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Rice yield and economic response to micronutrient application in Tanzania

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Highlights

- Foliar fertiliser application is only effective under drought-free conditions
- Sole application of micronutrients (Zn-B-Mg-S) is not effective in any environment
- Compared to NPK alone, yield increased 0.5-1.8 t ha^{-1} from NPK + micronutrients
- Micronutrient application to soil or foliar is profitable with adequate soil moisture

Abstract

Nutrient deficiencies limit rice production in sub-Saharan Africa. The conventional recommended remedy for this is the soil application of fertilisers composed of the macro-nutrients, N, P and K, whereas crop micronutrient requirements are neglected. This leads to nutrient mining and diminished fertiliser use efficiency. Application of micronutrients along with recommended NPK fertiliser rates can prevent nutrient mining and boost rice yields. In this study, we assessed the productivity and profitability of different soil- and foliar-applied micronutrients in 30 on-farm trials per year for two consecutive years (2015, 2016) in Tanzania, East Africa. Five locally available foliar formulations (combinations of macro- and micronutrients or micronutrients alone) and soil application of micronutrients (3-2-7.5-10 Zn-B-Mg-S kg ha^{-1}) were assessed under two NPK-fertilization regimes (80-17.5-33.2 and 0-0-0 kg N-P-K ha^{-1}) in three rice growing environments (RGEs): Irrigated Lowland (IL), Rainfed Lowland (RL), and Rainfed Upland (RU). The effect of foliar and soil applied micronutrients on yield was consistent in IL but was highly variable in the RL and RU conditions across years. The soil application of micronutrients in the absence of NPK was ineffective in any of the RGEs. In IL, without NPK, foliar application alone increased yield by 0.3-0.4 t ha^{-1}, compared to control (3.1 t ha^{-1}). Only NPK application increased yield by 1 t ha^{-1}, while NPK and micronutrients application increased yield by 1.5 t ha^{-1}, compared to control. The benefit-cost (B:C) ratio for NPK with soil applied micronutrients was 4 – 4.5 compared to NPK application alone. In RL, application of NPK alone increased yield in 2015 from 2.7 to 5.0 t ha^{-1} while NPK and soil applied micronutrients application increased yield to 6.8 t ha^{-1}. However, a drought incidence in 2016 nullified this effect. With NPK, two foliar products (F2 and F3) increased yield significantly by 1 t ha^{-1}. The highest B:C ratio was obtained with soil applied micronutrients (B:C of 14), and two of the foliar products obtained a B:C ratio of 7 and 7.2, respectively. In RU, no significant yield differences were observed among treatments in any year, likely due to drought. Foliar application was effective only under drought-free conditions across the rice growing environments. This study demonstrated that soil applied micronutrients together with NPK significantly increased yields in IL and RL in the absence of drought-stress. Application of macronutrients is a likely prerequisite for maximizing the benefits of applying micronutrients to increase rice yields in Tanzania.

Keywords: Foliar products; benefit cost analysis; upland rice; lowland rice; sub-Saharan Africa

1. Introduction

Demand for rice (*Oryza sativa*) in sub-Saharan Africa (SSA) is increasing more rapidly than supply from local production (Seck et al., 2012, 2010). Low yields in rice production in SSA are due to numerous constraints, including inadequate nutrient supply (Kwesiga et al., 2020, 2019; Nhamo et al., 2014; Niang et al., 2017; Senthilkumar et al., 2020; Tanaka et al., 2017).. On the global scale, application of N, P, and K contributed to increased rice production during the Green Revolution. However, use of NPK alone has led to soil depletion of certain micronutrients, resulting in micronutrients deficiency in agricultural soils (Alloway, 2009; Bindraban et al., 2020; Cakmak, 2008; Jones et al., 2013). Worldwide, crops are affected by multiple micronutrient deficiencies in soil, caused by inadequate replenishment following biological mining by plant roots (Dimkpa and Bindraban, 2016; Wortmann et al., 2019).

In SSA, average fertiliser use is about 13 kg ha^{-1} in 2018 (IFA, 2018). Several studies have reported the effect of NPK fertilizers on rice yields in Africa (e.g. Becker and Johnson, 1999; Daudu et al., 2018; Garba et al., 2018). In cases where N is applied in low quantities the yield responses were poor (Becker and Johnson, 2001; Kajiru et al., 1998; Meertens et al., 2003). Notably, high N rates increased the yield considerably in many cases, while yield responses to the addition of P and K were smaller (Djaman et al., 2016; Kaizzi et al., 2006, 2014; Niang et al., 2018). A limited number of studies have reported that the application of micronutrients together with NPK increased yield. In lowland rice in Rwanda, application of NPK together with Mg-S-Zn-B increased yield by 1.7 t ha^{-1}, compared to NPK alone (Nabahungu et al., 2020). Koné et al (2011) reported a 44% increase in yield due to micronutrient application in irrigated lowlands of Benin. Similarly, van Asten et al., (2004) reported a yield increase of 76% due to application of only Zn at the rate of 10 kg ha^{-1} in Zn-deficient lowland fields of Burkina Faso. A meta-analysis of yield responses of different crops to the application of secondary (Ca, Mg and S) and micronutrients indicated increased crop yield in SSA. However, most of the data source were for maize, sorghum and wheat; data from rice and other crops accounted for less than 5% (Kihara et al., 2017).

The lack of NPK effects reported in some cases on the quantity and quality of crop yield may be due to the fact that micronutrients' ability to enhance the use efficiency of NPK fertilisers has not been harnessed (Dimkpa and Bindraban, 2016; Kihara et al., 2017). The extent of limitation in crop yield observed with using NPK fertilisation alone has been noted by Vanlauwe *et al*. (2015), whereby S, Zn, Cu, Mg, Ca, B, Fe and Mn applied in combination with NPK were reported to increase yields of rice, maize, wheat, beans and potato in Ethiopia, Rwanda, Burundi and Mozambique by 20-70% above the yields realised with NPK alone. Hence, the application of micronutrients alongside macronutrients appears critical for increasing rice yields in SSA.

In SSA, nutrient application through foliar spray is occasionally performed among rice farmers. However, the efficiency of such foliar sprays and their cost-effectiveness in rice production are not well understood. Therefore, there is need to assess the efficiency and economics of the different foliar nutrient products available on the market in rural Africa. If the foliar nutrient sprays are proven to be effective in terms of productivity and economics, foliar application could then be included as a Good Agronomic Practices (GAP) for the region. Due to targeted application, use of foliar fertilizers could reduce the total amount of nutrients required to meet crop demand by reducing nutrient loss to the environment. However, whereas foliar application holds a strong promise, comparative data on efficiency and effectiveness of soil *vs* foliar-applied fertilizers are limited, and where available, inconclusive (Dimkpa and Bindraban, 2016; Joy et al., 2015).

The efficiency of soil and foliar applied fertilizers could differ based on the rice growing environments (RGEs): Irrigated lowlands (IL) provide growth conditions devoid of water deficits; in rainfed lowlands (RL), soil water deficits can occur occasionally (e.g. Rodenburg et al., 2014); while in rainfed uplands (RU), there is frequent water deficits. Based on these scenarios, we hypothesize that the efficiency of the micronutrients could vary among different RGEs.

The objectives of this study were to: (1) understand the efficiency of different combinations of soil-, foliar- and soil+foliar- applied macro and micronutrients in the three dominant rice growing environments in Africa (IL, RL and RU); and (2) analyze the cost effectiveness of soil and foliar nutrient applications in rice, and with that generate local recommendations to rice farmers on the use of such products.

2. Materials and Method

2.1. Location of experiments

Thirty experiments were conducted in farmers' fields in key rice growing areas in Tanzania in 2015 and 2016 with 10 different fields per year and RGE. For IL and RL, the experimental fields were in the Kilombero valley, roughly between 7° 47' S – 36° 54' E and 8° 60' S – 36° 30' E. For the RU, the experimental fields were in Matombo village near Morogoro, roughly between 7° 20' S – 37° 47' E and 7° 30' S – 37° 46' E. In 2016, two additional farmers were included for the IL and RU rice growing environments.

