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Micro-nutrients in East African lowlands: Are they needed to intensify rice production?

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ABSTRACT

Rice is a staple food and cash crop for smallholder farmers in sub-Saharan Africa; however, yields are very low, with indications that both macro and micro-nutrients may limit rice productivity in East Africa next to the need for good agronomic practices. Diagnostic on-farm experiments were conducted in Uganda and Tanzania between 2015 and 2017 to assess the contribution of macro, secondary and micro-nutrients on lowland rice yield and identify options by which smallholder farmers can increase productivity. All treatments included good agronomic practices combined with: zero fertilisation as a control, NPK fertilisation with and without secondary and micro-nutrients (B, Mn, Zn, Cu, Mg, S), and/or treatments where B, Mn and Zn were omitted one at a time from the NPK + secondary and micro-nutrient treatment.

NPK fertilisation significantly ($p < 0.05$) increased grain yield under irrigated condition by ca. 32 and 29 % during 2015 and 2016, and 24 and 100 % during 2016 and 2017 in Tanzania and Uganda, respectively; however, inconsistent effects were observed under rainfed condition. Observed higher yields corresponded mainly to higher panicle number with an additive effect of grains per panicle indicating major effects were at earlier growth stages supporting higher sink size development. Adding secondary and micro-nutrients to NPK enhanced yield significantly ($p < 0.05$) under irrigated condition in Tanzania 2015 and 2016 by 7 and 11 %, respectively, while varying results were obtained under rainfed condition. In Uganda, no significant ($p > 0.22$) effects of secondary and micro-nutrients were observed in both years and growing conditions.

This study indicates that the first step to improving lowland rice productivity is proper water management, under otherwise also good crop management in terms of timely transplanting and weeding, and further yield gains can be realised with NPK fertilisation. Secondary and micro-nutrients were effective only when NPK were applied and on the fluvisols of Tanzania, and were not co-limiting yield on the plintosols of Uganda.

1. Introduction

Rice (*Oryza sativa*) is the most rapidly growing food commodity in sub-Saharan Africa (SSA) driven mainly by urbanisation and changing consumer preference (Seck et al., 2013), and plays a vital role in rural household food security and national economies (Nhamo et al., 2014). Despite its importance, smallholder farm yields are very low, and in many countries domestic rice production has not been able to meet the growing demand (Nhamo et al., 2014; Senthilkumar et al., 2020), and the deficit in demand is met through imports. The low yield is attributed to, among other factors, soil-related constraints, sub-optimal production practices, drought, weeds, pests and diseases (Nhamo et al., 2014; Rodenburg et al., 2019; Senthilkumar et al., 2020). Thus, considering the contribution of rice to regional food security and economy, there is a need to understand important yield contributing factors to help increase farm yields.

Good agronomic practices considered as integrated crop, soil, water and weed management practices (Senthilkumar et al., 2018) have been

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shown to improve rice yields when compared to farmers' practice in different agroecologies. For instance, Nhamo et al. (2014) reported rice yield gains of 86.7 % and 91.6 %, respectively, from use of bunds to control water and improved weed management practices compared to farmers' practice in Eastern and Southern Africa. Similarly, Senthilkumar et al. (2018), Rodenburg and Johnson (2009), Touré et al. (2009), and Becker and Johnson (2001) recorded improved grain yields due to good agronomic practices - fine tillage, bunding, timely weeding and fertilisation, and attributed the gains to a lower weed biomass and increased use efficiency of applied fertiliser nutrients. While these studies report direct effects of good agronomic practices with or without fertiliser inputs on productivity, studies further show increase in yields with NPK application over nonapplication.

Studies have reported over 20 % and 140 % more yield of rice with NP and NPK application, respectively, compared to yields obtained in plots under farmers' practice without fertilisation (Haefele et al., 2001, 2002). Similarly, 68 % more grain yield due to NPK application was recorded, compared to unfertilised fields (Wanyama et al., 2015). Furthermore, improvements in grain yield due to NPK application in rice, maize, sorghum and finger millet have been observed, compared to no fertilisation (Kihara et al., 2016; Ndungu-Magiroi et al., 2017; Saito et al., 2019; Tanaka et al., 2013; Wade et al., 1999). Whereas NPK fertilisation improves grain yields, emerging evidence indicates that micro-nutrients can also constrain productivity, and their application in addition to NPK can enhance NPK use efficiency, leading to higher crop yields (Atique-ur et al., 2014; Dicko et al., 2018; Dimkpa and Bindraban, 2016; Khoshgoftarmanesh et al., 2010; Kihara et al., 2016; Ram et al., 2016; Vanlauwe et al., 2015). Studies with maize, rice, wheat, beans and potato indeed show that yields are co-limited by micro-nutrients. For instance, studies where boron (B), manganese (Mn), zinc (Zn), copper (Cu) and sulphur (S) were applied in combination with NPK reported increased yields of rice, maize, wheat, beans, sorghum, finger millet and potato in SSA compared to yields realised with NPK alone (Cyamweshi et al., 2018; Kihara et al., 2016, 2017; Ndungu-Magiroi et al., 2017; Vanlauwe et al., 2015; Wortmann et al., 2019). In East Africa, there are indications that micro-nutrients limit crop production, although previous studies have focused mainly on upland crops. Knowledge of the relevance of micro-nutrients in lowland rice where farmers seem to find low yield gains from NPK fertilisation (Saito et al., 2019) is limited.

The current study assessed the contribution of NPK, and combinations of NPK + secondary and micro-nutrients on lowland rice yield in East Africa. Assessments were made under irrigated and rainfed lowland conditions with otherwise good agronomic practices on two contrasting soil types: fluvisols in the alluvial floodplain of Kilombero, Tanzania, which are brown or grey, sandy loam or clay soils and the lake deposits of granite plintosols and laterite of Doho and Bugiri, Uganda, which are reddish brown, sandy loam or loam soils (Beck, 1964; Gabiri et al., 2018; Tenywa et al., 2016). We sought to understand whether there are yield gains from NPK fertilisation alone, or whether there is need for addition of micro-nutrients, to realise optimal yield gains from fertilisation in these lowlands. We hypothesised that micro-nutrients are important in limiting rice productivity and their application with NPK under good agronomic practices enhances grain yield under the different soil types.

