

Yield Response and Nutrient Use Efficiencies under Different Fertilizer Applications in maize (*Zea mays* L.) in Contrasting Agro ecosystems

Abstract

Variability in crop response and nutrient use efficiencies to fertilizer application is quite common under varying soil and climatic conditions. Understanding such variability is vital to develop farm- and area- specific soil nutrient management and fertilizer recommendations. Hence the objectives of this study were to assess maize grain yield response to nutrient applications for identifying yield-limiting nutrients, and to understand the magnitude of nutrient use efficiencies under varying soil and rainfall conditions. A total of 150 on-farm nutrient omission trials (NOTs) were conducted on farmers' field in high rainfall and moisture stress areas. The treatments were control, PK, NK, NP, NPK and NPK+ secondary and micronutrients. Maize grain yield, nutrient uptake, agronomic and recovery efficiencies of N and P differed between fertilizer treatments and between the contrasting agro-ecologies. The AE_N ranged from 24.8 to 32.5 kg grain kg^{-1} N in Jimma area and from 1.0 kg grain kg^{-1} N (NK treatment) to 10.2 kg grain kg^{-1} N (NPK treatment) at Adami Tullu and from 0.1 kg grain kg^{-1} N (NK treatment) to 8.3 kg grain kg^{-1} N (NPK treatment) at Bulbula. The differing parameters between the agro-ecologies were related to difference in rainfall amount and not to soil factors. Grain yield response to N application and agronomic efficiencies of N and P were higher in the high rainfall area than in the moisture stress areas. Grain yield responded the most to nitrogen (N) application than to any other nutrients at most of the experimental sites. Owing to the magnificent yield response to N fertilizer in the current study, proper management of nitrogen is very essential for intensification of maize productivity in most maize growing areas of Ethiopia.

Keywords: Ethiopia; *Zea mays* L.; Nutrient omission trials; Agronomic efficiency; Apparent recovery efficiency, Nutrient uptake

Abbreviations: AE_N , agronomic efficiency of applied N; AE_P , agronomic efficiency of applied P; ARE_N , apparent recovery efficiency of applied N; ARE_P , apparent recovery efficiency of applied P

1. Introduction

Food insecurity is a great concern in Sub-Saharan Africa (SSA) given the ever-increasing human population, changing climate and persistently low crop yields. This is particularly so in Ethiopia, which is the second most populous country in Africa with an average annual population growth rate of 2.7%. Maize (*Zea mays* L.) has increasingly become one of the most important staple food crops in Ethiopia. Its production and consumption have grown widely across many regions. However, the current average maize yield is 3944 kg ha^{-1} [1], which is much lower than its yield potential. One of the major reasons for the low maize productivity in SSA and in Ethiopia in particular is poor soil nutrients status. Nitrogen (N) and phosphorus (P) were specifically deficient in most parts of the country [2, 3]. The wider variability in soil fertility, climate and farmers nutrient management practices further contributed to low maize productivity at national

48 level. Farmers in the maize growing region apply small amounts of fertilizers containing mainly
49 N and P [4] Moreover, the recovery fractions of the applied nutrients are often quite low due to
50 nutrient losses, unbalanced nutrient application [5] and in some regions due to limited soil
51 moisture [6]. Moreover, poor crop and nutrient management practices such as lack of weeding,
52 low plant density and use of inappropriate blanket fertilizer recommendations can also reduce
53 nutrient use efficiency and crop yields [7, 8].

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55 In Ethiopia, regional fertilizer recommendations have been developed for maize [9], which is
56 slightly region specific than the earlier single blanket recommendation of 100 kg DAP and 200
57 kg Urea ha⁻¹. Yet cropping systems, crop management practices, soil types and fertility status,
58 climatic conditions and other factors governing yield response to nutrients, vary considerably in
59 space and time [10, 11]. Due to such localized differences in crop growing conditions and the
60 soils' indigenous nutrient supply capacity, grain yield response to fertilizer application as well as
61 nutrient use efficiencies could vary across the maize production regions of the country as
62 reported by [10] in many Sub-Sahara Africa countries, by [11] in Zimbabwe and by [9] in
63 Ethiopia. Both blanket and regional fertilizer recommendations often lead to either over-
64 fertilization or under-fertilization by individual farmers. Excessive application, especially of N
65 and P fertilizers, may result in loss of investment in fertilizer input, nutrient accumulation in the
66 soil (low nutrient use efficiency) and environmental pollution [12]. By contrast, under-
67 fertilization may lead to nutrient mining owing to the imbalance between nutrient removed by
68 the crop and the nutrient applied in the form of fertilizer. To increase nutrient use efficiencies,
69 minimize soil degradation and sustain intensification of crop productivity, more site-specific
70 nutrient management options are recommended, especially for SSA where the cropping systems
71 are highly heterogeneous [10, 13]. Several studies revealed that optimum N and P rates differed
72 for different maize growing locations [9, 14] and with different cropping system [15], suggesting
73 that the old tradition of using blanket fertilizer recommendation can no more be an appropriate
74 practice to follow. Other studies confirm that ignoring important soils nutrients, other than N and
75 P in any crop production in the country could result in significant grain yield losses at least in
76 specific locations [16, 17, 18] and hence need to be carefully handled.

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78 To develop strategies for improved nutrient management and optimize fertilizer
79 recommendations in specific regions, there is a need to understand the nutrient status of the soil,
80 the magnitude of crop response to fertilizer applications and the nutrient use efficiencies in a
81 particular location/region.

82 The objectives of this study were to: (1) assess maize grain yield response to different nutrients,
83 (2) identify yield limiting nutrients and (3) understand the magnitude of agronomic and apparent
84 fertilizer recovery efficiencies under variable soil and rainfall conditions.

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86 **2. Materials and Methods**