2.2. Soil and rainfall data

Soil samples from the top 0-20 cm soil layer of the entire experimental field were collected before the start of the experiments and analyzed for texture, and levels of macro- and micro nutrients, to determine the soils' suitability for rice cultivation (Fairhurst et al., 2007). The soil analysis was done by the Crop Nutrition Laboratory Services (CROPNUTS), based in Nairobi Kenya, and ISO 17025 accredited. The analytical methods [Potentiometric (soil:water 1:2) for soil pH and EC; Atomic emission spectrometry - Mehlich 3 for K, secondary and micronutrients; Colorimetric (sodium bicarbonate extractant) for Olsen-P; Colorimetric (UV-Vis) Kjeldahl digestion for N; Colorimetric (Walkley and Black method) for C; and Hydrometer method for soil texture] for soil samples were as previously described (Pansu and Gautheyrou, 2007; Ranst et al., 1999; Senthilkumar et al., 2018). The mean soil texture composition in IL and RU was 58-65% sand, 23-28% clay and 12-14% silt; hence, the soils are classified as 'sandy clay loam'. In RL, the texture was 68% sand, 14% clay and 18% silt; hence, the soils are classified as 'sandy loam', as per the USDA soil texture calculator. The soil taxonomy order of most experimental fields falls under Inceptisols or Entisols (Kalala et al., 2017; Msanya et al., 2004). Rainfall data from Delta-T WS-GP1 automatic weather stations were collected from Ifakara (20-40 km away from fields) and Morogoro (30 km away from fields) in 2015. In 2016, individual weather stations were installed within 5 km radius of the on-farm experiments in each IL, RL and RU rice growing environments. The quantity and distribution of monthly cumulative rainfall varied between the two years of the experimental period (Figure 1). In 2015, the rainfall started in all three RGEs in the month of January and continued until the completion of the cropping season, up to July (Figure 1). The rainfall received during this period was 562, 832, 626 mm in IL, RL and RU, respectively. In 2016, the rainfall started in all RGEs only after February 2016 and peaked in the month of April; limited rainfall occurred thereafter. The rainfall was 527, 423, 563 mm in IL, RL and RU, respectively; this was lower and more concentrated in one month (April), compared to 2015. Notably, this variation in rainfall amount and pattern influenced both the execution of foliar application and the results of the experiments in the RL and RU rice growing environments.

2.3. Experimental design and field selection

Yield and economic performance of the soil and foliar fertilizers were compared under two levels of NPK in a RCBD considering each farmers' field as a replication (10-12 numbers). The foliar products were evaluated without NPK (T2 to T6) and with NPK (T9 to T13) applied to the soil (as N:P:K @ 80:17.5:33.2 kg ha^{-1}) (Table 1). All soil applied macro and micronutrient rates were computed based on individual nutrient requirements for rice reported in the literature (Fageria et al., 2002; Pooniya et al., 2012; Wang et al., 2009; Wei et al., 2006) and based on expert knowledge according to standard operating procedure at the author's institution, AfricaRice. The quantity of individual macro, secondary, and micronutrients added per treatment per hectare is presented in Table S1.

All foliar applications were carried out in the morning, before 10 am, or in the evening, after 3 pm, to avoid leaf burning. Two reference treatments were included in the experiment. 1) Control (T1) – no application of any fertilizer, and 2) NPK only, applied via soil at locally recommended rate (T7). The soil applied micronutrient treatment (T8) comprised of Zn-B-Mg-S application at the rate of 3-2-7.5-10 kg ha^{-1}, along with NPK. Based on the results of 2015 studies, one additional treatment (T8b) was included in 2016. Treatment T8b comprised of Zn-B-Mg-S at the same rate as T8, but without NPK. This treatment was included to test whether Zn-B-Mg-S in the absence of NPK would have any effect on yield.

To avoid heterogeneity of crop management by the farmers, all the participating farmers followed the same crop management in all treatment plots. These crop management practices included bunding and leveling each plot, hand weeding at 20 and 40 days after sowing (DAS) or transplanting (DAT), no manure application, scaring of birds, and use of cv. SARO5 (120-d duration) for IL and RL and NERICA-1 (100-d duration, which is derived from hybridization of *O. sativa* and *O. glaberrima*) for RU. The researchers supplied certified seeds to the farmers. In IL, all farmers transplanted 21-d old seedlings at 20×20 cm spacing. The 80:17.5:33.2 kg ha^{-1} of N:P:K was applied in three splits as follows: a basal dose of 40:17.5:16.6 kg ha^{-1} of N:P:K applied within 0-4 DAT; 1st top-dressing of only N at 20 kg ha^{-1} applied between 36-40 DAT, and the 2nd top-dressing of 20:16.6 kg ha^{-1} of N:K applied between 54-57 DAT. In the case of RL and RU, all farmers dibbled 3-4 seeds per hill at a spacing of 20×20 cm and 20×12.5 cm, respectively. The NPK split in RL was same as in IL but applied on 0-4, 36-40, 54-57 DAS, respectively. In RU, the quantity of NPK was the same; however, the three splits were applied on 0-4, 23-27 and 33-37 DAS, as farmers used the variety NERICA-1. Pest and disease management practices were undertaken by the farmers, as and when required. All treatments were implemented under the supervision of research staff. The plot size was 20 m^2 (4 × 5 m). Each treatment plot had a buffer zone with rice of at least 2m all around. The gross field size ranged from 800 to 1000 m^2, based on the length and width of the field.

2.4. Foliar fertilizer product description

Five locally available foliar products (F1 to F5) were identified for testing at the rate recommended by the manufactures. The commercial name and spray recommendations of the foliar products for the 20m^2 treatment area were 1) Yara Vita Travel Bz (F1) comprising of a wettable powder formulation of N, P, K and micronutrients for a one-time spray by dissolving 8 g in 0.8 L of water; 2) Poly-feed starter & finisher (F2) comprising of ethylenediamine tetraacetic acid (EDTA)-chelated micronutrients as a two-times starter and one-time finisher product sprayed by dissolving 1g in 2 L of water; 3) OSA Rice (F3) containing Si as Orthosilicic acid 0.4% as a three-times spray by dissolving 3ml in 1.5 L of water; 4) Omex foliar feed (F4) which contains EDTA-chelated N, P, K and micronutrients as an emulsion to be sprayed twice, by dissolving 2ml in 2 L of water; and 5) Booster (F5) which contains liquid formulation of N and traces of micronutrients– three-times spray by dissolving 5ml in 1 L of water.

2.5. Field data collection and analysis

Grain yield data and corresponding moisture content (MC) were collected from 12 m^2 (3×4m) harvest area within each treatment area of 20 m^2 (4×5m). Tillers m^{-2}, average plant height (cm), and panicles m^{-2}, were collected from two 1 m^2 areas in each plot and averaged in both years. In 2016, harvest index (HI), grains panicle^{-1} and spikelet fertility (%) were additionally quantified from 12 randomly selected hills outside of the harvest area. Leaf greenness rating (LGR) was measured using a hand-held SPAD meter before each foliar spray (3 times during the cropping season). Readings of LGR of the uppermost leaves was measured near the top, middle and base of the leaf on five different hills per treatment. To determine the profitability of the micronutrients, the quantities and costs of both soil and foliar applied nutrients along with cost of labour to apply or spray the nutrients per unit area were quantified. The selling price of paddy was fixed at USD 400 t^{-1}, considering 2015-2016 prices. The Benefit:Cost (B:C) ratio was calculated by dividing the value of additional yield by the cost of applying the macro and micronutrients for a given treatment.

Data were analyzed using the linear mixed model. For each parameter, we considered treatment as fixed and replication as a random effect. Least-square means (LS-Means) of treatment and associated standard errors derived from the linear mixed model were computed. A generalized linear mixed model (McCullagh and Nelder, 1989) was used under the assumption of a Poisson distribution for analyses of the tiller number and the number of grains per panicles, and under a binomial distribution for the harvest index, the leaf greenness rating, and the spikelet fertility. For parameters for which there was a significant effect ($p<0.01$ or $p<0.05$), the models were followed by a comparison of means using Dunnett's method to compare each treatment with T1 and T7, respectively used as controls. Analyses were performed in R, Version 4.0.0 (R Development Core Team, 2020) using the lmerTest package (Kuznetsova et al., 2017) for the linear mixed models, the MASS package (Venables and Ripley, 2002) for the generalized linear mixed models, the emmeans package (Russell, L., 2020) for the LS-Means estimation and Dunnett multiple comparisons of means.