2. Materials and methods

2.1. Field trial set up

On-farm experiments were conducted in Uganda and Tanzania under irrigated lowland (IL) and rainfed lowland (RL) conditions for 2 successive years. In Uganda, trials were conducted at the Kibimba rice irrigation scheme (IL) and the Magoola swamp (RL) in Bugiri district (33°45'E and 0°33'N), and in the Doho rice irrigation scheme (IL) in Butaleja district (34°02'E and 0°56'N) in 2016 and 2017. In Tanzania, trials were conducted in the Kilombero valley at Idete - RL (36°30'E and 8°60'S) and in Msufini - IL (36°54'E and 7°47'S) in 2015 and 2016. The trials were conducted as researcher-managed, in farmers' fields.

In Uganda, an experimental field at the Kibimba rice irrigation scheme, which is a commercial farm, was used during the 2016 trial, while at the Doho rice irrigation scheme a volunteer farmer's field was used. Soil samples from each field at both locations were collected at 0−20 cm depth before planting and analysed for texture and nutrient contents. In 2017, to assess the effect of NPK + secondary and micro-nutrient application under RL condition, Magoola swamp was selected to represent RL ecology. Soil samples from four different farmers' fields within Magoola swamp and six fields within the Doho rice irrigation scheme were collected and analysed for texture and nutrient contents. In all cases, laboratory methods used for soil analyses were Kjeldahl for N; Mehlich 3 for K, S, Mg, Ca, Zn, B, Cu, Mn, Fe; sodium bicarbonate test for P; and hydrometer method for soil texture. The fields from which soil samples were obtained were evaluated and a single field was selected from the four and six sampled fields in Magoola and Doho, respectively, to conduct the trials, aiming for low levels of both macro and micro-nutrients. Except for B which was below critical level (<0.5 mg/kg) in all fields sampled, and Cu and N which were below critical levels (<0.1−0.3 mg/kg and <0.2 %) in some fields (Fairhurst et al., 2007; Senthilkumar et al., 2018), other nutrients, including, P, K, Zn, Mn, Fe, S, Mg and Ca, were above their critical levels for occurrence of deficiency in rice.

In Tanzania, ten farmers' fields were selected under each agroecology during both years, and soil samples were collected from each field and analysed using aforementioned laboratory methods, and all fields were used to conduct the trials. In this case, N and B were below critical levels in all the fields in both years and agroecologies, P, K, Mn, S, Mg and Ca were below their critical levels in some fields, while Zn, Cu and Fe were above their critical levels in all fields. Soil texture was silty clay loam in Uganda and, sandy clay loam in IL and sandy loam in RL of Tanzania.

For each location and year in Uganda, trials were arranged in a Randomised Complete Block Design, with four replications, except in Magoola swamp which had only three replications. In Tanzania, each farmer's field was treated as a replicate, ten replicates in each site and year. Rice varieties commonly grown within the trial sites were used; K 98 for Doho, Wita 9 for Kibimba, K 5 for Magoola, and SARO5 for Idete and Msufini. Plot sizes were 20 m^2 (4 m × 5 m) in Tanzania 2015 and 2016 and Uganda 2016, and 16 m^2 (4 m × 4 m) in Uganda 2017. Grain yield measurements were taken from a central 6 m^2 and 4 m^2 harvest area in 2016 and 2017, respectively, in the Uganda trials; and from 12 m^2, in the Tanzania trials.

Rainfall data for all trial locations for the trial duration were collected. In Tanzania 2015, rainfall data were collected from Delta-T WS-GP1 weather stations at Ifakara and Morogoro. In 2016, data were collected from a Delta-T WS-GP1 installed within 10 km radius at each experimental location. In Uganda, rainfall data for Kibimba 2016 and Magoola 2017 were collected from a Davis Vantage Pro2 weather station at Kibimba rice irrigation scheme. Data for Doho 2016 and 2017 were retrieved from Climate Hazards Group Infrared Precipitation with Stations (CHIRPS-v2) at a spatial resolution of 0.05° (https://www.chc.ucsb.edu/data/chirps) and data processed using ArcGIS 10.6.1.

2.2. Treatments and management

The treatments evaluated included no fertilisation as a control and only NPK fertilisation in both countries. In the Uganda trials further treatments were NPK + B, Mn, Zn, S soil applied (+MN soil), NPK + B, Mn, Zn, S foliar applied (+MN foliar), NP + B, Mn, Zn, S soil applied (K omission), NPK + Mn, Zn, S soil applied (B omission), NPK + B, Zn, S soil applied (Mn omission), NPK + B, Mn, S soil applied (Zn omission), and NPK + commercial micro-nutrient blend of Zn, B, Cu soil applied (+MN blend soil, Table 1). However, the last treatment was not included in Magoola in 2017 because the field that was suitable to run the trial was not large enough to accommodate all the treatment combinations.

Table 1
Treatments implemented and nutrient rates during the trials in Uganda 2016 and 2017, and Tanzania 2015 and 2016.