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88 **2.1 Study sites**

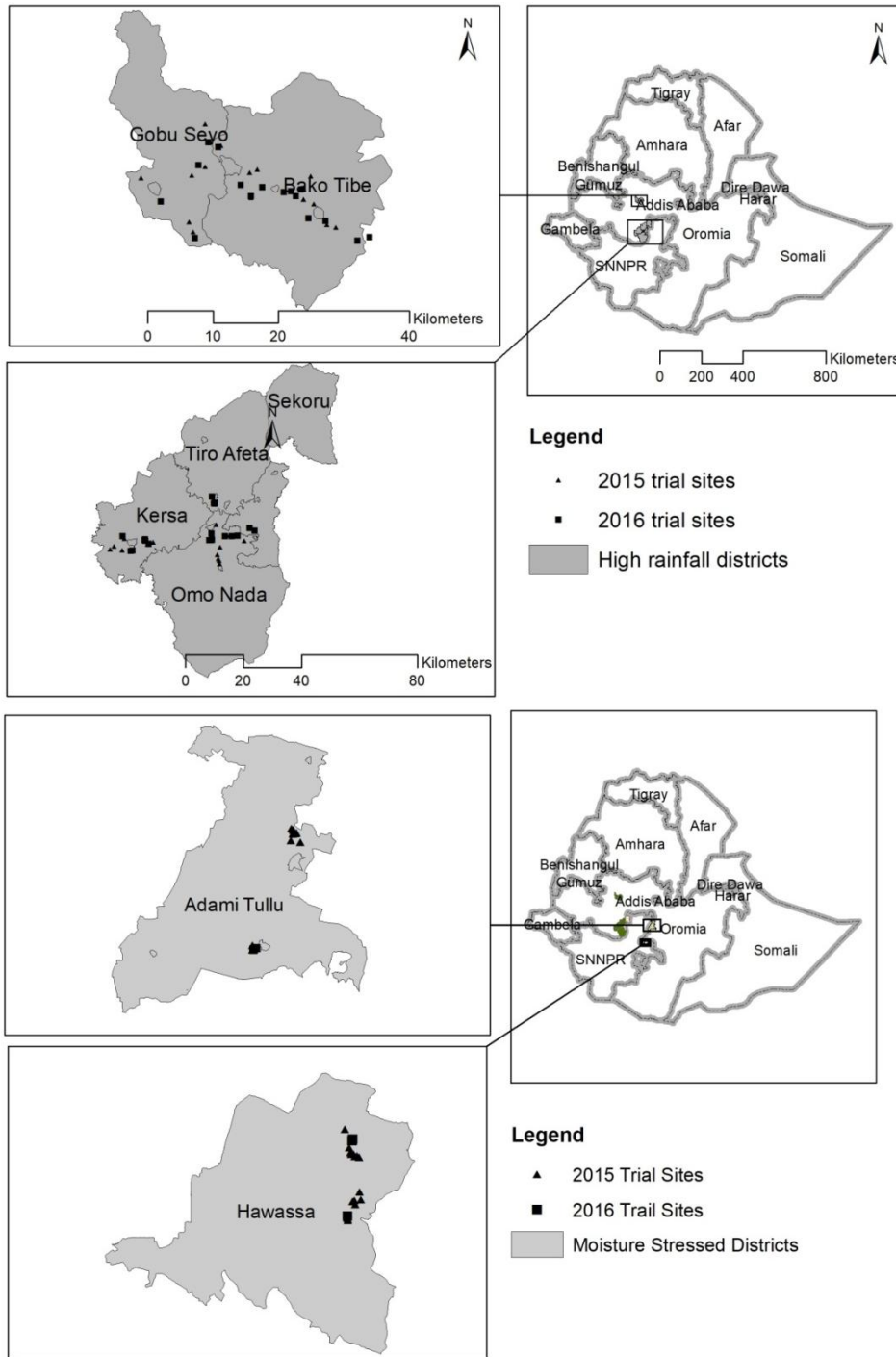
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90 Nutrient Omission Trials (NOTs) were conducted on farmers' fields in major maize production
91 areas of Ethiopia over two cropping seasons, 2015 and 2016. The NOTs study sites were
92 purposefully selected to cover a broad range of major maize growing areas in Ethiopia,
93 representing both high rainfall and moisture stress agro-ecologies. Selection of the study sites
94 were guided by soil and climate maps, and the African Soil Information System (AfSIS) crop

95 mask to classify major maize production areas in terms of 1 km pixel resolution [19]. Fields with
96 gentle slopes, minimum soil heterogeneity and that were large enough to accommodate six
97 treatments (described subsequently) were selected for the establishment of the NOTs. A total of
98 150 nutrient omission trials ($N = 88$ in 2015 and $N = 62$ in 2016) were established across eight
99 districts: Hawassa, Adami Tullu/Bulbula, Bako Tibe, Gobu Sayo, Omo Nada, Kersa, Tiro Afeta
100 and Sekoru (Fig. 1). Adami Tullu/Bulbula and Hawassa are characterized as semi-arid moisture
101 stress areas while the rest of the districts, hereafter described as Bako and Jimma areas for 2016
102 season summary data, are characterized as high rainfall sub-humid areas. The total monthly
103 rainfall of all the experimental sites during the two cropping seasons is presented in Fig. 2. The
104 soils in Adami Tullu/Bulbula and Hawassa are sandy loam dominated by andosol with neutral
105 soil pH whereas the soils in Bako and Jimma areas are generally clay dominated by reddish or
106 reddish brown nitisols with acidic soil pH (Table 1).

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UNDER PEER REVIEW



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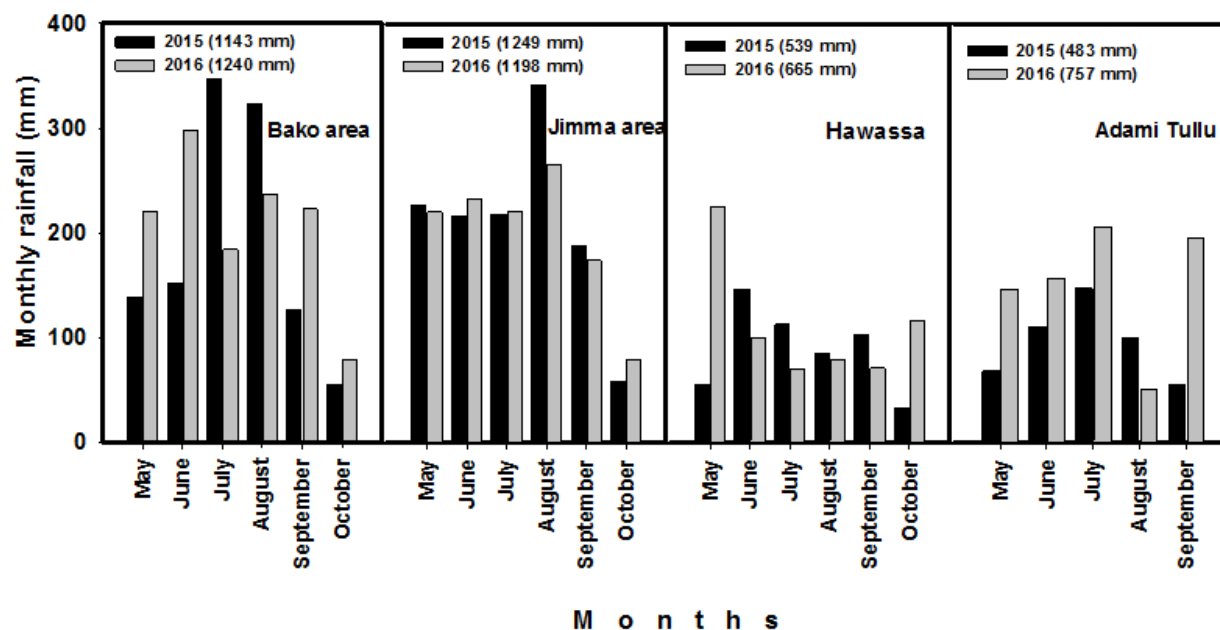
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Fig. 1: Multi-location nutrient omission trial (NOTs) study sites located across major maize production areas in contrasting agro ecological zones in Ethiopia.