3. Results

3.1. Soil fertility

The soil fertility status of the experimental fields is presented in Table 2. When compared with the critical levels below which nutrient deficiency for individual nutrients occurs for rice production (Fairhurst et al., 2007), N was the most limiting among the macro nutrients as 95 to 100% of the fields had N contents below the critical level of < 0.2%. P was limiting in 60, 82, 50% of the RL, IL and RU fields, respectively, being below the critical level of < 5 ppm for rice in these field. K was below the critical level of < 58.5 ppm in 30% of RL, in 36% of IL, and only in 5% of RU. The secondary nutrients, Ca and Mg, were limiting in 40 and 65% of the fields respectively in RL, but not in IL and RU. Similarly, S was limiting in 40% of RL, 32% of RU, and 9% of the IL fields. Among the micronutrients, B was the most limiting across the RGE, as 100% of RL and IL fields, and 68% of the RU field, had B contents below the critical level of < 0.5 ppm. Mn was below the critical level of < 20 ppm, only in 5% of the fields in RL. The other micronutrients such as Cu and Zn were above the critical levels of < 0.3 ppm and < 0.6 ppm, respectively, in all three RGEs.

3.2. Effect of rainfall on the treatment

With good rainfall in 2015, all foliar applications were administered in the three RGEs as planned. However, in 2016, the 2nd and 3rd foliar applications in RL, and the 2nd foliar application in 2016 were not administered as the crop showed severe water stress symptoms such as rolled leaves. This was to prevent aggravating the water stress and leaf scorching, as observed in RU after the 3rd spray. The water stress in RL in 2016, and in RU in both years, negatively affected the efficiency of the foliar products.

3.3. Effect of foliar and soil applied micronutrients without NPK application

3.3.1. Irrigated Lowland

Under IL conditions, the overall grain yield ranged from 3.09 to 4.61 t ha^{-1} in 2015 and 3.73 to 5.41 t ha^{-1} in 2016 (Table 3). Without NPK application, foliar products F2, F3, F4 and F5 in 2015, and foliar products F2, F3 and F4 in 2016, increased grain yield over the control (T1) (Table 3 and Table 4). There was no treatment effect on tiller number, panicle number and 1000-grain wt. However, in 2015, the SPAD values were higher for F5 at 77 DAS and for F4 at 103 DAS, relative to the control. Similarly, in 2016, higher SPAD values were observed for F3, F4 and F5 at 70 and 95 DAS, and for all foliar products at 108 DAS, compared to the control (Table S2).

3.3.2. Rainfed Lowland

Under RL conditions, the overall grain yield ranged from 2.58 to 6.83 t ha^{-1}, and from 0.77 to 1.72 t ha^{-1}, in 2015 and 2016, respectively (Table 5). Without NPK application, no foliar product was effective in enhancing plant performance in both years, compared to the control. Similar to IL, the sole application of soil applied micronutrients was ineffective in increasing grain yield, in 2016. The SPAD values were higher for F1, F2 and F5 at 80DAS, and for F4 at 106 DAS, in 2015 (Table S3).

3.3.3. Rainfed upland

Under RU condition, the overall grain yield ranged from 1.31 to 2.72 t ha^{-1} and from 0.24 to 0.91 t ha^{-1} in 2015 and 2016, respectively (Table 6). Similar to the RL, both the foliar products and the sole application of Zn-B-Mg-S were ineffective in increasing grain yield under RU conditions. However, the SPAD values were higher for all the five foliar products at 73DAS in 2015, and 3 out of 5 foliar products at 96DAS, in 2016 than control (Table S3). The application of only Zn-B-Mg-S also increased the SPAD values in 2016.

3.4. Effect of foliar and soil applied micronutrients with NPK application

3.4.1. Irrigated Lowland

Under IL conditions and with NPK application, all treatments increased yield in both years, compared to the control, and application of NPK alone increased the yield by 0.98 and 1.08 t ha^{-1} in 2015 and 2016, respectively. This increase in yield was supported by increases in the yield attributing characteristics such as tiller number, plant height and panicle number, for most treatments (Table 3). SPAD values were always higher for NPK and NPK+ treatments, compared to the control, in both years (Table S2).

Compared to NPK alone, in 3 out of 10 instances the foliar products increased yield across years (Table 3). The corresponding increase in plant height and SPAD values was observed in 2016. Application of NPK+Zn-B-Mg-S increased the yield by 0.54 and 0.60 t ha^{-1} in 2015 and 2016, respectively. Compared to NPK alone, the SPAD values were always higher for NPK+Zn-B-Mg-S across years, except the measurement at 103DAS in 2015 (Table S2). The yield increase with soil applied micronutrients was supported by the corresponding increase in plant height, tiller number, HI in 2016 as presented in Table 3, and in Table S2, for SPAD values in both years.

3.*4.2. Rainfed Lowland*

Under RL conditions and with NPK application, all treatments increased yields over the control in 2015, and application of NPK alone increased the yield from 2.69 t ha^{-1} (in control) to 4.96 t ha^{-1}. The yield increase is supported by higher tiller number, plant height, panicle number and 1000-grain weight in all treatments, when compared to control (Table 5). In 2016, the experiments were affected by terminal drought; hence, yield increases ($p<0.05$) were observed only in 3 out of 7 NPK applied treatments, compared to the control. However, higher number of tillers in all NPK applied plots over control was observed. Higher panicle number in 5 out of 7, and higher grain number per panicle in 3 out of 7 NPK applied plots, were observed. Further, HI and fertility percentage were lower in all NPK applied plots, compared to control in 2016. The SPAD values were always higher for NPK applied plots, compared to the control, in both years (Table S3).

Application of NPK+Zn-B-Mg-S increased the yield by 1.87 t ha^{-1} in 2015, compared to NPK alone. Foliar products F1 and F3 also increased the yield by 0.99 to 1.07 t ha^{-1}, in 2015. This increase in yield was associated with higher plant height, 1000-grain wt and high SPAD values at 36 and 106 DAS for NPK+Zn-B-Mg-S. However, only higher grain weight supported increased yield, in the case of F1. In 2016, no yield increase was observed for any of the NPK + Zn-B-Mg-S or foliar products, when compared to the NPK alone. This was because the experiment was affected by terminal drought. There was no difference in the SPAD values for the NPK + foliar treatments, compared to NPK alone (Table S4).

3.4.3. Rainfed upland

Under RU conditions and with NPK application, the grain yield ranged from 2.13 to 2.72 t ha^{-1} and from 0.58 to 0.86 t ha^{-1} in 2015 and 2016, respectively (Table 6). All treatments except F5 increased the grain yield in 2015, while the application of NPK alone increased the yield by 0.79 t ha^{-1}, compared to the control (1.59 t ha^{-1}). The grain yield increase was concomitant with a higher tiller number, plant height and panicle number, compared to the control (Table 6). In 2016, all treatments except F4 increased yield, compared to the control. Significantly higher tiller numbers, plant heights, panicle numbers, HIs, number of grains per panicle, and spikelet fertility percentages contributed to the yield increases in most of the treatments.

There was no significant grain yield increase with any of the NPK + foliar, NPK + soil applied micronutrient in both years, compared to NPK alone (data not presented). However, increased tiller numbers in 2016 and higher SPAD values in both years were observed for NPK+Zn-B-Mg-S; increased plant heights for NPK+F3 and NPK+F5 in 2016 were observed, compared to NPK alone (Table S4). Higher SPAD values were observed in four of the foliar products at 73 DAS in 2015, and in all five at 56 DAS in 2016, compared to NPK alone. However, there were no difference in SPAD values observed between NPK and NPK+foliar products at 96 DAS, as the treatments were affected by terminal drought in 2016 (Table S4).

3.5. Benefit:Cost analysis of foliar and soil applied micronutrients

A Benefit:Cost (B:C) analysis was conducted to estimate the profitability of applying the foliar and/or soil applied macro and micronutrients in rice. In IL, without NPK the incremental B:C ratio was always positive and higher than 2 for the five foliar products, and for the sole application of Zn-B-Mg-S, compared to control. The highest B:C ratio was for F2 and F4 at 9.0 and 7.9 respectively in 2016 (Figure 3a). With NPK, the B:C ratios for all foliar and the soil applied micronutrients were positive, ranging from 1 to 6.6, across the two years, compared to NPK application alone (Figure 3b). In RL, without NPK, only four foliar registered a B:C ratio of above 2 in 2015. In 2016, all treatments registered B:C ratios below 1 (Figure 3c), compared to control. With NPK, NPK+Zn-B-Mg-S registered a very high B:C ratio of 13.9 in 2015. Similarly, all five foliar products registered high B:C ratios ranging from 4 to 10.7, compared to NPK alone. However, in 2016, the B:C ratios were mixed, with mostly negative values. This was as a result of the experiments being affected by drought (Figure 3d). In RU, the B:C ratios were also mixed for both ‘without NPK’ and ‘with NPK’ treatments, in both years (Figure 3e and 3f).