Treatment	Nutrient rates (kg ha^{-1})															
Uganda	2016								2017							
	N	P	K	B	Mn	Zn	Mg	S	N	P	K	B	Mn	Zn	Mg	S
No fertilisation (control)																
NPK	80	40	40						100	50	50					
+MN soil	80	40	40	2.0	20.0	5.8		14.7	100	50	50	2.0	12.5	6.3		10.6
+MN foliar	80	40	40	1.5	15.0	4.4		11.0	100	50	50	1.5	9.4	4.7		8.0
K omission	80	40		2.0	20.0	5.8		14.7	100	50		2.0	12.5	6.3		10.6
B omission	80	40	40		20.0	5.8		14.7	100	50	50		12.5	6.3		10.6
Mn omission	80	40	40	2.0		5.8		14.7	100	50	50	2.0		6.3		10.6
Zn omission	80	40	40	2.0	20.0			14.7	100	50	50	2.0	12.5			10.6
+MN blend soil[1]	80	40	40	0.6		1.8			100	50	50	2.0		6.3		
Tanzania	2015								2016							
	N	P	K	B	Mn	Zn	Mg	S	N	P	K	B	Mn	Zn	Mg	S
No fertilisation (control)																
NPK	80	40	40						80	40	40					
+MN soil	80	40	40	2.0		3.0	7.5	10.0	80	40	40	2.0		3.0	7.5	10.0
+MN blend YVT foliar[2]	80	40	40	0.2	0.004	0.2	0.2	0.2	80	40	40	0.2	0.004	0.2	0.2	0.2
+MN blend OSA foliar[3]	80	40	40	0.005		0.02			80	40	40	0.005		0.02		
NPK omission foliar[2]				0.2	0.004	0.2	0.2	0.2				0.2	0.004	0.2	0.2	0.2
+MN soil[4]									80	40	40	0.4		0.6	7.5	10.0
NPK omission soil												2.0		3.0	7.5	10.0

[1] Commercial micro-nutrient product (Elfert-F) also included 0.3 kg ha^{-1} Cu.
[2] Commercial micro-nutrient product (YaraVita Tracel Bz) also included 0.004 kg ha^{-1} of Cu and Mo each.
[3] Commercial micro-nutrient product (OSA Rice) also included 0.002 kg ha^{-1} Mo and 0.03 kg ha^{-1} Si.
[4] Cu rate in the NPK + B, Zn, Cu, Mg, S soil applied treatment in 2016 was 0.3 kg ha^{-1}. The use and mentioning of any commercial product does not reflect specific preferences of the research team, these were available on the local market.

Treatments for the Tanzania trials in 2015 included NPK + B, Zn, Mg, S soil applied (+MN soil); NPK + foliar application of two commercial micro-nutrient blends of: B, Mn, Zn, Cu, Mg, S, Mo (+MN blend YVT foliar), and B, Zn, Mo, Si (+MN blend OSA foliar); and only foliar application of B, Mn, Zn, Cu, Mg, S, Mo blend without application of NPK (NPK omission foliar). In 2016, additional treatments of NPK + B, Zn, Cu, Mg, S soil applied (+MN soil) and B, Zn, Mg, S soil applied without NPK application (NPK omission soil) were added to the 2015 treatments (Table 1).

All treatment plots were managed under good agronomic practices. Components of good agronomic practices included fine field tillage; bunding and levelling before transplanting (at all locations in Uganda and Msufini, Tanzania) or sowing (in Idete, Tanzania); timely and line transplanting (21-day old seedlings at spacing of 20 cm × 20 cm for varieties K 98, K 5 and SARO5, and 25 cm × 25 cm for Wita 9) or dibbling 3–4 seeds per hill at 20 cm × 20 cm spacing; timely weeding (14–21 days after transplanting - DAT or days after sowing - DAS, and subsequent weeding done when and as necessary) using a hand hoe; and good water management (sufficient water supply to treatment plots by irrigation), except under rainfed conditions in Magoola and Idete.

All nutrients supplied through soil were applied as basal: 14 DAT for Uganda, and 0–4 DAT or DAS for Tanzania. The exceptions to this procedure were N and K that were split into three at 50, 25 and 25 %, and applied 14 DAT, at panicle initiation and at flowering, respectively, for Uganda. For Tanzania, N was split into 50, 25, and 25 %, and applied at 0–4 DAT or DAS, at panicle initiation and at flowering, while K was split into 50 and 50 %, and applied at 0–4 DAT or DAS and at flowering, respectively. Foliar application for Uganda trials was split into three at 40, 30, and 30 %, and applied at 28 DAT, at panicle initiation and at flowering, respectively. At each foliar application, 0.5, 0.04, 0.3, 0.1 and 0.03 % Zn, B, Mn, S and surfactant (Silwet gold) in the foliar solution, respectively, were used. For the Tanzania trials, the commercial micro-nutrient products Yara Vita Tracel Bz (contained Zn, B, Mn, Cu, Mg, S, Mo) was foliar applied during maximum tillering, and OSA Rice (had Zn, B, Mo, Si) was applied in three equal portions at maximum tillering, panicle initiation and flowering, as recommended by the manufacturers. Foliar solution contained 1.0 and 0.2 % of Yara Vita Tracel Bz and OSA Rice, respectively, and only in 2015, 0.02 % surfactant (Integra). All foliar applications were done using a Knapsack sprayer either in the early morning, between 7.00 and 9.00 a.m., or late afternoon, after 4 p.m., except in Doho 2017 when foliar application was done between 10.00 and 10.30 a.m.. Nutrient sources for N, P, K, Zn, B, Mn and S used were urea, triple super phosphate, muriate of potash, $ZnSO_4.7H_2O$, borax (11.5 % B), $MnSO_4.H_2O$ and sulphur dust, respectively.

2.3. Measurements

In Uganda, within the harvested net plot of 6 or 4 m^2, 12-hill and 9-hill samples were systematically selected in 2016 and 2017, respectively, by taking every 4th hill within and between rows to determine yield components (number of tillers and panicles per hill, total grains per panicle, filled grains per panicle, 1000-grain weight), total above-ground plant dry matter per hill and harvest index (HI) based on grain weight and total dry matter of sampled hills. Panicles m^{-2} were derived from grain yield expressed in Mg ha^{-1} and, the observed grains per panicle and 1000-grain weight. Total grain yield was determined by harvesting the remaining panicles from the harvest area using a sickle and combining this grain weight with the grain weight of the sub-sampled hills. In Tanzania, yield component data (tillers and panicles m^{-2} in both years; total grains per panicle, filled grains per panicle and 1000-grain weight in 2015) were the average of data collected from all plants in two areas, each 1 m^2 directly adjacent to the harvest area in each treatment plot. In 2016, 1000-grain weight and harvest index were quantified from 12 randomly selected hills outside the harvest area. Filled grains per panicle were then calculated from grain yield in Mg ha^{-1} and, the observed panicles m^{-2} and 1000-grain weight. Total grain yield was based on all panicles from the 12 m^2 harvest area cut using a sickle.

