, D., 1998. Variation in water-use efficiency and its relation to carbon isotope ratio in cotton. Crop Sci. 38, 782–787. https://doi.org/10.2135/cropsci1998.0011183X003800030027x.

Sarle, W.S.,1983. The Cubic Clustering Creterion, SAS Technical Report A-108, Cary, NC: SAS Institute, Inc.

SAS Institute Inc., 2017. JMP® 13 documentation library. Cary, NC: SAS Institute Inc.

Sattari, S.Z., van Ittersum, M.K., Bouwman, A.F., Smit, A.L., Janssen, B.H., 2014. Crop yield response to soil fertility and N, P, K inputs in different environments: Testing and improving the QUEFTS model. F. Crop. Res. 157, 35–46. https://doi.org/10.1016/j.fcr.2013.12.005.

Schulz, S., Diels, J., Lyasse, O., 2002. Rehabilitation of severely degraded soil through the application of limiting nutrient: an example from Shika farm. In: Improving and intensifying cereal–legume systems in the moist and dry savanna of West and Central Africa.

Sharon, E.N., 2013. The West African Sahel: A review of recent studies on the rainfall regime and its interannual variability. ISRN Meteorol. Volume 201.

Sheahan, M., Barrett, C.B., 2014. Understanding the agricultural input landscape in sub-Saharan Africa : recent plot, household, and community-level evidence. World Bank Policy Res. Work. Pap. 7014 1–87. https://doi.org/10.1596/1813-9450-7014

Shehu, B.M., Merckx, R., Jibrin, J.M., Kamara, A.Y., Rurinda, J., 2018. Quantifying variability in maize yield response to nutrient applications in the Northern Nigerian savanna. Agronomy 8, 18. https://doi.org/10.3390/agronomy8020018

Shehu, B. M., Jibrin, J.M., Samndi, A.M., 2015. Fertility status of selected soils in the Sudan savanna biome of northern nigeria. Int. J. Soil Sci. 10, 74–83. https://doi.org/10.3923/ijss.2015.74.83

Shehu, B.M., Lawan, B.A., Jibrin, J.M., Kamara, A.Y., Mohammed, I.B., Rurinda, J., Zingore, S., Craufurd, P., Vanlauwe, B., Adam, A.M., Merckx, R., 2019. Balanced nutrient requirements for maize in the Northern Nigerian Savanna: Parameterization and validation of QUEFTS model. Field Crops Res. 241, 107585. https://doi.org/https://doi.org/10.1016/j.fcr.2019.107585

Sileshi, G., Akinnifesi, F.K., Debusho, L.K., Beedy, T., Ajayi, O.C., Mong'omba, S., 2010. Variation in maize yield gaps with plant nutrient inputs, soil type and climate across sub-

Saharan Africa. Field Crops Res. 116, 1–13.

Sillanpää, M., 1982. Micronutrients and the nutrient status of soils: A global study, FAO soils bulletin CN - S592.6.T7 S538 1982.

Sinclair, A.G., Morrison, J.D., Smith, L.C., Dodds, K.G., 1997. Determination of optimum nutrient element ratios in plant tissue. J. Plant Nutr. 20, 1069–1083. https://doi.org/10.1080/01904169709365319

Smaling, E.M.A., Janssen, B.H., 1993. Calibration of QUEFTS, a model predicting nutrient uptake and yields from chemical soil fertility indices. Geoderma 59, 21–44.

Smaling, E.M.A., Nandwa, S.M., Janssen, B.H., 1991. Soil fertility in Africa is at stake. In: Buresh RJ, Sanchez PA & Calhoun F (eds) Replenishing soil fertility in Africa,. SSSA Special Publication 51. SSSA, ASA, Wadington.

Smeltekop, H., Clay, D.E., Clay, S.A., 2002. The Impact of intercropping annual 'sava' snail medic on corn production. Agron. J. 94, 917–924. https://doi.org/10.2134/agronj2002.9170.

Snapp, S.S., Mafongoya, P.L., Waddington, S., 1998. Organic matter technologies for integrated nutrient management in smallholder cropping systems of Southern Africa. Agric. Ecosyst. Environ. 71, 185–200. https://doi.org/https://doi.org/10.1016/S0167-8809(98)00140-6.

Sowunmi, F.A., Akintola, J.O., 2010. Effect of climatic variability on maize production in Nigeria. Res. J. Environ. Earth Sci. 2, 19–30.

Swets, J.A., 1988. Measuring the accuracy of diagnostic systems. Science 240, 1285-1293.