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132 **Fig. 2:** Crop growing season monthly rainfall (mm) received in the nutrient omission studied sites in
133 major maize production areas in Ethiopia.

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135 **2.2 Nutrient omission trials set up and management**

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137 The nutrient omission trials (NOTs) consisted of six treatments that included: the control, PK
138 (0-40-40), NK (120-0-40), NP (120-40-0) NPK (120-40-40) in kg ha^{-1} and NPK + secondary
139 nutrients such as sulphur (S), calcium (Ca), magnesium (Mg) + micro-nutrients such as boron
140 (B) and zinc (Zn), which here after is denoted as NPK+ (Table 3). The rates of each nutrient in
141 the last treatment were 120-40-40-20-10-10-5-5 (kg ha^{-1}) in that order. The treatments were
142 replicated across individual farmers' fields. To understand the temporal variability of yield
143 response to fertilizer application, the NOTs were repeated in 2016 cropping season in the same
144 fields used for 2015 season, using different new plots to avoid confounding effects of residual
145 nutrients.

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147 The experimental fields for all NOTs were prepared with an oxen-drawn mouldboard plough.
148 The plot sizes of each treatment were 8 m \times 8 m (64 m²), and a hybrid maize variety
149 recommended for each area was used as a test crop. In Jimma and Bako areas, a hybrid variety,
150 BH661 (with 160 average days to maturity) was used. In Hawassa and Adami Tullu/Bulbula
151 areas a hybrid variety, BH540 (with 145 average days to maturity) was used. Plant spacing of 75
152 cm (inter-row) \times 25 cm (intra-row) was used in order to maintain a plant population of 53,000
153 plants ha⁻¹. In each area, the planting time was adjusted to match farmers planting windows. All
154 nutrients were applied at planting except N, which was applied in three equal splits, 1/3 at
155 planting, 1/3 at V6 (21 days after planting, DAP), and 1/3 at V10 (35 DAP). Urea, triple super
156 phosphate (TSP), murate of potash (MOP), hydrated forms of magnesium, calcium and zinc
157 sulphates and borax were used as fertilizer sources for N, P, K, Mg, Ca, Zn and B, respectively.
158 Nutrient application rates were assumed to be non-limiting at each site. The trials were uniformly
159 managed by researchers for weeds, diseases and pests using appropriate control measures.
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2.3 Soil and plant analyses

Soil samples were collected from a depth of 0-20 cm at trial establishment before the application of fertilizers. Soil samples were obtained from four points in each experimental field based on a Y-frame methodology, and the four samples collected in each field were thoroughly mixed to form a composite sample. The composite soil samples were analyzed at IITA Laboratory in Ibadan, Nigeria for major soil properties. The soil properties analyzed included soil organic carbon (OC) using chromic acid digestion [20], Total N using Kjeldahl digestion [21], soil pH (1:2.5 soil: water suspension) according to [22], available P, Exchangeable cations and micronutrients (Zn, Cu, Mn, and Fe) were determined using Mehlich 3 extraction procedure [23].

At harvest the stover and grains samples were oven dried and ground for N and P analyses. Phosphorus was determined using ascorbic acid method following a procedure described by [24], while N was determined after digesting the plant samples with sulphuric acid following a procedure described by [25].

184 **Table 1:** pH, organic carbon (OC), total nitrogen (TN), available phosphorus (P) and exch. potassium (K), Calcium (Ca), magnesium (Mg), zinc
 185 (Zn), copper (Cu), manganese (Mn) and iron (Fe) contents of soils in the different nutrient omission experimental sites

Soil Parameters	Experimental Locations						
	Bako Tibe	Gobu Sayo	Omo Nada	Kersa	Adami Tullu	Bulbula	Hawassa
pH (H ₂ O)	4.6-5.8 (5.1)	4.7-5.8 (5.1)	4.6-5.6 (5.1)	4.5-6.0 (5.1)	6.8-7.9 (7.2)	6.7-7.5 (7.2)	6.7-7.4 (7.1)
OC (%)	1.3-2.7 (2.2)	2.0-2.9 (2.3)	0.8-2.4 (1.6)	1.0-2.1 (1.7)	0.6-1.1 (0.8)	0.6-0.9 (0.7)	0.4-0.7 (0.6)
TN (%)	0.13-0.23(0.19)	0.19-0.29(0.23)	0.12-0.27(0.17)	0.11-0.23(0.19)	0.05-0.13(0.09)	0.09-0.10(0.10)	0.03-0.08(0.05)
Available P (mg kg ⁻¹)	3.9-61.8 (11.5)	5.5-10.6 (7.7)	5.5-42.7 (17.0)	4.3-19 (11.1)	11.9-61.4(26.0)	26.2-56.2(41.5)	18.2-55.7(31.0)
Exch. K (mg kg ⁻¹)	49-1488 (514)	133-868 (541)	249-716 (514)	379-771 (556)	127-564 (276)	116-222 (144)	50-228 (146)
Ca (g kg ⁻¹)	1.6-5.3(3.6)	1.8-4.0(3.2)	2.2-3.9(2.7)	1.4-5.3(2.8)	0.9-4.6(2.3)	0.99-2.5(1.6)	0.77-2.5(1.9)
Mg (g kg ⁻¹)	0.4-1.5(0.9)	0.6-1.1(0.9)	0.45-1.1(0.67)	0.3-1.5(0.7)	0.12-0.47(0.25)	0.17-0.36(0.26)	0.08-0.28(0.16)
Zn (ppm)	2-16(8)	3-7(5)	5-19(13)	4-18(8)	0.5-1.6(1.0)	0.6-1.0(0.8)	0.4-0.9(0.6)
Cu (ppm)	1-4(3)	2.9-5.8(4.8)	1-9(5)	7-26(11)	15.7-41.4(24.4)	13.5-20.1(16.0)	20.0-27.7(22.3)
Mn (ppm)	29-115(66)	58-98(87)	64-261(142)	73-231(149)	45-130(84)	68-106(88)	61-112(79)
Fe (ppm)	44-189 (92)	50-113(75)	145-233(177)	69-189(137)	0.03-0.1(0.06)	0.02-0.06(0.04)	0.02-0.04(0.024)

186 *Values are ranges and those in parentheses are mean.*

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189 2.4 Determination of grain yield and nutrient use efficiencies

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191 Harvesting was done at physiological maturity from a net plot area of 4 m × 4.5 m (18 m²). The
192 field grain weight was recorded and the grain yield was determined after adjusted to the standard
193 12.5% moisture content. Agronomic efficiency and apparent fertilizer recovery efficiency were
194 determined using the following formulas according to [26]:

195 Agronomic efficiency (AE) was determined as:

$$196 \quad AE = \frac{GYt - GYc}{Na} \dots\dots\dots(1)$$

197 Where, *GYt* is the grain yield of fertilizer treated plot (kg), *GYc* is the grain yield of the fertilizer
198 untreated plot (kg) and *Na* is the amount of nutrient applied (kg).