Sample hills were threshed, and straw and filled and empty grains were separately oven-dried to constant weight at 70 °C. Filled and empty

Table 2
Grain yield and yield components under irrigated lowland conditions for different fertilisation treatments in Doho, Uganda, 2016.

Treatment	Grain yield (Mg ha^{-1})	Panicles m^{-2}	Filled grains/panicle	Filled grains m^{-2} (x10^3)	1000-grain weight (g)
Control	5.5	254	104	26.2	21.1
NPK	6.8	330	101	33.1	20.6
+MN soil	6.6	323	104	33.5	19.8
+MN blend soil	6.7	310	110	33.2	20.1
K omission	7.2	344	109	36.5	19.6
B omission	6.2	270	119	31.4	19.9
Mn omission	6.7	298	111	32.9	20.3
Zn omission	7.1	343	103	35.3	20.1
+MN foliar	6.3	296	113	31.5	20.1
Mean	6.6	308	108	32.6	20.2
S.e.d.	0.53	38.6	10.6	2.9	0.50
p-value contrast 1[1)]	**0.01**	**0.05**	**0.56**	**<0.01**	**0.01**
p-value contrast 2[1)]	**0.78**	**0.53**	**0.28**	**0.86**	**0.10**

All plots were managed under good agronomic practices, including water management. +MN soil or foliar = NPK + BMnZnS soil or foliar applied; +MN blend soil = NPK + BZnCu soil applied; K, B, Mn and Zn omission was from the NPK + BMnZnS soil applied treatment. Differences between NPK + secondary and micro-nutrient treatments were not significant ($p > 0.05$). [1)] Contrast 1: Control vs fertilisation and, contrast 2: NPK only vs NPK + secondary and micro-nutrients.

Table 3
Grain yield and yield components under irrigated lowland conditions for different fertilisation treatments in Doho, Uganda, 2017.

Treatment	Grain yield (Mg ha^{-1})	Panicles m^{-2}	Filled grains/panicle	Filled grains m^{-2} (x10^3)	1000-grain weight (g)
Control	4.6	324	70	21.9	20.8
NPK	9.2	635	69	44.0	21.0
+MN soil	8.2	489	81	39.8	20.5
+MN blend soil	9.5	625	73	45.4	20.9
K omission	9.2	611	73	44.0	21.0
B omission	8.8	522	82	42.3	20.8
Mn omission	9.1	623	72	44.2	20.5
Zn omission	9.7	625	74	46.0	21.2
+MN foliar[1)]	4.0	556	35	19.4	20.5
Mean	8.0	557	70	38.5	20.8
S.e.d.	0.44	49.5	4.9	2.3	0.33
p-value contrast 1[2)]	**<.001**	**<.001**	**0.17**	**<.001**	**0.97**
p-value contrast 2[2)]	**0.65**	**0.18**	**0.10**	**0.85**	**0.42**

All plots were managed under good agronomic practices, including water management. +MN soil or foliar = NPK + BMnZnS soil or foliar applied; +MN blend soil = NPK + BZnCu soil applied; K, B, Mn and Zn omission was from the NPK + BMnZnS soil applied treatment. Differences between NPK + secondary and micro-nutrient treatments were significant ($p < 0.05$). [1)] This Foliar treatment was not included in the treatment comparisons as errors were made in timing of the application. [2)] Contrast 1: Control vs fertilisation and, contrast 2: NPK only vs NPK + secondary and micro-nutrients.

grains were separated by first pouring all grains from the sampled hills of a plot in to a beaker with distilled water. After stirring for 10–15 s, the empty grains still float at the surface, and were separated from the filled grains at the bottom. Total above-ground plant dry matter was calculated as the sum of straw yield and filled and empty grains expressed in Mg ha^{-1}. To obtain grain yield, panicles from the harvest area were threshed, sun-dried, and the grains were winnowed to remove empty grains. Grain weight was determined using a digital weighing scale (Mini Crane scale model MNCS-M), and moisture content determined using a digital grain moisture meter (SATAKE Moistex Model SS-7). Measurements were done inhouse under room temperature and recorded to 1 and 2 decimal places for moisture content and grain yield, respectively. Rice grain yield adjusted to 14 % moisture content for all sites was expressed in Mg ha^{-1}.

All data were subjected to analysis of variance (ANOVA) using Genstat (19th edition) at 5% probability. Data for each location and year were separately analysed using a one-way ANOVA with randomised blocks, taking the different replicates in Uganda and farmers' fields for Tanzania as blocks, and fertiliser combinations as treatments. In addition to testing for an overall treatment effect, groups of comparable treatments were compared using orthogonal contrasts. These were used to test for the differences in yields in the unfertilised controls versus all other fertilised treatments, yields using only NPK versus NPK with secondary and micro-nutrients and as last contrast between different secondary and micro-nutrient treatments. Where overall differences were not significant, no post-hoc tests were conducted as differences were not considered significant. Where the orthogonal contrast analyses showed yields of NPK, and NPK + secondary and micro-nutrient plots differed significantly, Tukey's post-hoc test was used to separate treatment means that were significantly different from others.