Tabi, O.T., Diels, J., Ogunkunle, A.O., Iwuafor, E.N.O., Vanlauwe, B., Saginga, N., 2008. Potential nutrient supply , nutrient utilization efficiencies , fertilizer recovery rates and maize yield in northern Nigeria. Nutr. Cycl. Agroecosys. 80, 161–172. https://doi.org/10.1007/s10705-007-9129-z

Tahirou, A., Diakalia, S., Langyintuo, A., Bamire, S.A., Olanrewaju, A., 2009. Assessing the constraints affecting production and deployment of maize seed in DTMA countries of West Africa. International Institue for Tropical Agriculture (IITA), Ibadan, Nigeria. https://doi.org/https://pdfs.semanticscholar.org/6ccc/194e3c8e0d632eaebe52c57523c7e9467996.pdf

Tittonell, P., Vanlauwe, B., Leffelaar, P.A., Shepherd, K.D., Giller, K.E., 2005. Exploring diversity in soil fertility management of smallholder farms in Western Kenya: II. Within-farm variability in resource allocation, nutrient flows and soil fertility status. Agric. Ecosyst. Environ. 110, 166–184. https://doi.org/10.1016/j.agee.2005.04.003

Tittonell, P, Vanlauwe, B., Leffelaar, P.A., Shepherd, K.D., Giller, K.E., 2005. Exploring diversity in soil fertility management of smallholder farms in western Kenya: II. Within-farm variability in resource allocation, nutrient flows and soil fertility status. Agric. Ecosyst.

Environ. 110, 166–184. https://doi.org/https://doi.org/10.1016/j.agee.2005.04.003

Turner, N.C., Schulze, E.-D., Gollan, T., 1985. The responses of stomata and leaf gas exchange to vapour pressure deficits and soil water content. Oecologia 65, 348–355. https://doi.org/10.1007/BF00378908

Ufiobor, K.A., 2017. Nigeria Agriculture and Sustainability: Problems and Solutions.MSc Thesis, YRKESHOGSKOLAN NOVIA, pp. 9-12.

USDA, 1993. Soil survey manual, United State Department of Agriculture (USDA) handbook, 18. U.S. Gov. Print Office, Washington, DC.

Vanlauwe, B., Chianu, J., Giller, K.E., Merckx, R., Mokwunye, U., Pypers, P., Shepherd, K., Smaling, E., Woomer, P.L., Sanginga, N., 2010. Integrated soil fertility management: Operational definition and consequences for implementation and dissemination. Outlook Agric. 39, 17–24. https://doi.org/10.5367/000000010791169998

Vanlauwe, B., Kihara, J., Chivenge, P., Pypers, P., Coe, R., Six, J., 2011. Agronomic use efficiency of N fertilizer in maize-based systems in sub-Saharan Africa within the context of integrated soil fertility management. Plant Soil 339, 35–50. https://doi.org/10.1007/s11104-010-0462-7

Vanlauwe, B., Ramisch, J.J., Saginga, N., 2006. Integrated Soil Fertility Management in Africa: from knowledge to implementation. In: Boil Approaches Sustainable Soil Systems, pp. 257–272. Tropical Soil Biology and Fertility Institute (TBSF), International Center for Tropical Agriculture (CIAT), Nairobi, Kenya

Vitousek, P.M., Porder, S., Houlton, B.Z., Chadwick, O.A., 2010. Terrestrial phosphorus limitation: mechanisms, implications, and nitrogen–phosphorus interactions. Ecol. Appl. 20, 5–15. https://doi.org/10.1890/08-0127.1

Vocasek, F.F., Friedericks, J.B., 1994. Soil micronutrient extraction by mehlich-3 compared to CaCl2-DTPA. Commun. Soil Sci. Plant Anal. 25, 1583–1593. https://doi.org/10.1080/00103629409369137

Voncir N., Mustapha, S., Tenebe V.A., Kumo, A.L., Kushwaha, S., 2008. Content and profile distribution of extractable zinc (Zn) and some physicochemical properties of soil along a toposequence at Bauchi, Northern Guinea savanna of Nigeria. Int. J. Soil Sci. 3, 62–68.

Walworth, J.L., Sumner, M.E., 1987. The Diagnosis and Recommendation Integrated System (DRIS) BT - Advances in Soil Science, in: Stewart, B.A. (Eds.), Springer New York, New York, NY, pp. 149–188.

Ware, G.O., Ohki, K., Moon, L.C., 1982. The Mitscherlich plant growth model for determining critical nutrient deficiency levels1. Agron. J. 74, 88–91. https://doi.org/10.2134/agronj1982.00021962007400010024x.

WBD, 2019. World Bank Data (WBD), Employment in agriculture (% of total employment) (modeled ILO estimate) [WWW Document]. URL https://data.worldbank.org/indicator/SL.AGR.EMPL.ZS (accessed 4.26.19).

Weil, R.R., Mughogho, S.K., 2000. Sulphur nutrition of maize in four regions of Malawi. Agron. J. 92, 649–656. https://doi.org/10.2134/agronj2000.924649x.