4. Discussion

The soil fertility status of the experimental plots, prior to the experiment, were in agreement with previous reports on macro nutrient status in SSA (Saito et al., 2019) and the micronutrient status in Tanzania (Senthilkumar et al., 2018). The observed deficiencies for many essential soil nutrients confirm that fertiliser application would indeed be necessary in the majority of the farmers' fields across rice growing environments in SSA to increase and sustain rice yields.

4.1. Effect of foliar application on yield

Foliar applications of both macro and micronutrients in rice is a common practice in Asian countries (Hussain et al., 2012; Voogt et al., 2013), and significantly increase leaf greenness rating, the photosynthetic rate and yield of different crops, including rice and sorghum (Boldrin et al., 2013; He et al., 2013; Voogt et al., 2013). Furthermore, reports indicate that foliar application of Zn, B, and Cu incidentally decreased disease incidence in rice (Liew et al., 2012). In the current study, foliar application increased the yield with or without the application of NPK under irrigated lowlands in both years. Under rainfed lowlands, foliar products increased the yield only in 2015 with sufficient rainfall and with application of NPK application. It was not effective in the drought-hit rainfed uplands and the rainfed lowland in 2016. This implies that, in order to be effective, foliar application of nutrients needs a drought-stress free condition, as also previously indicated (Hu et al., 2008).

4.2. Effect of micronutrient on yield under varying soil properties and moisture status

In the current study, sole soil-applied micronutrients did not increase yield in 2016. However, the SPAD values were always higher with sole soil-applied micronutrients throughout the cropping season, compared to the control. Previous reports indicate individual or combinations of secondary and micronutrients together with NPK increased cereal crop yields in many countries, including Tanzania (Kihara et al., 2017, 2016; Njoroge et al., 2018; Shivay, et al., 2008; Wortmann et al., 2019). In the current study, application of these nutrients (namely, Zn-B-Mg-S) without NPK was not effective in enhancing rice yield in any of the RGEs (Figure 2). In this regard, a positive interaction of NPK and secondary and micronutrients leading to increased rice yield has been noted (Dash et al., 2015). The general soil fertility status of the experimental fields showed that N and P were the most limiting nutrients in Tanzania (Table 2), in agreement with the observation of Kihara et al. (2016) and many other studies (e.g. Dash et al., 2015; Nabahungu et al., 2020; Tsujimoto et al., 2017). Notably, these nutrients represent the general yield limiting factors of rice soils in SSA (Saito et al., 2019). Hence, application of macronutrients (NPK) is a likely pre-requisite for harnessing the benefits of applying secondary and micronutrients in rice cropping systems.

Soil water deficit is known to impact the growth and yield of cereal crops, while micronutrients are known to alleviate such stress, as shown in sorghum and wheat (Dimkpa et al., 2020a, 2019). However, application of micronutrients with NPK was effective in increasing rice yield in this study only when plants did not experience water deficit, as in 2015 in RL, and both years in IL. This effect may be due to the severity of the drought stress, as noted by Dimkpa et al. (2020b), which will be even more significant for rice, given its water requirements. In the IL, which had no soil water deficit due to supplementary irrigation, yield increased by 0.5 to 0.6 t ha^{-1} across the years for Zn-B-Mg-S application, compared to NPK alone (Figure 2b). In the RL, without water deficit due to sufficient rainfall in 2015, yield increased by 1.8 t ha^{-1}. However, this yield advantage was not realized due to the soil water deficit in 2016 (Figure 1 & Figure 2d). A higher yield advantage was achieved in RL, compared to IL in 2015 for the same amount of Zn-B-Mg-S with NPK application. This could be due to the low levels of secondary nutrients present in the RL soils, compared to the IL soils. Mg and S were below the critical levels in 65 and 40% of the RL soils, compared to only 5 and 9% of the IL soils (Table 2). These levels of secondary and micronutrients that are below the critical threshold are in agreement with findings by Wortmann et al. (2019). Hence, when the limiting secondary nutrients (Mg and S) were applied, the RL yields outperformed the IL, particularly under ‘no soil water deficit’ conditions. In RU, the effect of micronutrients was masked by severe soil water deficit conditions. Taken together, our data show that the application of micronutrients together with NPK was effective in increasing the yield in IL; was dependent on rainfall in RL, and was ineffective in RU, as the latter is prone to frequent drought.

Further, the mean pH of the IL was lower than those of other RGEs, with the RU being the least acidic (Table 2). The more acidic condition would allow for greater dissolution and potentially higher bioavailability of many of the nutrients, especially P, K, and the secondary and micronutrients. However, the higher mean clay content in the IL soils could counteract the bioavailability of the solubilized nutrients due to a higher sorption capacity. This contrasts with the RL environment which combined low pH and clay content, implying a potential for greater nutrient bioavailability than the IL. It is noteworthy to mention that the specific role of soil chemistry was not accessed in this study. Nevertheless, it could have contributed to the different agronomic effects observed in the RGEs for the soil-applied treatments, especially during the first year when drought was not a complicating external factor. Under the water deficit condition experienced in the RL and RU conditions in 2016, the uptake of most nutrients from the soil would be significantly affected (Dimkpa et al., 2020b, 2020a). With respect to the foliar applications, the fact that except for B, the nutrients involved in the foliar treatments were not deficient in the soil could have affected the efficacy of these treatments. The plants would take up these nutrients from the soil where the soil chemistry better supports their bioavailability, as in the IL and RL. This negates the supposed benefit of targeted fertilization provided by foliar fertilization. This assumption is supported by the fact that both soil and foliar treatments improved yield significantly.

Evidently, determining the micronutrient contents of rice grains was not a focus of the current study, but would certainly deserve of attention. Studies indicate that Zn and Fe were more efficiently delivered to the grain of rice plants when foliar applied than when soil applied (Aciksoz et al., 2011; Joy et al., 2015). Improving the grain content of key micronutrients lacking both in the soil and in human diets, such as Zn and Fe, is important for combating human micronutrient deficiency prevalent in many parts of the globe (Smith and Myers, 2018).

4.3. Economic benefits of using foliar and soil micronutrients

The incremental B:C analysis showed that the application of both foliar and soil micronutrients is profitable when there is adequate soil moisture either through irrigation or rainfall. Hence, this can be added to the GAP basket for the IL and favorable RL rice growing environments.

For drought prone RL and RU RGEs, farmers may not achieve profitability and hence foliar or soil-applied micronutrients should not be recommended as a standard practice to the GAP basket. However, this may depend on specific soil fertility conditions; foliar or soil application of micronutrients have been demonstrated in field studies to enhance the productivity of cereal crops when deficient in the soil, due likely to increasing water use efficiency (e.g. Ashraf et al., 2014; Bagci et al., 2007; Karim et al., 2012). Notably, the soils used in the present study were not completely lacking these nutrients, except for B. Nevertheless, there could be residual effect of soil applied micronutrients in the subsequent crop cycles, contingent upon adequate rainfall.

5. Conclusions

Our objective in this study was to analyse the productivity and profitability of different combinations of soil-, foliar- and soil+foliar- applied macro and micronutrients in representatives of the three dominant rice growing environments (RGEs) of Africa. The productivity and profitability of foliar and soil applied micronutrients in rice varied across the three growing environments in Tanzania. Foliar application was found to be effective in drought-stress free conditions in IL and RL. Similarly, soil applied micronutrients (Zn-B-Mg-S) together with NPK significantly increased the yields in IL and RL in absence of drought-stress. However, the effectiveness of these fertilisers is not clear in RU, as this RGE experienced soil water deficit in both study years. The sole application of micronutrients (namely, Zn-B-Mg-S) in the absence of NPK was not effective in any of the RGEs. This suggests that the application of macronutrients is a likely prerequisite to maximizing the benefits of applying micronutrients to increase rice yields in Tanzania. Both foliar and soil applied micronutrients can be profitable in drought-stress free IL conditions, and can be significantly influenced by the soil water status in RL and RU rice growing environments. However, there could be a residual effect of applied soil micronutrients in RL and RU the following season, if adequate rainfall occurs. Analyzing the effect of individual micronutrients through micronutrient omission trails in IL could help to identify the most limiting nutrient in SSA to further tailor fertiliser compositions.