199 Apparent fertilizer recovery efficiency (ARE) was determined as:

$$200 \quad ARE = \frac{NUt - NUC}{Na} \dots\dots\dots(2)$$

201 Where, *NUt* is the nutrient uptake (in grain and straw) of the fertilizer treated plot and *NUc* is the
202 nutrient uptake (in grain and straw) of fertilizer untreated plot.

203 2.5 Data analysis

204 The effects of fertilizer treatments on maize grain yield, nutrient uptake, agronomic and apparent
205 recovery efficiencies were analyzed using analysis of variance (ANOVA) procedures using a
206 Statistical Analysis System (SAS), version 9.3 Software, (SAS institute INC., Cary, USA). The
207 ANOVA was computed based on PROC GLM procedure and when ANOVA showed the
208 presence of significant treatment effects, mean separation was carried out using Tukey's test at
209 $\alpha=5\%$ level of significance.

210 3. Results

211 3.1 Grain yield at different locations of the two agro-ecologies

212
213 Grain yield generally tended to be higher at the high rainfall areas than at the moisture stress
214 areas, especially during 2015 season. At the high rainfall areas, grain yield ranged from 2916 kg
215 ha⁻¹ for control treatment at Kersa to 8301 kg ha⁻¹ for NPK treatment at Gobu Sayo during the
216 same year (Fig . 3). At the moisture stress areas, however, it ranged between 1061 kg ha⁻¹ for
217 NK treatment at Bulbula to 5925 kg ha⁻¹ for NPK+ treatment at Hawassa (5A). During 2016
218 season, grain yield in the high rainfall areas ranged from 1434 kg ha⁻¹ for the control treatment to
219 7796 kg ha⁻¹ for the NPK treatment in Jimma area. Grain yield during the same year ranged from
220 1787 kg ha⁻¹ to 6928 kg ha⁻¹, for the control and NPK+ treatments at Adami Tullu, in the
221 moisture stress area (Fig 5B).
222

223 For high rainfall areas, grain yields obtained from NP, NPK and NPK+ were consistent between
224 seasons. By contrast, grain yields from control, N and P omitted treatments were lower in 2016
225 compared with 2015. In the moisture stress areas, particularly at Adami Tullu and Bulbula, grain
226 yield were higher in 2016 cropping season than in 2015 season, which was characterized by
227 erratic rainfall (Fig. 5).

228 3.2 Maize yield response to N

229
230 There was a wide spatial and temporal variability in maize yield response to nutrients across the
231 study sites. Maize grain yield responded drastically to nitrogen (N) application almost at all the
232 study sites. The magnitude of the response to N application was, however, much higher for the

233 high rainfall than low rainfall/moisture stress areas. The grain yield response ranged from 2657
 234 to 4266 kg ha⁻¹ in 2015 and from 3648 to 5454 kg ha⁻¹ in 2016 in high rainfall areas, while it
 235 ranged from 383 to 1513 kg ha⁻¹ in 2015 and from 1500 to 3310 kg ha⁻¹ in 2016 in moisture
 236 stress areas (Table 2).

237 Maize showed little or no response to N application at eight experimental fields in Bako and
 238 Jimma areas during 2015 season (data not presented). At these few sites with non-responsive
 239 soils, the average grain yield for N omitted plots was 7.9 t ha⁻¹ compared with an average grain
 240 yield of 8.3 t ha⁻¹ for the NPK treated plots.

241 3.3 Maize yield response to P

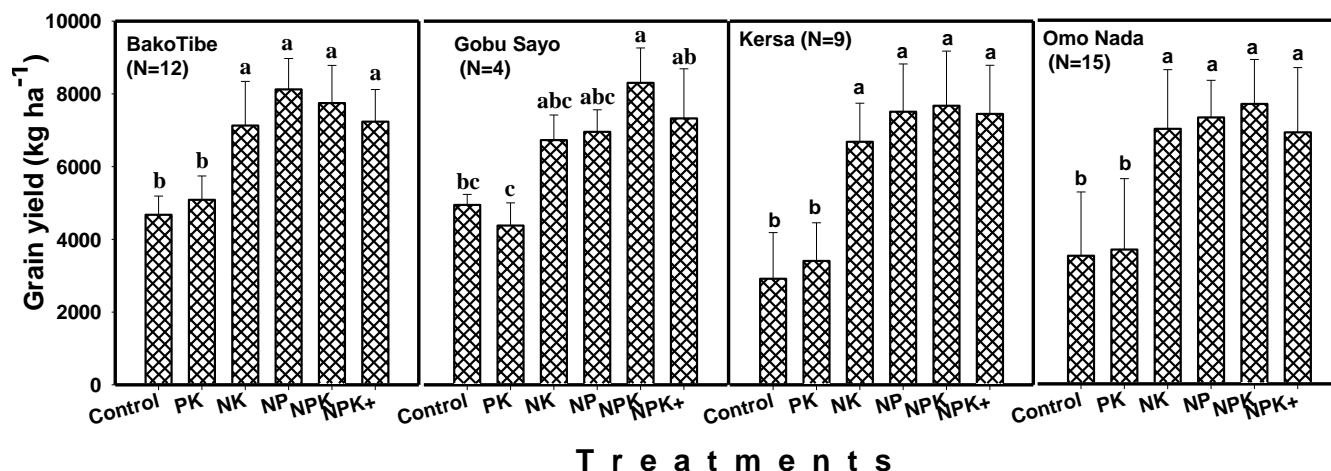
242 During 2015, grain yield on average increased by 967 kg ha⁻¹ (range of 616 to 1574 kg ha⁻¹) in
 243 high rainfall areas and by 801 kg ha⁻¹ (range of 498 to 1104 kg ha⁻¹) in moisture stress areas due
 244 to P application across all experimental sites except at Hawassa. During 2016, grain yield on
 245 average increased by 1202 kg ha⁻¹ (range of 349 to 2056 kg ha⁻¹) in high rainfall areas and by
 246 1609 (range of 1320 to 1880 kg ha⁻¹) in moisture stress areas due to P application across all
 247 experimental sites (Table 2).

248 During 2015 season, the highest yield response to P was observed at Gobu Sayo (1574 kg ha⁻¹)
 249 and Bulbula (1104 kg ha⁻¹). During 2016 season, yield responses to P application of 2056, 1880
 250 and 1628 kg ha⁻¹ were observed in Jimma area and at Bulbula and Adami Tullu, respectively
 251 (Table 2).