Wendt, J., Rijpma, J., 1997. Sulphur, zinc, and boron deficiencies in the Dedza Hills and Thiwi-Lifidzi regions of Malawi, Tropical Agriculture, 74,81-89.

Wier, R.G., Cresswell, G.C., 1994. Plant nutrient disorders, 4 (pasture and field crops). Inkata, Melbourne, Australia.

Wilding, L.P., 1985. Spatial variability: its documentation, accomodation and implication to soil surveys. in D.R. Nielsen and J. Bouma (Eds.), Soil Spatial Variability. Pudoc, Wageningen, Netherlands.

Witt, C., Dobermann, A., Abdulrachman, S., Gines, H.C., Guanghuo, W., Nagarajan, R., Satawatananont, S., Thuc Son, T., Sy Tan, P., Van Tiem, L., Simbahan, G.C., Olk, D.C., 1999. Internal nutrient efficiencies of irrigated lowland rice in tropical and subtropical Asia. Field Crops Res. 63, 113–138. https://doi.org/10.1016/S0378-4290(99)00031-3

Wright, G.C., Hubick, K.T., Farquhar, G.D., 1988. Discrimination in carbon isotopes of leaves correlates with water-use efficiency of field-grown peanut cultivars. Funct. Plant Biol. 15, 815–825.

Wuenscher, R., Unterfraune, H., Peticzka, R., Zehetner, F., 2015. A comparison of 14 soil phosphorus extraction methods applied to 50 agricultural soils from Central Europe. Plant, Soil Environ. 61, 86–96.

Xu, X., He, P., Pampolino, M.F., Chuan, L., Johnston, A.M., Qiu, S., Zhao, S., Zhou, W., 2013. Nutrient requirements for maize in China based on QUEFTS analysis. Field Crops Res. 150, 115–125. https://doi.org/10.1016/j.fcr.2013.06.006

Yang, H., Yu, Q., Sheng, W., Li, S., Tian, J., 2017. Determination of leaf carbon isotope discrimination in C_4 plants under variable N and water supply. Sci. Rep. 7, 351. https://doi.org/10.1038/s41598-017-00498-w

Yruela, I., 2005. Copper in plants . Brazilian J. Plant Physiol., 17: 145-156.

Zhao, B., Kondo, M., Maeda, M., Ozaki, Y., Zhang, J., 2004. Water-use efficiency and carbon isotope discrimination in two cultivars of upland rice during different developmental stages under three water regimes. Plant Soil 261, 61–75. https://doi.org/10.1023/B:PLSO.0000035562.79099.55

Zhao, F.J., Bilsborrow, P.E., Evans, E.J., McGrath, S.P., 1997. Nitrogen to sulphur ratio in rapeseed and in rapeseed protein and its use in diagnosing sulphur deficiency. J. Plant Nutr. 20, 549–558. https://doi.org/10.1080/01904169709365273

Zingore, S., Delve, R.J., Nyamangara, J., Giller, K.E., 2008. Multiple benefits of manure: The key to maintenance of soil fertility and restoration of depleted sandy soils on African smallholder farms. Nutr. Cycl. Agroecosys. 80, 267–282. https://doi.org/10.1007/s10705-007-9142-2

List of publications

Shehu, B.M., Lawan, B.A., Jibrin, J.M., Kamara, A.Y., Mohammed, I.B., Rurinda, J., Zingore, S., Craufurd, P., Vanlauwe, B., Adam, A.M., Merckx, R., 2019. Balanced nutrient requirements for maize in the Northern Nigerian savanna: Parameterization and validation of QUEFTS model. Field Crops Res. **241**, 107585. https://doi.org/10.1016/j.fcr.2019.107585.

Shehu, B.M., Merckx, R., Jibrin, J.M., Kamara, A.Y., Rurinda, J., 2018. Quantifying variability of maize yield response to nutrient applications in the Northern Nigerian savanna. *Agronomy* ***8***(2), 18. https://doi.org/10.3390/agronomy8020018.

Ogunwole, J.O., Pires, L.F., Shehu, B.M., 2015. Changes in the structure of a Nigerian soil under different land management practices. Rev. Bras. Cienc. do Solo **39,** 830-840. https://doi.org/10.1590/01000683rbcs20140017.

In preparation

Shehu, B.M., Garba, I.I., Jibrin, J.M., Kamara, A.Y., Rurinda, J., Craufurd, P., Adam, A.M., Merckx, R., 2019. Diagnosis of nutrient limitations and imbalances in maize in the Northern Nigerian savanna, *in prep*.

Shehu, B.M., Merckx, R., Jibrin, J.M., Kamara, A.Y., 2019. Influence of nutrient limitation and rainfall on ^{13}C isotope discrimination of maize in Northern Nigerian savanna, *in prep*.