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Table 1: Treatments description for the on-farm trails under three rice growing environments for 2015 and 2016 in Tanzania.

Treatment No	Block	Treatment details	Treatment description	Selected fertilizer and foliar product for the treatment
T1	No NPK	C (Reference Treatment 1)	Control - No application of either soil or foliar nutrient	-
T2		F1	Only foliar nutrient, no soil application	F1=Yara vita Tracel Bz (YVT)
T3		F2	,,	F2= Poly-feed starter & finisher (PFS)
T4		F3	,,	F3= OSA Rice (OSA)
T5		F4	,,	F4= Omex foliar feed (OMF)
T6		F5	,,	F5= Booster (BOS)
Tx1		ZnBMgS	Only ZnBMgS – same rate as in T8	Granular Zn, Granular B and MgSO4 mixed with sand and soil applied as basal
T7	NPK	NPK (Reference Treatment 2)	N:P:K @ 80:17.5:33.2 kg ha^{-1}	NPK applied as urea, DAP and MoP
T8		NPK+ZnBMgS	N:P:K @ 80:17.5:33.2 kg ha^{-1} + Zn:B:Mg:S @ 3:2:7.5:10 kg ha^{-1}	NPK + Granular Zn (35% Zn), Granular B (14.5% B) and MgSO4 mixed with sand and applied as basal
T9		NPK+F1	N:P:K @ 80:17.5:33.2 kg ha^{-1} + F1	F1=Yara vita Tracel Bz (YVT)
T10		NPK+F2	N:P:K @ 80:17.5:33.2 kg ha^{-1} + F2	F2= Poly-feed starter & finisher (PFS)
T11		NPK+F3	N:P:K @ 80:17.5:33.2 kg ha^{-1} + F3	F3= OSA Rice (OSA)
T12		NPK+F4	N:P:K @ 80:17.5:33.2 kg ha^{-1} + F4	F4= Omex foliar feed (OMF)
T13		NPK+F5	N:P:K @ 80:17.5:33.2 kg ha^{-1} + F5	F5= Booster (BOS)
Tx2		NPK+ZnBMgSCu	N:P:K @ 80:17.5:33.2 kg ha^{-1} + Zn:B:Mg:S:Cu @ 0.6:0.35:7.5:10:0.3 kg ha^{-1}	ZnBCu applied as Dry Dispersible Powder (DDP) mixed with DAP; MgSO4 mixed with sand and applied as basal.
Tx3		NPK+MgS+F1	N:P:K @ 80:17.5:33.2 kg ha^{-1} + F1+ Mg:S @ 7.5:10 kg ha^{-1}	MgSO4 mixed with sand and applied as basal; F1=Yara vita Tracel Bz (YVT)

Treatments Tx1, Tx2 and Tx3 are additionally included in 2016 (with gray shade); DAP = Di-Ammonium Phosphate; MoP = Muriate of Potash.

Table 2. Soil chemical properties of the experimental fields in three rice growing environments of Tanzania from sampling the 0-20 cm depth in 2015 and 2016. The critical soil nutrient levels for rice cultivation obtained from Fairhurst et al., (2007).

Parameter	Unit	Critical soil	**Irrigated lowland (n=22)**				**Rainfed lowland (n=20)**				**Rainfed upland (n=22)**			
			Min	Max	Mean	% samples	Min	Max	Mean	% samples	Min	Max	Mean	% samples
pH	-	-	5.1	6.1	5.6	-	5.0	7.1	5.7	-	5.8	7.3	6.4	-
EC (S)	uS/cm	-	38.0	157.0	88.8	-	30.0	126.0	63.8	-	27.0	205.0	92.9	-
N	%	< 0.2	0.1	0.2	0.2	**95**	0.0	0.2	0.1	**100**	0.1	0.2	0.1	**100**
P(Olsen)	ppm	< 5	0.5	10.0	4.2	82	1.9	8.9	5.0	**60**	0.3	20.0	5.1	**50**
K	ppm	< 58.5	34.0	147.0	69.4	**36**	34.8	402.0	96.4	**30**	56.7	271.0	135.4	**5**
Ca	ppm	< 200	511.0	1900.0	921.1	**0**	113.0	2160.0	585.4	**40**	940.0	3770.0	1848.1	**0**
Mg	ppm	< 120	96.4	638.0	369.4	**5**	24.1	636.0	145.7	**65**	189.0	1110.0	528.0	**0**
Mn	ppm	< 12-20	24.8	154.0	57.5	**0**	18.3	115.0	48.8	**5**	62.7	567.0	242.0	**0**
S	ppm	< 5-9	5.2	49.8	19.3	**9**	5.8	15.1	9.5	**40**	3.6	18.2	9.7	**32**
Cu	ppm	< 0.1-0.3	1.0	7.6	4.4	**0**	0.8	4.7	2.2	**0**	1.4	7.2	3.3	**0**
B	ppm	< 0.5	0.0	0.2	0.1	**100**	0.0	0.3	0.1	**100**	0.2	1.4	0.5	**68**
Al	ppm	-	355.0	1140.0	962.4	-	327.0	1050.0	592.2	-	653.0	970.0	800.9	-
Zn	ppm	< 0.6	1.9	22.6	6.4	**0**	1.0	13.8	4.7	**0**	1.4	22.6	8.0	**0**
Fe	ppm	< 2-5	289.0	508.0	406.7	**0**	90.9	357.0	200.7	**0**	85.1	189.0	128.5	**0**
Na	ppm	-	21.7	88.9	52.2	-	14.1	74.2	40.8	-	13.5	80.0	38.2	-
C.E.C	meq/100	-	4.7	19.5	11.9	-	1.7	22.0	6.5	-	8.2	29.7	16.3	-
%Silt	%	-	7.6	23.8	13.6	-	6.3	37.7	17.9	-	8.0	16.3	11.6	-
%Sand	%	-	43.8	74.1	58.1	-	25.9	87.0	68.0	-	41.0	82.3	65.2	-
%Clay	%	-	10.7	35.2	28.3	-	2.4	36.4	14.0	-	9.6	46.6	23.3	-
C	%	-	1.5	4.4	2.1	-	0.4	2.3	1.2	-	1.2	2.9	1.8	-

Table 3. Rice yield and yield attributes in the Irrigated Lowland (IL) significance compared to 'Control' and 'NPK' for 2015 and 2106 in Tanzania.