252 253 3.4 Maize yield response to K and other nutrients

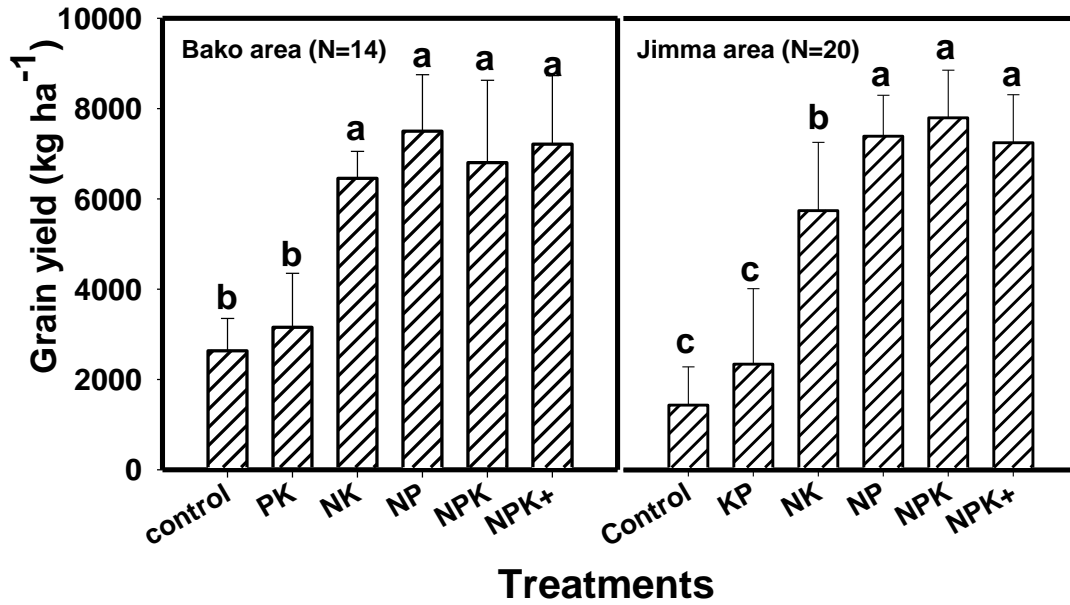
255 Overall, there was little or no yield response to all other nutrients applied (i.e. potassium, and
 256 secondary and micronutrients) (Table 2). However, maize responded to K application (1346 kg
 257 ha⁻¹) in Gobu Sayo in 2015 season and to secondary and micronutrients (1496 kg ha⁻¹) at Adami
 258 Tullu in a good rainfall season in 2016 (Table 2).

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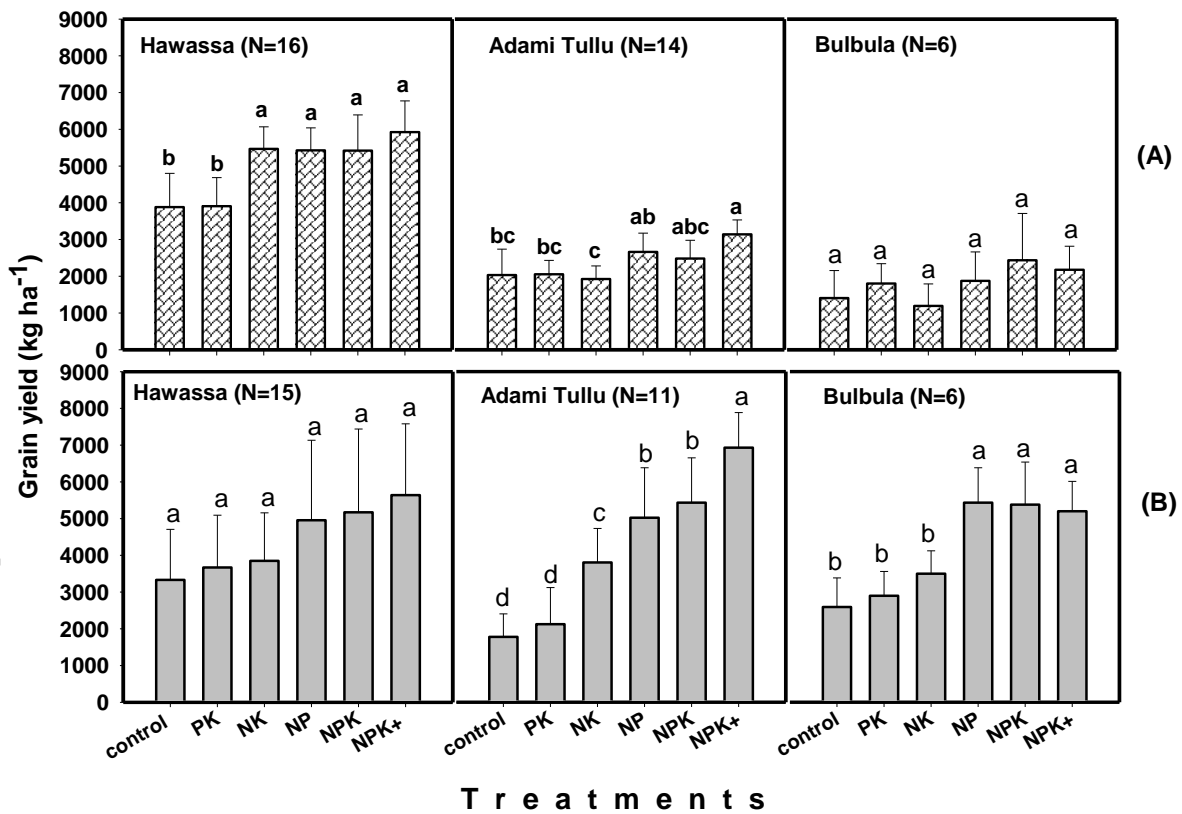
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261 **Fig. 3:** Effects of fertilizer treatments on responsive soils at Bako Tibe, Gobu Sayo, Kersa



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263 **Fig. 4:** Effects of fertilizer treatments on responsive soils in Bako (three districts) and Jimma areas (four
 264 districts) during 2016 cropping season (Bars followed by the same letter for the same location are not
 265 significantly different)



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267 **Fig. 5:** Effects of fertilizer treatments on maize grain yield at Hawassa, Adami Tullu and Bulbula in 2015
 268 (A) and 2016 (B) cropping seasons. (Bars followed by the same letter for the same site are not
 269 significantly different).