3. Results

3.1. Effect of NPK fertilisation under good agronomic practices on rice grain yield

Overall, NPK fertilisation significantly increased grain yields across locations and years under irrigated conditions, compared to yields from good agronomic practices only ($p < 0.05$). In contrast, inconsistent effects were observed under rainfed condition. Under irrigated conditions, yields increased in Doho 2016 and 2017 by 23.6 and 100 %, respectively, and in Kibimba 2016 by 43.8 % due to only NPK application, compared to yields obtained from unfertilised control plot (Tables 2–4). Whereas in Magoola 2017 under rainfed condition with good agronomic practices, yields were low across all treatments due to drought (Table 5 and Supplementary Table S4) and NPK fertilisation had a small positive effect, with 87.5 % yield difference when NPK was applied, compared to yield from control plots. The yield differences between treatments in Doho and Kibimba under irrigated lowland conditions were explained by a significantly higher number of filled grains m^{-2} while 1000-grain weights either did not differ, or had an inverse relation to yield differences in Doho 2016 (Table 2), where more filled grains m^{-2} were

Table 4
Grain yield and yield components under irrigated lowland conditions for different fertilisation treatments in Kibimba, Bugiri, Uganda, 2016.

Treatment	Grain yield (Mg ha^{-1})	Panicles m^{-2}	Filled grains/ panicle	Filled grains m^{-2} ($x10^3$)	1000-grain weight (g)
Control	4.8	188	120	22.8	21.1
NPK	6.9	240	129	31.2	22.1
+MN soil	7.0	286	114	32.6	21.4
+MN blend soil	6.8	288	115	32.9	20.6
K omission	5.8	244	113	26.8	21.6
B omission	7.5	317	113	35.3	21.2
Mn omission	6.1	224	125	28.2	21.8
Zn omission	8.0	341	109	36.9	21.7
+MN foliar	6.9	270	118	32.0	21.4
Mean	6.6	266	117	31.0	21.4
S.e.d.	0.82	38.3	8.3	4.0	0.52
p-value contrast 1[1)]	**<0.01**	**0.01**	**0.59**	**<0.01**	**0.35**
p-value contrast 2[1)]	**0.94**	**0.17**	**0.03**	**0.76**	**0.07**

All plots were managed under good agronomic practices, including water management. +MN soil or foliar = NPK + BMnZnS soil or foliar applied; +MN blend soil = NPK + BZnCu soil applied; K, B, Mn and Zn omission was from the NPK + BMnZnS soil applied treatment. Differences between NPK + secondary and micro-nutrient treatments were significant ($p < 0.05$). [1)] Contrast 1: Control vs fertilisation and, contrast 2: NPK only vs NPK + secondary and micro-nutrients.

Table 5
Grain yield and yield components under rainfed lowland conditions for different fertilisation treatments in Magoola swamp, Bugiri, Uganda, 2017.

Treatment	Grain yield (Mg ha^{-1})	Panicles m^{-2}	Filled grains/panicle	Filled grains m^{-2} ($x10^3$)	1000-grain weight (g)
Control	0.8	198	19	4.0	20.5
NPK	1.5	361	19	6.9	21.5
+MN soil	1.2	270	22	5.8	21.5
+MN blend soil	–	–	–	–	–
K omission	2.1	628	15	9.9	21.5
B omission	2.2	396	27	10.3	21.5
Mn omission	2.3	320	31	10.3	22.0
Zn omission	2.2	345	32	10.3	21.0
+MN foliar[1)]	1.0	453	13	4.6	20.5
Mean	1.7	371	22	7.8	21.3
S.e.d.	0.52	133.7	4.8	2.3	0.66
p-value contrast 1[2)]	**0.01**	**0.09**	**0.16**	**0.01**	**0.07**
p-value contrast 2[2)]	**0.22**	**0.77**	**0.13**	**0.20**	**0.95**

All plots were managed under good agronomic practices other than water management. +MN soil or foliar = NPK + BMnZnS soil or foliar applied; +MN blend soil = NPK + BZnCu soil applied; K, B, Mn and Zn omission was from + MN soil applied treatment. Differences between NPK + secondary and micro-nutrient treatments were not significant ($p > 0.05$). [1)] Foliar treatment was not included in treatment comparisons due to the very low yields attained because of drought that resulted to leaf scorching. [2)] Contrast 1: Control vs fertilisation and, contrast 2: NPK only vs NPK + secondary and micro-nutrients.

accompanied by a slightly lower 1000-grain weight. The significantly higher number of filled grains m^{-2} was mainly explained by the number of panicles m^{-2}, with only a small role for grain number per panicle in some trials. The latter was generally in the same direction; so, higher panicle number was accompanied by higher number of grains per panicle. In Magoola under rainfed lowland condition, yield differences were explained by significantly more filled grains m^{-2} and a slightly positive effect of 1000-grain weight. The higher number of filled grains m^{-2} was explained by the additive effect of panicles m^{-2} and grains per panicle that were both not significant (Table 5). HI was 40–55 % under irrigated conditions, and averaged 20 % under rainfed lowland conditions.

In Tanzania in the irrigated lowland at Msufini, yield increased by 31.6 and 28.9 % due to NPK application during 2015 and 2016, respectively, compared to yields in the control plot (Tables 6 and 7). In the rainfed lowland in Idete 2015, with ample rain, 84.6 % more yield was recorded due to NPK application (Table 6). In 2016, however, rainfall was too low; as such, the 51.2 % yield difference with NPK application, compared to the control plot, was not significantly different (Table 8). Under irrigated conditions in Msufini, yield differences among treatments were due to a significantly higher number of filled grains m^{-2} and, only in 2016 grains per panicle while 1000-grain weights did not differ. The higher number of filled grains m^{-2} was for the most part explained by the number of panicles m^{-2} and to a lower extent by grain number per panicle in 2015. Under rainfed condition with adequate rain in Idete, differences in yield between treatments were due to higher numbers of grains per panicle, filled grains m^{-2} and 1000-grain weights. The higher number of grains m^{-2} was due to higher number of panicles m^{-2} and more grains per panicle. HI was 48–60 % under irrigated conditions, and averaged 34 % in the rainfed lowland conditions.