IL	**2015**					**2016**							
Treatment*	**Yield (t ha^{-1})**	**Tiller m^{-2}**	**Plant height (cm)**	**Panicle m^{-2}**	**1000 grain wt (g)**	**Yield (t ha^{-1})**	**Tiller m^{-2}**	**Plant height (cm)**	**Panicle m^{-2}**	**Harvest Index**	**Grains panicle^{-1}**	**Fertility (%)**	**1000 grain wt (g)**
a) Significance *vs* Control													
C	3.09	173	93.0	160	29.2	3.73	189	97.8	177	0.48	112	79.0	32.3
F1	3.29	181	92.9	170	29.3	4.02	187	98.8	176	0.48	110	80.2	32.4
F2	3.34*	174	92.0	163	29.2	4.17*	190	98.5	174	0.49	113	80.6	32.1
F3	3.40*	173	90.9	162	29.2	4.23*	193	100.2	171	0.45	120	79.8	32.0
F4	3.38*	174	88.5	167	29.3	4.32*	186	99.1	173	0.47	114	79.8	31.6
F5	3.50*	183	92.5	175	29.3	4.10	189	96.8	178	0.49	105	80.6	32.0
ZnBMgS						4.01	182	106.9*	172	0.49	118	75.7	32.6
NPK	4.06*	236*	103.0*	216*	29.4	4.81*	202	96.1	195*	0.54*	130	80.7	32.6
NPK+ZnBMgS	4.61*	240*	103.2*	219*	29.7*	5.41*	224*	108.3*	201*	0.60*	126	81.1	32.9
NPK+F1	4.24*	238*	103.4*	224*	29.4	5.26*	215*	105.5*	199*	0.56*	126	80.4	32.7
NPK+F2	4.24*	235*	102.2*	216*	29.4	5.14*	215*	105.8*	205*	0.52*	110	79.1	32.9
NPK+F3	4.21*	230*	101.4*	212*	29.5	5.35*	215*	107.0*	194*	0.58*	131*	80.0	32.6
NPK+F4	4.20*	234*	103.7*	217*	29.5	5.10*	211*	104.9*	192	0.55*	128	77.9	32.9
NPK+F5	4.38*	221*	103.6*	203*	29.5	5.13*	212*	108.4*	199*	0.53*	125	79.1	32.4
NPK+ZnBMgSCu						5.41*	225*	106.2*	212*	0.57*	123	80.3	32.8
NPK+MgS+F1						5.25*	210*	107.9*	203*	0.54*	116	80.0	32.8
LSD	***0.24***	***22.51***	***4.62***	***21.03***	***0.51***	***0.40***	***14.98***	***4.10***	***15.33***	***0.04***	***18.41***	***4.49***	***0.74***
b) Significance *vs* NPK													
NPK	4.06	236	103.0	216	29.4	4.81	202	96.1	195	0.54	129.8	80.7	32.6
NPK+ZnBMgS	4.61**	240	103.2	219	29.7	5.41**	224**	108.3**	201	0.60**	126.5	81.1	32.9
NPK+F1	4.24	238	103.4	224	29.4	5.26**	215	105.5**	199	0.56	126.0	80.4	32.7
NPK+F2	4.24	235	102.2	216	29.4	5.14	215	105.8**	205	0.52	110.4	79.1	32.9
NPK+F3	4.21	230	101.4	212	29.5	5.35**	215	107.0**	194	0.58**	130.7	80.0	32.6
NPK+F4	4.20	234	103.7	217	29.5	5.10	211	104.9**	192	0.55	127.8	77.9	32.9
NPK+F5	4.38**	221	103.6	203	29.5	5.13	212	108.4**	199	0.53	125.2	79.1	32.4
NPK+ZnBMgSCu						5.41**	225**	106.2**	212**	0.57	122.7	80.3	32.8
NPK+MgS+F1						5.25**	210	107.9**	203	0.54	116.2	80.0	32.8
LSD	***0.24***	***22.51***	***4.62***	***21.03***	***0.51***	***0.40***	***14.98***	***4.10***	***15.33***	***0.04***	***18.41***	***4.49***	***0.74***

For treatment details see Table 1; LSD = Least Significant Differences; * Significantly different over 'Control' in section (a); **Significantly different over 'NPK' in section (b).

Table 4. ANOVA for the on-farm trails under three rice growing environments for 2015 and 2016 in Tanzania.

Rice growing environment (RGE)	**Irrigated Lowland (IL)**					**Rainfed Lowland (RL)**					**Rainfed Upland (RU)**				
Year	**2015**					**2015**					**2015**				
Response	**SS**	**MS**	**df**	**F**	**P value**	**SS**	**MS**	**df**	**F**	**P value**	**SS**	**MS**	**df**	**F**	**P value**
Yield (t ha^{-1})	31.5	2.6	12	36.1	0.000	280.9	23.4	12	32.4	0.000	26.2	2.2	12	4.8	0.000
Tiller m^{-2}	108164.1	9013.7	12	14.0	0.000	120800.7	10066.7	12	9.8	0.000	69439.5	5786.6	12	6.4	0.000
Panicle m^{-2}	81284.9	6773.7	12	12.0	0.000	105771.5	8814.3	12	10.3	0.000	45374.7	3781.2	12	3.9	0.000
Plant height (cm)	4309.2	359.1	12	13.2	0.000	12360.1	1030.0	12	29.4	0.000	15450.6	1287.5	12	16.8	0.000
SPAD (1st)	453.5	37.8	12	13.2	0.000	1754.3	146.2	12	45.6	0.000	1093.3	91.1	12	32.8	0.000
SPAD (2nd)	590.9	49.2	12	17.8	0.000	928.7	77.4	12	10.8	0.000	1962.2	163.5	12	59.0	0.000
SPAD (3rd)	675.0	56.3	12	16.4	0.000	921.9	76.8	12	16.7	0.000	2372.0	197.7	12	52.6	0.000
1000 grain wt (g)	2.6	0.2	12	0.7	0.774	92.7	7.7	12	9.3	0.000	11.6	1.0	12	1.0	0.447
Year	**2016**					**2016**					**2016**				
Response	**SS**	**MS**	**df**	**F**	**P value**	**SS**	**MS**	**df**	**F**	**P value**	**SS**	**MS**	**df**	**F**	**P value**
Yield (t ha^{-1})	65.4	4.4	15	17.5	0.000	16.8	1.1	15	2.4	0.004	10.1	0.7	15	6.0	0.000
Tiller m^{-2}	38898.4	2593.2	15	7.5	0.000	219094.1	14606.3	15	13.6	0.000	142740.1	9516.0	15	9.6	0.000
Plant height (cm)	3775.4	251.7	15	9.7	0.000	9116.5	607.8	15	22.7	0.000	4465.0	297.7	15	9.3	0.000
Panicle m^{-2}	35557.1	2370.5	15	6.5	0.000	68874.9	4591.7	15	3.9	0.000	34480.6	2298.7	15	2.2	0.009
SPAD (1st)	1262.2	84.1	15	57.8	0.000	3280.6	218.7	15	58.4	0.000	1856.8	123.8	15	83.7	0.000
SPAD (2nd)	1093.3	72.9	15	130.6	0.000	na	na	na	na	na	na	na	na	na	na

SPAD (3rd)	950.1	63.3	15	57.5	0.000	na	na	na	na	na	6332.1	422.1	15	40.0	0.000
Harvest Index	0.4	0.0	15	8.6	0.000	0.3	0.0	15	5.1	0.000	0.1	0.0	15	1.4	0.170
Grains pPanicle^{-1}	11696.6	779.8	15	1.5	0.113	131992.8	8799.5	15	2.3	0.006	8453.7	563.6	15	9.4	0.000
Fertility %	312.6	20.8	15	0.7	0.810	6957.8	463.9	15	4.7	0.000	2451.2	163.4	15	1.4	0.135
1000 grain wt (g)	26.5	1.8	15	2.1	0.012	49.5	3.3	15	1.0	0.418	57.0	3.8	15	1.2	0.256

na = data not available

Table 5. Rice yield and yield attributes in the Rainfed Lowland (RL) significance compared to ‘Control’ and ‘NPK’ for 2015 and 2016 in Tanzania.

RL	**2015**					**2016**							
Treatment*	**Yield (t ha^{-1})**	**Tiller m^{-2}**	**Plant height (cm)**	**Panicle m^{-2}**	**1000 grain wt (g)**	**Yield (t ha^{-1})**	**Tiller m^{-2}**	**Plant height (cm)**	**Panicle m^{-2}**	**Harvest Index**	**Grains $panicle^{-1}$**	**Fertility (%)**	**1000 grain wt (g)**
a) Significance *vs* Control													
C	2.69	197	84.4	176	29.2	0.99	178	63.3	108	0.36	64.4	58.0	26.4
F1	2.98	195	86.9	176	29.7	1.02	172	61.4	111	0.36	62.8	57.8	27.5
F2	2.81	209	87.7	189	29.5	0.90	175	59.3	101	0.35	62.6	58.1	26.5
F3	2.58	202	82.0	179	29.5	0.92	166	60.0	102	0.34	62.2	51.8	26.3
F4	3.23	198	87.8	180	29.5	0.77	170	60.1	97	0.34	64.1	56.0	26.1
F5	2.98	200	86.0	181	29.5	0.92	191	61.8	108	0.35	73.2	54.2	25.6
ZnBMgS						0.86	177	61.6	108	0.32	63.0	51.6	26.4
NPK	4.96*	258*	102.3*	232*	30.2*	1.53	238*	76.0	146*	0.27	145.6*	46.5	27.0
NPK+ZnBMgS	6.83*	260*	109.7*	242*	32.2*	1.70*	255*	80.8	156*	0.25	125.2*	40.7	26.7
NPK+F1	5.95*	277*	107.0*	251*	31.2*	1.32	240*	74.4	149*	0.26	115.7	39.8	26.2
NPK+F2	5.30*	264*	104.5*	229*	31.0*	1.63*	253*	76.8	154*	0.26	98.3	43.9	27.2
NPK+F3	6.03*	251*	105.4*	232*	30.5*	1.43	232*	74.1	132	0.25	141.5*	40.4	26.3
NPK+F4	5.26*	263*	101.8*	242*	30.8*	1.38	229*	72.8	125	0.27	96.8	44.8	26.6
NPK+F5	5.44*	243*	102.6*	222*	30.6*	1.62*	242*	74.9	154*	0.29	94.3	47.5	27.6
NPK+ZnBMgSCu						1.27	282*	75.2	114	0.23	109.7	40.3	26.4
NPK+MgS+F1						1.72*	243*	77.4	138	0.26	114.9	45.9	27.6