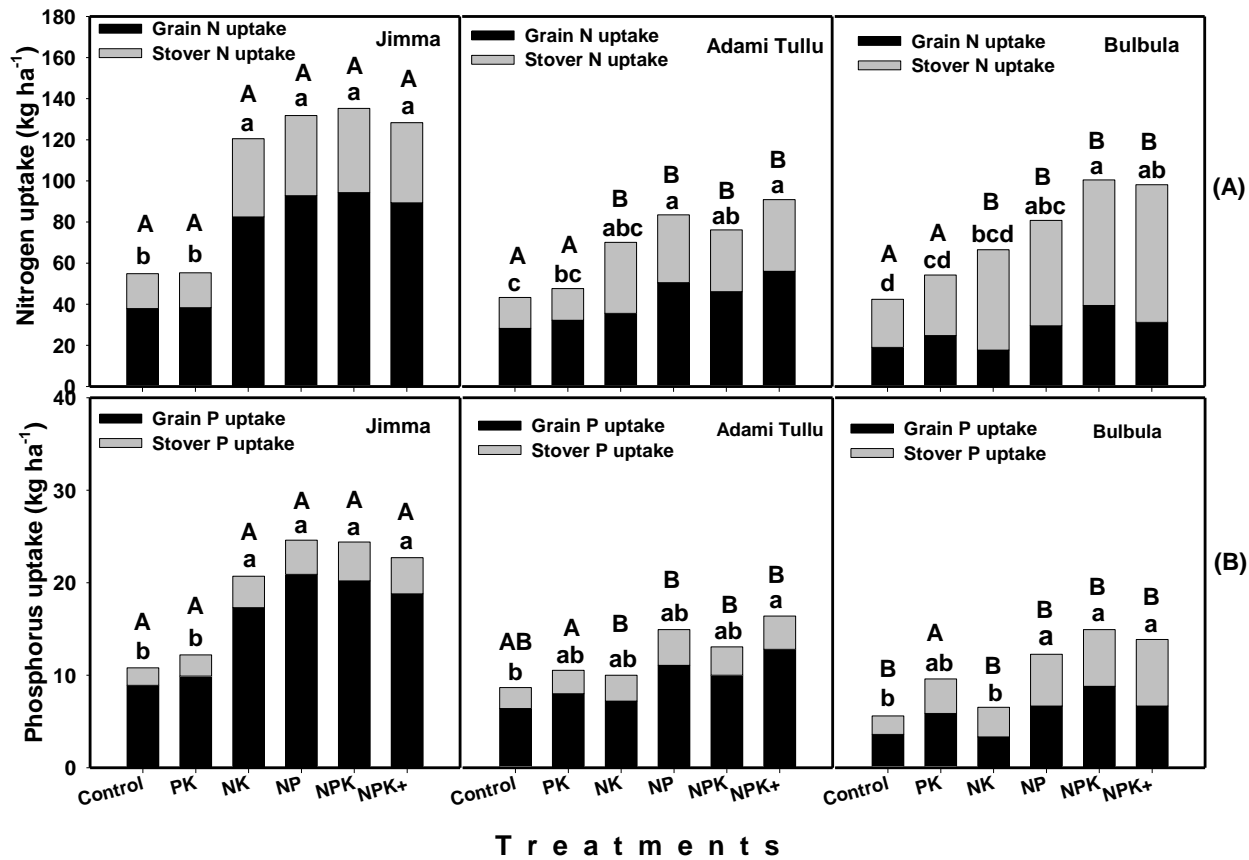
270 **Table 2:** Maize grain yield response to each nutrient applied in the nutrient omission trials
 271 (NOTs) established in 2015 and 2016 seasons

Year	Study sites	Maize yield response (kg ha ⁻¹)			
		N	P	K	(S, Mg, Ca, B, Zn)
2015	Bako Tibe	2657	616	-378	-508
	Gobu Sayo	3922	1574	1346	-976
	Omo Nada	4005	685	371	-778
	Kersa	4266	991	163	-224
	Hawassa	1513	-47	-6	505
	Adami Tullu	383	498	-159	586
	Bulbula	562	1104	498	-229
2016	Bako area	3648	349	-695	407
	Jimma area	5454	2056	407	-549
	Hawassa	1500	1320	213	469
	Adami Tullu	3310	1628	411	1496
	Bulbula	2479	1880	-55	-179

272
 273 *Yield response was calculated considering yield from NPK plot as maximum yield and subtracting the*
 274 *yield obtained from missing nutrient (e.g Yield from NPK plot –Yield from PK plot =Yield response due*
 275 *to N)*

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 277 **3.5 N and P Uptake**

278
 279 Total N uptake significantly differed between the high rainfall and moisture stress areas for every
 280 same treatment (except for control and PK) as well as between treatments of every same location
 281 (Fig. 6A). The total N uptake for every same treatment (except for control and PK) was
 282 significantly higher in high rainfall area (Jimma area) than in moisture stress areas (Adami Tullu
 283 and Bulbula) (Fig. 6A). Total N uptake, however did not significantly differ between the two
 284 moisture stress locations. The average N uptake (for all treatments) by the crop is 1.7-fold higher
 285 at high rainfall compared to the moisture stress area. The total N uptake was significantly lower
 286 for the control and N omitted treatments compared to other treatments at all experimental sites.
 287 In Jimma, the total N uptake ranged from 55 kg ha⁻¹ (for the control and N omitted treatments) to
 288 135 kg ha⁻¹ (for the NPK treatment). At Adami Tullu and Bulbula, the total N uptake ranged
 289 from 38.5 (for control) to 82 kg ha⁻¹ (for NPK treatment), and from 40.1 (for control) to 89.2 kg
 290 ha⁻¹, (for NPK treatment), respectively. In Jimma area and at Adami Tullu, a higher proportion of
 291 the total N was taken up by the grain than the stover, while at Bulbula a higher proportion of
 292 total N was taken up by the stover than by the grain (Fig. 6A).



293

294 (Different small letters denote significant difference between treatments at each location whereas;
 295 different capital letters denote significant difference between locations for similar treatment).

296 **Fig. 6:** Total plant uptake of nitrogen (A) and phosphorus (B) in Jimma area, Adami Tullu and Bulbula

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298 Similar to total N uptake, the total P uptake also significantly differed between the high rainfall
 299 and moisture stress areas for every same treatment (except PK) as well as between treatments of
 300 same location (Fig. 6B). The total P uptake for every same treatment (except PK) was
 301 significantly higher in high rainfall area (Jimma area) than in moisture stress areas (Adami Tullu
 302 and Bulbula) (Fig. 6B). The average P uptake (for all treatments) by the crop is 2.3-fold higher at
 303 high rainfall compared to the moisture stress areas. The total P uptake for NP, NPK and NPK+
 304 treatments were significantly higher than for the control, N and P omitted plots, especially in
 305 Jimma area and at Bulbula. The total P uptake was generally lower for the control and N omitted
 306 treatments at Jimma and for the control and P omitted plots at Bulbula (Fig.6B). In Jimma area,
 307 the P uptake ranged from 10.8 kg ha⁻¹ (for the control) to 24 kg ha⁻¹ (for NP and NPK
 308 treatments). However, at the moisture stress areas, P uptake was lower ranging from 6.5 kg ha⁻¹
 309 to 12.5 kg ha⁻¹ at Adami Tullu and from 4.3 to 11.0 kg ha⁻¹ at Bulbula. Conversely to the grain
 310 and stover N uptake, the grain P uptake was consistently higher than the stover P uptake for all
 311 the three locations (Fig. 6B).