3.2. Contributions of secondary and micro-nutrient fertilisation to rice yield gains

Yield gains from secondary and micro-nutrient addition to NPK was significant ($p < 0.05$) across years for irrigated lowland in Msufini, Tanzania, and under sufficient rain in 2015 in rainfed lowlands in Idete, Tanzania. However, the yield gains were not that large (Tables 6 and 7). In the rainfed lowlands in Idete under limited water supply in 2016, no significant differences were observed. In general, yield gains from secondary and micro-nutrient addition to NPK were lower than gains from only NPK application (compared to the unfertilised control). In none of the Ugandan sites did addition of secondary and micro-nutrients to NPK improve grain yield significantly ($p > 0.22$), compared to only applying NPK (Tables 2-5).

In the irrigated lowland in Msufini, yield gains from secondary and micro-nutrients averaged 7.0 and 11.3 % in 2015 and 2016, respectively, compared to yield from only NPK fertilisation (Tables 6 and 7). In the rainfed lowland in Idete 2015 with ample rain, yield gain from secondary and micro-nutrients averaged 26.4 %, compared to yield from only NPK fertilisation (Table 6). Applying secondary and micro-nutrients only without NPK, either through soil or foliar, resulted to

Table 6
Grain yield and yield components under irrigated and rainfed lowland conditions, for different fertiliser treatments in Msufini and Idete, Kilombero valley, Tanzania, 2015.

Treatment	Msufini - Irrigated Lowland					Idete - Rainfed Lowland				
	Grain yield (Mg ha^{-1})	Panicles m^{-2}	Filled grains/ panicle	Filled grains m^{-2} (x10^3)	1000-grain weight (g)	Grain yield (Mg ha^{-1})	Panicles m^{-2}	Filled grains/ panicle	Filled grains m^{-2} (x10^3)	1000-grain weight (g)
Control	3.1^a	160^a	66^a	10.6^a	29.2^a	2.7^a	176^a	54^a	9.1^a	29.2^a
NPK	4.1^b	216^b	65^a	13.8^b	29.4^a	5.0^b	233^b	70^{ab}	16.4^b	30.2^{ab}
+MN soil	4.6^c	219^b	71^a	15.5^c	29.7^a	6.8^c	242^b	90^c	21.2^c	32.2^c
+MN blend YVT foliar	4.2^{bc}	224^b	67^a	14.4^{bc}	29.4^a	5.9^{bc}	251^b	75^{bc}	18.9^{bc}	31.2^{bc}
+MN blend OSA foliar	4.2^{bc}	212^b	69^a	14.2^{bc}	29.5^a	6.0^{bc}	232^b	88^{bc}	19.7^{bc}	30.6^{ab}
NPK omission foliar	3.3^a	170^a	66^a	11.2^a	29.3^a	3.0^a	176^a	56^a	10.0^a	29.7^a
Mean	3.9	200	67	13.3	29.4	4.9	218	72	15.9	30.5
S.e.d.	0.15	11.4	3.26	0.54	0.24	0.38	13.6	6.0	1.17	0.46
p-value contrast 1[1)]	**<.001**	**<.001**	**0.56**	**<.001**	**0.14**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**
p-value contrast 2[1)]	**0.03**	**0.77**	**0.09**	**0.05**	**0.36**	**<.001**	**0.43**	**0.01**	**<.001**	**0.004**

All plots were managed under good agronomic practices, including water management in Msufini. Idete received adequate rain during the entire crop growth period. +MN soil = NPK + BZnMgS soil applied; +MN blend YVT foliar = NPK + BZnMnCuMgSMo foliar applied; +MN blend OSA foliar = NPK + BZnMoSi foliar applied; NPK omission foliar = BZnMnCuMgSMo foliar applied. [1)] Contrast 1: Control vs fertilisation and, contrast 2: NPK only vs NPK + secondary and micro-nutrients. Values followed by the same letters are not statistically different.

yields that were similar to unfertilised control plots, and lower compared to only NPK fertilisation. This is an indication that NPK are major yield limiting nutrients, rather than secondary or micro-nutrients, in these soils. Soil application of secondary and micro-nutrients along with NPK was more effective, compared to foliar application of secondary and micro-nutrients with NPK. The observed yield differences between treatments under irrigated conditions were explained by a significantly higher number of filled grains m^{-2} and in 2016 also grains per panicle, whereas 1000-grain weight did not vary. The significantly higher number of filled grains m^{-2} was due to the additive effect of panicle number and grains per panicle. Under rainfed condition with adequate rain, the observed yield differences were due to significantly higher grain number per panicle, filled grains m^{-2}, and 1000-grain weight.

4. Discussion

In this study, substantial yield gains were observed with NPK fertilisation under good water and crop management; however, NPK effect was minimal under poor water management, despite the otherwise good crop management practices. The yield gains observed could be attributed to improvement mainly in the number of panicles per unit area, with in some cases a limited additional positive effect of more filled grains per panicle resulting in higher numbers of filled grains per unit area in fertilised plots, compared to unfertilised control plots. This indicates that NPK fertilisation made the vegetative and early reproductive crop stages more effective, resulting in the production of more reproductive organs and filled grains per unit area. The additional gain of applying NPK under good agronomic practices was significantly bigger when water was sufficient, either in terms of adequate rain or through irrigation. Only minimal effects were observed where water control was poor and crops suffered from drought. This was the case under rainfed conditions in Magoola 2017 and Idete in 2016, where yields were low due to poor grain filling, and the resultant harvest indices were lower than those observed in similar treatments under adequate water supply. The minimal effect of fertiliser application observed in this study due to drought relates with previous studies where limited fertilisation effect and low rice yields have been reported as a result of drought at panicle initiation, flowering or grain filling stage (Banayo et al., 2020; Castillo et al., 2006; Yang et al., 2019). Drought during our study occurred from panicle initiation to grain filling stage in Magoola 2017, and at vegetative, panicle initiation and grain-filling stage in Idete 2016 (Supplementary Table S4). The limited fertiliser effect due to drought has been associated with reduced nutrient availability, spikelet sterility and poor grain filling (Cai et al., 2006; Fukai et al., 1999; Haefele et al., 2016). This implies that for fertilisation under good agronomic practices to be effective in improving rice productivity, any problem with water supply, especially in rainfed lowlands, should first be resolved. Otherwise, both fertiliser application and good agronomic practices do not bring about a yield increase. This calls for support to farmers by regional governments to facilitate area specific feasible solutions to the water problem in rainfed lowlands, if smallholder farmers are to benefit from NPK fertilisation under good agronomic practices and, hence, sustainably improve rice productivity in East Africa (Nhamo et al., 2014; Raes et al., 2007; Touré et al., 2009).