LSD	***0.75***	***28.37***	***5.24***	***25.96***	***0.81***	***0.60***	***28.94***	***4.57***	***30.43***	***0.06***	***54.82***	***8.76***	***1.57***
b) Significance *vs* NPK													
NPK	4.96	258	102.3	232	30.2	1.53	238	76.0	146	0.27	145.6	46.5	27.0
NPK+ZnBMgS	6.83**	260	109.7**	242	32.2**	1.70	255	80.8	156	0.25	125.2	40.7	26.7
NPK+F1	5.95**	277	107.0	251	31.2**	1.32	240	74.4	149	0.26	115.7	39.8	26.2
NPK+F2	5.30	264	104.5	229	31.0	1.63	253	76.8	154	0.26	98.3	43.9	27.2
NPK+F3	6.03**	251	105.4	232	30.5	1.43	232	74.1	132	0.25	141.5	40.4	26.3
NPK+F4	5.26	263	101.8	242	30.8	1.38	229	72.8	125	0.27	96.8	44.8	26.6
NPK+F5	5.44	243	102.6	222	30.6	1.62	242	74.9	154	0.29	94.3	47.5	27.6
NPK+ZnBMgSCu						1.27	282*	75.2	114	0.23	109.7	40.3	26.4
NPK+MgS+F1						1.72	243	77.4	138	0.26	114.9	45.9	27.6
LSD	***0.75***	***28.37***	***5.24***	***25.96***	***0.81***	***0.60***	***28.94***	***4.57***	***30.43***	***0.06***	***54.82***	***8.76***	***1.57***

For treatment details see Table 1; LSD = Least Significant Differences; * Significantly different over 'Control' in section (a); **Significantly different over 'NPK' in section (b).

Table 6. Rice yield and yield attributes in the Rainfed Upland (RU) significance$^{\$}$ compared to 'Control' for 2015 and 2016 in Tanzania.

For treatment details see Table 1; LSD = Least Significant Differences; * Significantly different over ‘Control’. $^{\$}$The significant variables compared to ‘NPK’ is presented in the Table S4 together with SPAD values.

RU	**2015**				**2016**						
Treatment	**Yield (t ha^{-1})**	**Tiller m^{-2}**	**Plant height (cm)**	**Panicle m^{-2}**	**Yield (t ha^{-1})**	**Tiller m^{-2}**	**Plant height (cm)**	**Panicle m^{-2}**	**Harvest Index**	**Grains panicle^{-1}**	**Fertility (%)**
C	*1.59*	*226*	*80.2*	*206*	*0.34*	*215*	*49.4*	*111*	*0.18*	*22.3*	*35.4*
F1	1.31	217	77.0	185	0.25	200	48.4	105	0.18	17.7	40.6
F2	1.70	246	83.9	217	0.27	192	48.6	107	0.22	22.0	44.0
F3	1.66	238	88.3*	211	0.30	207	48.2	116	0.21	22.3	42.0
F4	1.80	219	87.7	202	0.25	193	49.4	122	0.19	19.7	40.8
F5	1.68	232	83.9	208	0.24	182	47.7	133	0.22	20.5	47.8*
ZnBMgS					0.24	165	48.1	134	0.22	21.3	45.1*
NPK	2.38*	265*	101.7*	238*	0.76*	231	56.3*	134	0.23*	34.9*	44.3
NPK+ZnBMgS	2.64*	287*	108.3*	251*	0.81*	260*	57.8*	141*	0.26*	35.7*	52.6*
NPK+F1	2.40*	271*	101.3*	232	0.73*	245*	57.8*	140*	0.24*	36.9*	47.6*
NPK+F2	2.61*	264*	106.0*	234*	0.68*	237	57.6*	126	0.22	35.7*	45.8*
NPK+F3	2.72*	265*	103.7*	234*	0.86*	252*	61.7*	143*	0.24*	35.8*	46.4*
NPK+F4	2.23*	267*	103.7*	234*	0.58	235	57.9*	139	0.21	33.1*	46.7*
NPK+F5	2.13	285*	106.2*	245*	0.84*	257*	62.5*	153*	0.23	34.5*	47.2*
NPK+ZnBMgSCu					0.52	229	56.9*	146*	0.21	29.8*	43.0
NPK+MgS+F1					0.91*	270*	59.8*	150*	0.24*	37.9*	49.4*
LSD	***0.6***	***26.5***	***7.8***	***27.6***	***0.3***	***27.8***	***5.0***	***28.5***	***0.05***	***6.9***	***9.4***

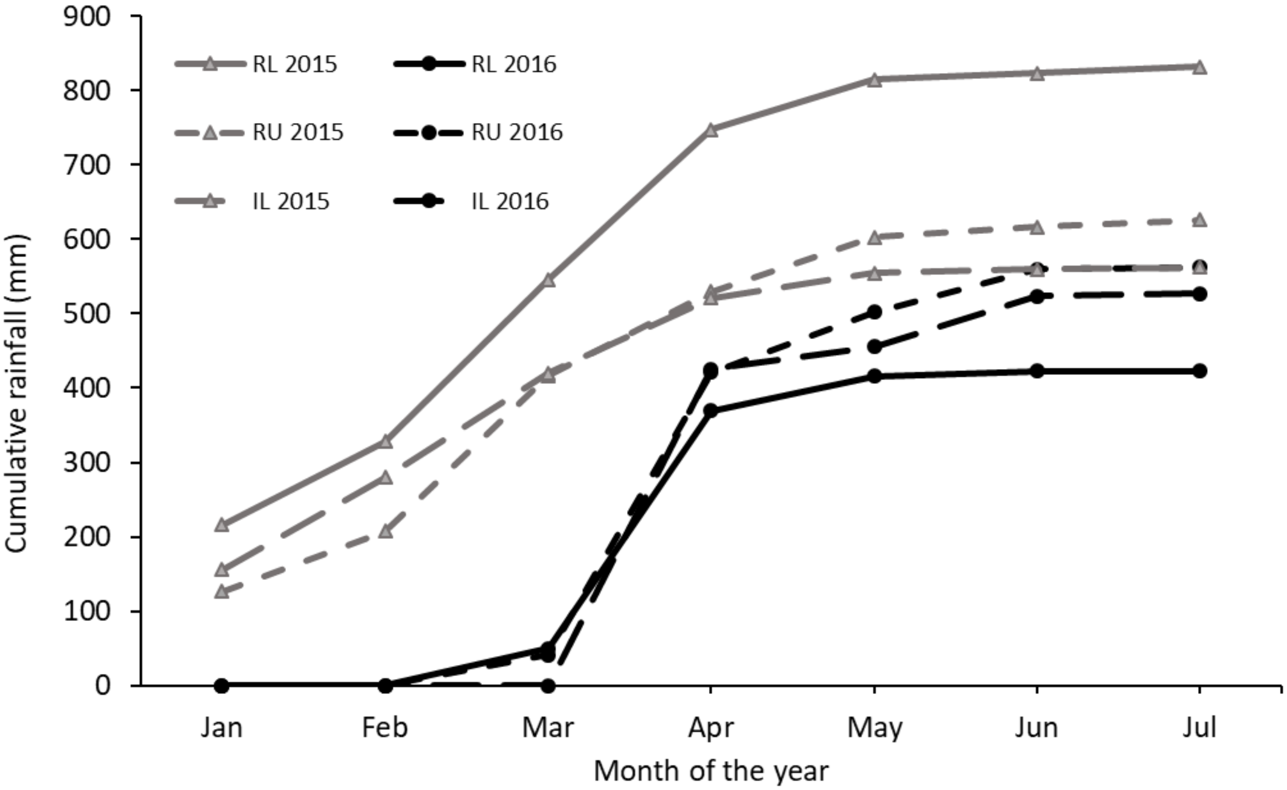

Figure 1. Monthly cumulative rainfall over the cropping season in the three experimental rice growing conditions. IL: Irrigated lowland, RL: Rainfed lowland, and RU: Rainfed upland. The cropping season for IL and RL is from Jan to May and for RU from Mar to June.