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315 **3.6 Agronomic efficiency of N and P**

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317 The agronomic efficiency of nitrogen (AE_N) did not vary between treatments in Jimma area but
318 varied at the moisture stress areas. It also varied between locations for the same treatment (Table
319 3). The AE_N ranged from 24.8 to 32.5 kg grain kg^{-1} N in Jimma area. At the moisture stress areas
320 it ranged from 1.0 kg grain kg^{-1} N (NK treatment) to 10.2 kg grain kg^{-1} N (NPK treatment) at
321 Adami Tullu and from 0.1 kg grain kg^{-1} N (NK treatment) to 8.3 kg grain kg^{-1} N (NPK
322 treatment) at Bulbula. The AE_N was significantly lower for the NK treatment compared to the
323 rest of the treatments both at Adami Tullu and Bulbula. On the other hand, for every same
324 treatment, the AE_N was significantly higher for the high rainfall than low rainfall areas (Table 3).

325
326 The agronomic efficiency of phosphorus (AE_P) varied between treatments at all experimental
327 sites. In Jimma area, the agronomic efficiency of phosphorus (AE_P) ranged from 3.3 kg grain kg^{-1}
328 1 of P (N omitted plot) to 100.8 kg grain kg^{-1} of P (NPK treatment). Compared to the high
329 rainfall area, the AE_P in the moisture stress areas was remarkably lower and ranged from 1.4 to
330 27.6 kg grain kg^{-1} P and from 13.5 kg grain kg^{-1} P to 27.6 kg grain kg^{-1} P at Adami Tullu and
331 Bulbula, respectively (Table 3). The AE_P was significantly lower when N was omitted for Jimma
332 area and Adami Tullu. For every same treatment the AE_P was also significantly higher for the
333 high rainfall area than for the moisture stress areas, except for the PK treatment where there was
334 no significant difference in AE_P (Table 3).

335 336 **3.7 Apparent recovery efficiency of N and P**

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338 The apparent recovery fraction of N (ARE_N) did not differ between treatments at the other two
339 locations except at Bulbula but differed between locations for every same treatment (Table 4). At
340 Bulbula, the ARE_N ranged from 0.16 (NK treatment) to 0.41 kg N kg^{-1} applied N (NPK
341 treatment) (Table 4). For every same treatment, the ARE_N was significantly higher at the high
342 rainfall area compared to moisture stress areas. However, the ARE_N did not differ between the
343 two moisture stress areas.

344
345 The apparent recovery fraction of P (ARE_P) significantly varied between treatments at all
346 locations and also between high rainfall and moisture stress areas for every same treatment
347 except for the PK treatment (Table 4). However, the ARE_P did not differ between the two
348 moisture stress areas. In Jimma area, the P recovery fraction ranged from 0.04 kg P kg^{-1} of
349 applied P (for PK treatment) to 0.35 kg P kg^{-1} of applied P (for NP treatment). At the moisture
350 stress areas, it ranged from 0.03 kg P kg^{-1} applied P (for PK) to 0.15 kg P kg^{-1} applied P (for
351 NPK+ treatment) at Adami Tullu and from 0.07 kg P kg^{-1} of applied P (for PK treatment) to 0.15
352 kg P kg^{-1} of applied P (NPK) at Bulbula.

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360 **Table 3:** Agronomic efficiency of nitrogen (N) and phosphorus (P) as affected by fertilizer
 361 treatments in major maize production areas in 2015

Treatments	Agronomic Efficiency of N (kg grain kg ⁻¹ N applied)			Agronomic Efficiency of P (kg grain kg ⁻¹ P applied)		
	Jimma	Adami Tullu	Bulbula	Jimma	Adami Tullu	Bulbula
Control	-	-	-	-	-	-
PK	-	-	-	3.3bA	1.4bA	13.5bA
NK	24.8aA	1.0bB	0.1bB	-	-	-
NP	31.3aA	8.0aB	4.2abB	97.1aA	20.9aB	15.1bB
NPK	32.5aA	8.4aB	8.3aB	100.8aA	16.1aB	27.6aB
NPK+	29.9aA	10.2aB	4.4abB	93aA	27.6aB	15.8bB
LSD	8.4	6.9	8.0	23.45	14.3	11.2

362 *Different small letters and capital letters denote significant difference between treatments for the same*
 363 *location and between locations for the same treatment, respectively*

364
 365 **Table 4:** Apparent recover fraction of applied N and P fertilizer as affected by fertilizer
 366 treatments

Treatments	Apparent Recovery Fraction of N (kg N taken up kg ⁻¹ of N applied)			Apparent Recovery Fraction of P (kg P taken up kg ⁻¹ of P applied)		
	Jimma	Adami Tullu	Bulbula	Jimma	Adami Tullu	Bulbula
Control	-	-	-	-	-	-
PK	-	-	-	0.04 ^{bA}	0.03 ^{bA}	0.07 ^{bA}
NK	0.54 ^{aA}	0.20 ^{aB}	0.16 ^{bB}	-	-	-
NP	0.63 ^{aA}	0.30 ^{aB}	0.26 ^{abB}	0.35 ^{aA}	0.12 ^{abB}	0.13 ^{abB}
NPK	0.67 ^{aA}	0.26 ^{aB}	0.41 ^{aB}	0.34 ^{aA}	0.09 ^{abB}	0.17 ^{aB}
NPK+	0.61 ^{aA}	0.37 ^{aB}	0.37 ^{aB}	0.30 ^{aA}	0.15 ^{aB}	0.15 ^{abB}
LSD	0.17	0.21	0.198	0.10	0.106	0.09

367 *Different small letters and capital letters denote significant difference between treatments for the same*
 368 *location and between locations for the same treatment, respectively*

370 4. Discussion

371 4.1 Grain yield response to N application

372 The higher grain yield response to nitrogen (N) application than any other nutrients at all study
 373 sites clearly shows that N is the most limiting essential plant nutrient for maize intensification in
 374 major maize growing areas of Ethiopia and hence needs special attention. The highly
 375 magnificent yield response to the application of 120 kg N ha⁻¹ in the high rainfall areas compared
 376 to the moisture stress areas explains the fact that application of high dose of N fertilizer in
 377 moisture stress areas only slightly improves maize productivity. This is because soil moisture
 378 being the medium of nutrient transport to the absorbing root (28), plays a key role in influencing
 379 crop response to fertilizer application. Integrating soil moisture conservation with fertilizer

380 management could, therefore, be one of the vital strategies to improve maize productivity in
381 moisture stress areas. The higher grain yield response to N application in the high rainfall area
382 compared to the moisture stress areas is in agreement with the findings of [27], who also
383 reported higher magnitude of yield response to nitrogen application under favourable rainfall
384 conditions than unfavourable conditions. The higher grain yield response under favourable
385 rainfall could be attributed to the availability of more available N forms in the soil solutions
386 owing to sufficient soil moisture as well as to the high water flux, both of which increase the
387 mass flow of nitrogen ions to the root surface enhancing N uptake since mass flow rate is a
388 function of both water flux in the root rhizosphere and nutrient concentration in the soil solution
389 [28].