In addition to this more often observed positive effect of applying macronutrients, significant and consistent yield gains from addition of secondary and micro-nutrients to NPK application were observed on the fluvisols in Tanzania under good water and crop management. However, the additional overall yield gains from secondary and micronutrients were lower than the gains made with NPK application, compared to not applying any fertilisers. The observed yield gains due to secondary and micro-nutrients applied with NPK could be attributed mainly to enhanced grain filling, resulting in higher numbers of filled grains per panicle, and an additional small effect on panicle number that jointly resulted in higher numbers of filled grains m^{-2} in the secondary

Table 7
Grain yield and yield components under irrigated lowland conditions for different fertiliser treatments in Msufini, Kilombero valley, Tanzania, 2016.

Treatment	Grain yield (Mg ha^{-1})	Panicles m^{-2}	Filled grains/panicle	Filled grains m^{-2} ($x10^3$)	1000-grain weight (g)
Control	3.7^{a}	177^{abc}	65^{a}	11.6^{a}	32.3^{a}
NPK	4.8^{b}	195^{cd}	76^{bcd}	14.8^{b}	32.6^{a}
+MN soil[1)]	5.4^{c}	201^{d}	82^{cd}	16.5^{b}	32.9^{a}
+MN soil[2)]	5.4^{c}	201^{d}	81^{cd}	16.5^{b}	32.8^{a}
NPK omission soil	4.0^{a}	172^{a}	72^{abc}	12.4^{a}	32.6^{a}
+MN blend YVT foliar	5.3^{bc}	199^{d}	81^{cd}	16.1^{b}	32.7^{a}
+MN blend OSA foliar	5.3^{bc}	194^{bcd}	85^{d}	16.5^{b}	32.6^{a}
NPK omission foliar	4.0^{a}	176^{ab}	70^{ab}	12.4^{a}	32.4^{a}
Mean	4.8	189	77	14.6	32.6
S.e.d.	0.18	5.9	3.4	0.58	0.36
p-value contrast 1[3)]	**<.001**	**0.002**	**<.001**	**<.001**	**0.20**
p-value contrast 2[3)]	**<.001**	**0.40**	**0.02**	**<.001**	**0.70**

All plots were managed under good agronomic practices, including water management. [1)] NPK + BZnMgS; [2)] NPK + BZnCuMgS; NPK omission soil = ZnBMgS soil applied; +MN blend YVT foliar = NPK + BZnMnCuMgSMo foliar applied; +MN blend OSA foliar = NPK + BZnMoSi foliar applied; NPK omission foliar = BZnMnCuMgSMo foliar applied. [3)] Contrast 1: Control vs fertilisation, and contrast 2: NPK only vs NPK + secondary and micro-nutrients. Values followed by the same letters are not statistically different.

Table 8
Grain yield and yield components under rainfed lowland conditions for different fertiliser treatments in Idete, Kilombero valley, Tanzania, 2016.

Treatment	Grain yield (Mg ha^{-1})	Panicles m^{-2}	Filled grains/panicle	Filled grains m^{-2} ($x10^3$)	1000-grain weight (g)
Control	1.2	122	38	4.5	27.1
NPK	1.8	168	36	6.3	28.2
+MN soil[1)]	2.1	186	37	7.2	27.9
+MN soil[2)]	1.6	131	39	5.6	27.1
NPK omission soil	1.0	116	32	3.6	27.3
+MN blend YVT foliar	1.6	171	31	5.7	27.0
+MN blend OSA foliar	1.8	155	38	6.1	27.7
NPK omission foliar	1.1	122	35	4.2	27.0
Mean	1.5	146	36	5.4	27.4
S.e.d.	0.36	17.9	5.5	1.03	0.68
p-value contrast 1[3)]	**0.20**	**0.04**	**0.56**	**0.22**	**0.54**
p-value contrast 2[3)]	**0.78**	**0.63**	**0.92**	**0.76**	**0.18**

All plots were managed under good agronomic practices other than water management. [1)] NPK + BZnMgS; [2)] NPK + BZnCuMgS; NPK omission soil = ZnBMgS soil applied; +MN blend YVT foliar = NPK + BZnMnCuMgSMo foliar applied; +MN blend OSA foliar = NPK + BZnMoSi foliar applied; NPK omission foliar = BZnMnCuMgSMo foliar applied. [3)] Contrast 1: Control vs fertilisation, and contrast 2: NPK only vs NPK + secondary and micro-nutrients.

and micro-nutrient treated plots. Secondary and micro-nutrient effect on enhancing grain yield was thus during later crop stage at grain development and early filling, the lack of any consistent effect on grain weights implies that during late grain filling limited gains were made. It is plausible that the rice plants accumulated more secondary and micro-nutrients later in the vegetative growth stage and proximal to the onset of reproductive development, than at earlier crop stage, as observed in upland rice by Crusciol et al. (2016). Notably, the time-dependent enhanced secondary or micro-nutrient uptake could have also corresponded with enhanced N uptake, resulting in yield increase, as observed in some pot studies by Dimkpa et al. (2017).