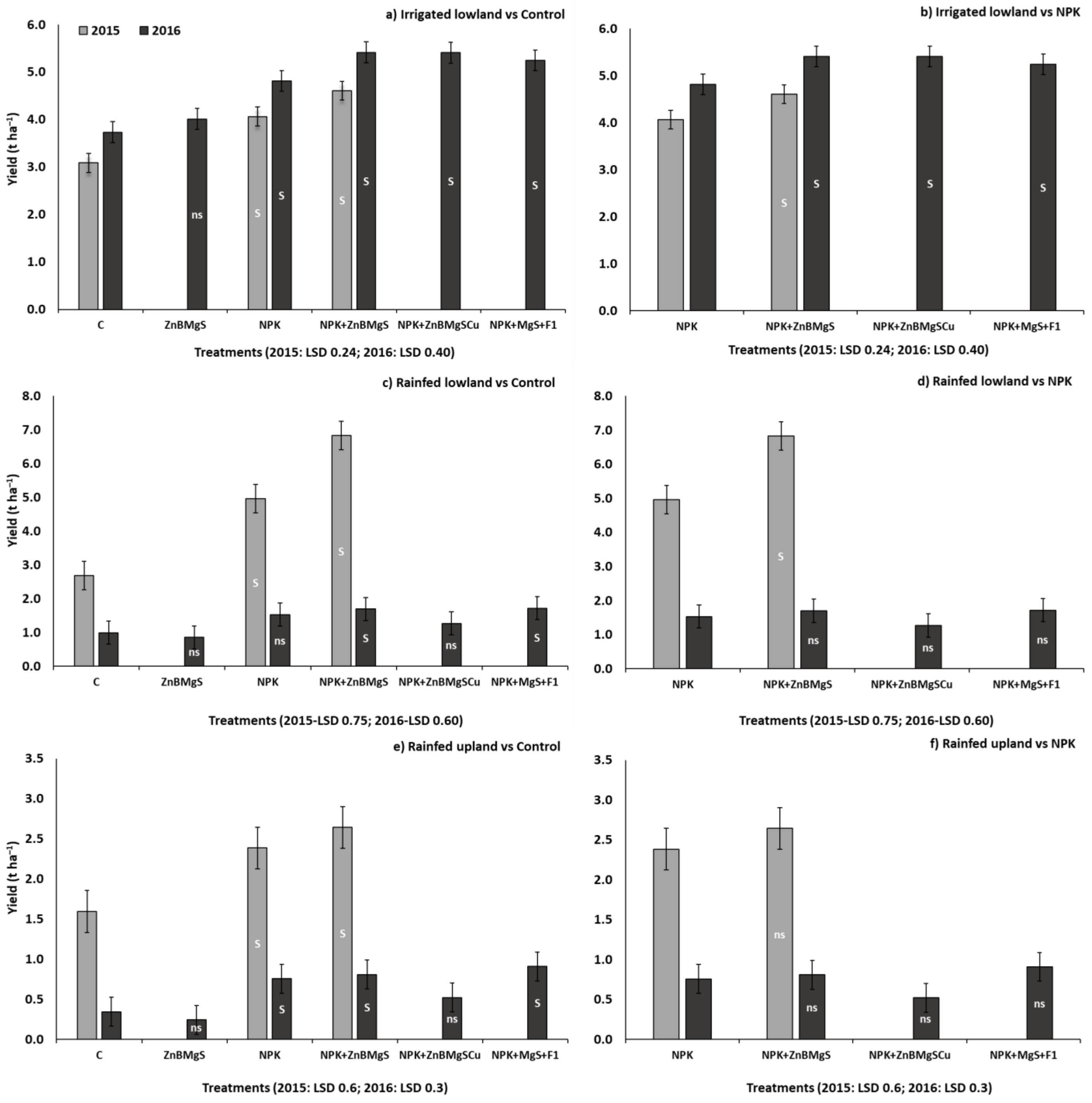

Figure 2. Yield advantage realized with soil applied micronutrients alone or in combination with foliar product compared to reference treatments (control and NPK) in the three rice growing environments for two consecutive years in Tanzania. S=significant; ns=not significant.

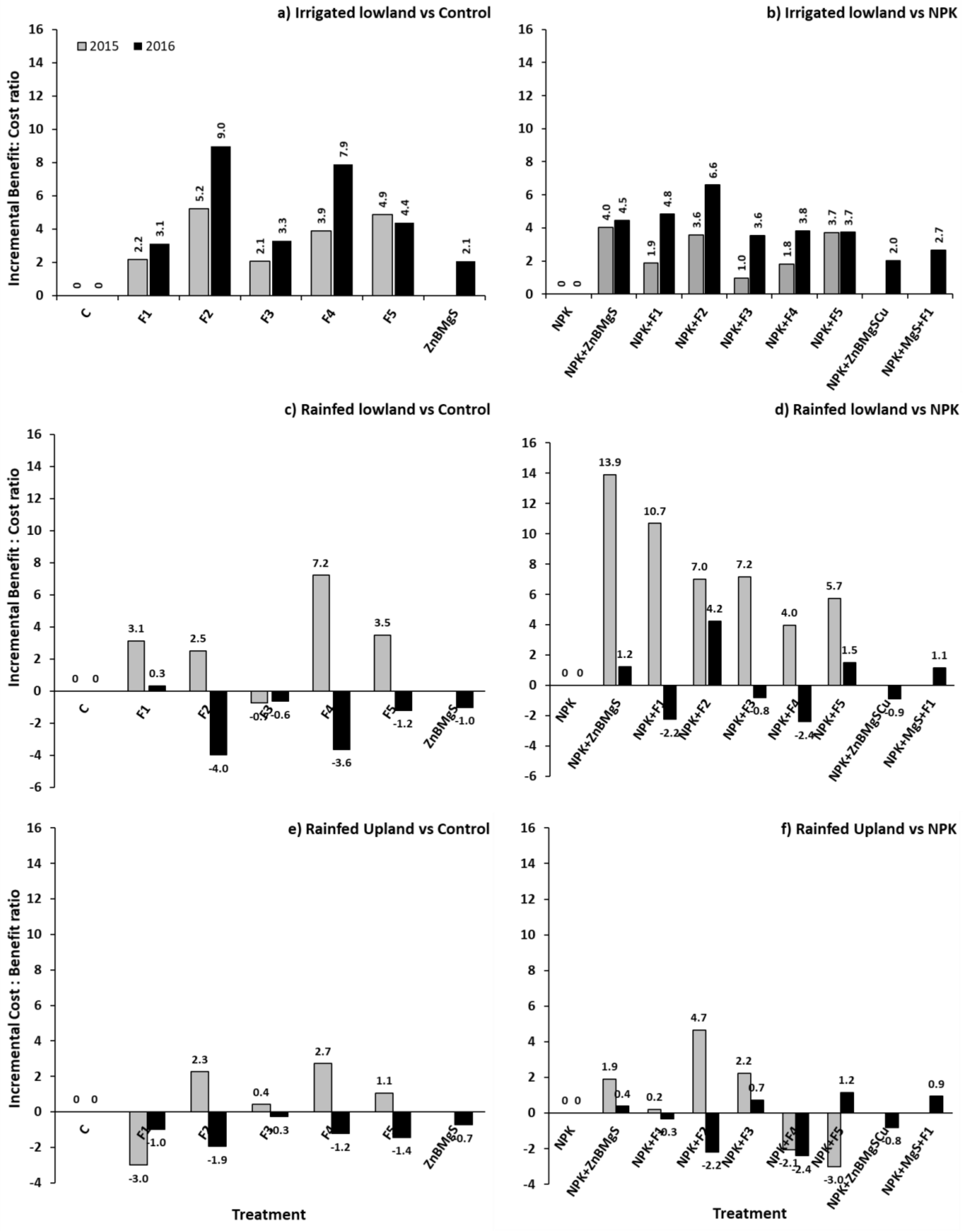

Figure 3. The incremental B:C ratio calculated for the additional yield increase for the treatment effect under three rice growing environments (IL, RL and RU) in 2015 and 216. Figure 3a, 3c and 3e without NPK compared to control. Figure 3b, 3d and 3f are with NPK treatments compared to sole application of NPK.