Soil application of secondary and micro-nutrients with NPK was more effective than foliar application. This may be due to nutrient uptake through roots being easier in rice rather than through leaves. However, studies have shown contrasting effects on crop yield between foliar and soil application in different crops including rice, with some studies reporting improved grain yield with soil application, combined soil + foliar application or no difference in yield effect of the application methods (Dimkpa et al., 2017; Imran and Rehim, 2017; Khan et al., 2016; Phattarakul et al., 2012; Prakash et al., 2014; Rehman et al., 2016; Saha et al., 2017; Sreedhu et al., 2015; Yin et al., 2016; Zhang et al., 2012; Zou et al., 2012). In fact the observed effectiveness of soil application of secondary and micro-nutrients with NPK presents a good opportunity for farmers in East Africa to use micro-nutrients alongside NPK fertilisation as soil application is more convenient and commonly used by farmers, and may result in positive residual effects on crop yield (Kihara et al., 2020; Nadeem and Farooq, 2019). As observed also in our 2017 trial in Doho, Uganda, a single wrongly timed foliar application may result in severe yield losses (Table 3). Applying secondary and micro-nutrients only either through soil or foliar without NPK resulted in lower yields, similar to unfertilised control plot. The lack of yield gain from sole application of secondary and micro-nutrients clearly shows that there are no major severe deficiencies of secondary or micro-nutrients in the studied lowlands and that NPK are the most yield limiting nutrients in these systems. This result suggests that farmers can safely use NPK fertilisation under good agronomic practices to increase yields and, when options to improve soil micro-nutrient levels become available and economical, these nutrients could further but marginally increase the efficacy of NPK application.

This study also clearly demonstrated no significant yield gains from micro-nutrient fertilisation in the lowland plintosols and laterite soils of Uganda. This could be attributable to the fact that the soils currently contain sufficient bio-available amounts of these nutrients. Even while B was sometimes below critical values according to soil analyses (supplementary materials, Table S1), we observed no clear effect so no direct reasons for its application. Continued monitoring of micro-nutrient effects in these major lowland rice production areas would be relevant still to provide an early indication of when micro-nutrients may become a real co-limitation due to micro-nutrient mining. Especially, if more effort is made of making macro-nutrient fertilisers available to farmers and as farmers continue to cultivate these soils with only rice without any micro-nutrient replenishment. Most emphasis should go into B, but probably also Cu. Although we did not test Cu rigorously given estimated levels in experimental fields, we did see indications from soil analyses of fields not included in the experiment because of size limitations that it might be locally near critical values. It does thus seem relevant to include at least B and Cu in monitoring of potential emerging micronutrient co-limitations. The observed difference in response to secondary and micro-nutrient application in the fluvisols of Tanzania, and the plintosols and laterite of Uganda could be attributed to difference in parent materials and geological processes from which these soils have been formed (Gabiri et al., 2018; Leemhuis et al., 2017; Tenywa et al., 2016), and cropping intensities the soils have been subjected to, the past decades, resulting to variation in soil nutrient contents.

In Tanzania, we did not have the omission of micro-nutrients from treatment combinations to provide an indication of which micro-nutrients were most yield limiting. Such omission analyses may provide further more targeted insights of relevant micro-nutrients to apply. However, soil analyses showed that B was below critical level in all the fields in both years and agroecologies. Boron may therefore be important to look into as it has elsewhere been shown to affect reproductive success (Atique-ur et al., 2015), and indeed we observed more filled grains that resulted to higher yields in the secondary and micro-nutrient treated plots compared to only NPK plots (Tables 6 and 7). Boron plays an essential role during rice reproductive stage, related to panicle fertility, and its deficiency is reported to result in panicle sterility due to poor development of anthers and pollen, and failure of pollen germination (Atique-ur et al., 2015). Application of B to these soils may, therefore, be essential to avert such adverse effects on rice productivity. A study by Atique-ur et al., 2014 in soils where soil B levels ranged between 0.5 – 0.6 mg/kg reported rice yield gains of up to 24 % with soil B application at 1 kg B ha^{-1}, compared to zero B fertilisation. In our study, yield gains of up to 13 and 38 %, respectively, in irrigated and rainfed lowland were observed from combination of secondary and micro-nutrients that included B and applied together with NPK through the soil, compared to only NPK application. While also nutritional quality of rice, especially in terms of grain Zn concentration, could be affected by micro-nutrient application (Cakmak et al., 2010; Imran and Rehim, 2017; Joy et al., 2015; Phattarakul et al., 2012; Ram et al., 2016; Wang et al., 2012; Yin et al., 2016; Zhang et al., 2012), the current analysis and recommendations are based on the fact that nutritional quality of rice does not affect the price farmers get for their produce. In this paper we have not made a full economic analysis but any application of micro-nutrients adds to production costs and thus has to affect yield quantity to be of interest for farmers.

5. Conclusion

This study has shown large yield gains with NPK fertilisation under good water and crop management, but with minimal yield gains under poor water management, even though good agronomic practices were followed. This indicates that for smallholder farmers to improve lowland rice productivity under rainfed condition, water is the first production input that needs to be in adequate supply during crop growth, and further yield gains can be realised with NPK fertilisation under good agronomic practices. Micro-nutrients were only effective when applied with NPK as seen in the fluvisols of Tanzania, but were not co-limiting grain yield in the plintosols and laterite of Uganda and therefore not yet to be considered in this agroecology of Uganda. This indicates that NPK are the major limitation to yield, though their effect could be marginally improved by micro-nutrients. We conclude that boosting rice productivity in East Africa would require resolving the water problem for rainfed lowland farmers, following good agronomic practices, and applying NPK. There were no acute problems arising from micro-nutrients omission in our study areas, and therefore, there is need to first focus on attaining full potential for grain yield enhancement from NPK application rather than micro-nutrients. However, in some areas of the region it may be worthwhile to monitor the effects of micro-nutrient application to timely alert on the need for redressing emerging limitations.

Author's contribution

Kalimuthu Senthilkumar, **Christian O. Dimkpa**, **George William Otim-Nape**, **Bas Kempen**, **Thomas Awio and TjeerdJan Stomph**: Methodology, Validation. **Thomas Awio**: Investigation. **Paul C. Struik**, **Thomas Awio and TjeerdJan Stomph**: Formal analysis, Writing - Original draft preparation. **Kalimuthu Senthilkumar**, **Christian O. Dimkpa and Bas Kempen**: Writing – Reviewing and editing.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fcr.2021.108219.

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