390 At Gobu Sayo, only 14% of the fields had a soil total N content that is rated as low while at Bako
391 Tibe 66% of the fields had a soil total N content that is rated as low, and yet the yield response to
392 nitrogen application was higher at Gobu Sayo (3922 kg ha⁻¹) than at Bako Tibe (2657 kg ha⁻¹).
393 This suggests that total N content of soil might not necessarily reflect availability of nitrogen for
394 plant uptake. However, at Omo Nada, where 87% of fields had a soil total N that is rated as low,
395 the yield response to N application during 2015 was also correspondingly very high (4005 kg ha⁻¹)
396).

397 **4.2 Grain yield response to P application**

398 Yield response to P was significantly large at Gobu Sayo (1574 kg ha⁻¹) and Bulbula (1104 kg
399 ha⁻¹) during 2015 season and at Jimma (2056 kg ha⁻¹), Bulbula (1880 kg ha⁻¹) and Adami Tullu
400 (1628 kg ha⁻¹) in 2016 season (Table 2). The yield response to P was quite small although not nil
401 at Bako Tibe and inconsistent between years at Hawassa. The yield response to P during both
402 years was, however, not as high as the yield response to N application and such lesser yield
403 response to P application can be attributed to P fixing nature of the weathered nitisols and
404 calcareous soils of the high and low rainfall areas, respectively. It may also be due to the
405 carryover effects of previous P fertilizer application, especially in some sites where the available
406 P before planting was already in the high range (Table 1).

407 Grain yield response to application of 40 kg ha⁻¹ P was remarkably higher at Gobu Sayo and
408 Bulbula compared to the other experimental sites during 2015, while the response was higher for
409 all experimental sites except for Bako Tibe during 2016. This differential yield response to P
410 application across the experimental sites may only partly and not fully be explained by the
411 difference in the levels of available soil P across the locations. In the high rainfall areas such as
412 Gobu Sayo, none of the fields (Table 1) had available soil P that is above the critical P for maize
413 (12-17 mg kg⁻¹ soil) suggested by [29], which can explain the higher yield response to P
414 application (Table 2). At Bako Tibe, however, only 19% of the fields had available soil P content
415 that was greater than the critical soil P of 12-17 mg kg⁻¹ soil [29] and yet yield response to P
416 application was lower (Table 2) perhaps due to the P fixation as a result of acidity. At Omo Nada
417 and Kersa, 40% and 44% of the fields had available soil P content that was greater than the
418 critical soil P of 12-17 mg kg⁻¹ soil [29] and consequently the yield response to P application was
419 lower compared to Gobu Sayo (Table 2) perhaps due to the carryover effect of previously
420 applied P in most farms.

421 However, in the moisture stress areas such as Bulbula, Hawassa and Adami Tullu, the soil
422 available P were above the critical level of 12-17 mg kg⁻¹ soil in almost all the fields, and yet
423 there was a grain yield response to P application. Thus, under these conditions, the amount of
424 available P in the soil in relation to the critical level cannot explain the yield response to P

425 application. In those moisture stress areas, rather only a small fraction of the available P goes to
426 the soil solution and hence transport to the root surface via diffusion is highly constrained due to
427 both limited water availability and lower nutrient concentration in the soil solution since the rate
428 of diffusion depends on both water availability in the root rhizosphere and the concentration of
429 the nutrient ions in the soil solution [28]. Thus, more P needs to be applied to compensate for the
430 soil water limitation.

431

432 **4.3 Grain yield response to K application**

433 Crop response to K application was limited to few sites unlike the response to N and P
434 application. At Gobu Sayo, only one field had a soil K content that was less than the critical soil
435 K level (234 to 312 mg kg⁻¹ soil) suggested by [30], for maize production and yet there was an
436 average grain yield response of 1346 kg ha⁻¹ to potassium application (Table 2). At Omo Nada
437 and Kersa, all the fields had soil potassium content above the critical level suggested by [30] for
438 maize and consequently there was no remarkable grain yield response to K application at these
439 experimental sites. Surprisingly, at Hawassa, nearly all the fields (94%) had soil K content that
440 were below the critical soil K content for maize production and yet there was no yield response
441 to K application. This could probably be due to dependency of the critical K levels on soil types
442 [31] and thus Hawassa could have lower critical K level than the critical level described by [10]
443 [30] for soils in Nigeria. Even within the same country, critical nutrient levels for a crop could
444 vary with locations/regions [31, 32]. At Bulbula, 83% of the fields had a soil K contents that
445 were below the critical K of 234 -312 mg kg⁻¹ soil for maize production and consequently, there
446 was a grain yield response of 498 kg ha⁻¹ to the application of 40 kg ha⁻¹ K (Table 2). Unlike
447 2015 season, where there was no yield response to K application in most sites, except at Gobu
448 Sayo and Bulbula, there was a tendency of yield response to K application in the other sites as
449 well during 2016 season. However, the magnitude of increase in grain yield due to the
450 application of 40 kg K ha⁻¹ was smaller ranging only from 213 to 411 kg ha⁻¹.

451 **4.4 Grain yield response to secondary (S, Mg, Ca) and micronutrients (Zn, B)**

452 The remarkable grain yield response to application of secondary (S, Ca, Mg) and micronutrients
453 (Zn, B) at Adami Tullu, cannot be attributed to any single nutrient effect as they were applied to
454 the plots altogether. However, analysis of the pre-planting soil samples taken from the
455 experimental fields showed that the soil S content (data not shown) were above the critical soil
456 sulphur level of 10 mg kg⁻¹ soil for all fields at Adami Tullu, which may confirm that the grain
457 yield response is less likely due to S application. The soil Ca and Mg content in these two
458 experimental sites were in the sufficient range of 151-350 mg kg⁻¹ soil according to rating by
459 [33] for Mg and 1200-2500 mg kg⁻¹ soil for Ca, suggesting that the grain yield response might
460 not be related to the application of Ca and Mg containing fertilizers. Moreover, [34], reported
461 that maize grain yields remained unaffected under a wide range of Mg levels with a Ca/Mg ratio
462 ranging between 1.8 to 36.9, suggesting that grain yield response cannot be expected due to Mg
463 application with the narrow Ca/Mg ratio ranging between 6.8 (at Bulbula) and 13.0 (at Hawassa).
464 Thus, the grain yield response could be due to Zn and B application since the Zn contents of all
465 NOTs fields at Bulbula, Hawassa and Adami Tullu were below the critical level of 5-10 mg kg⁻¹
466 soil suggested by [30] or 1.5 mg kg⁻¹ soil suggested by [35] and [33] for maize production. The
467 Zn contents of all NOTs fields in the high rainfall areas were, however, in the high to very high
468 range (Table 1) according to [33] rating and thus response could not be expected. The grain yield

469 response could also be due to B, besides Zn. However there is need for a further study to
470 understand the impact of each of the secondary and micro-nutrients on maize productivity in
471 those locations where response to combined application of these nutrients were noticed.

472

473 **4.5 N and P uptake**

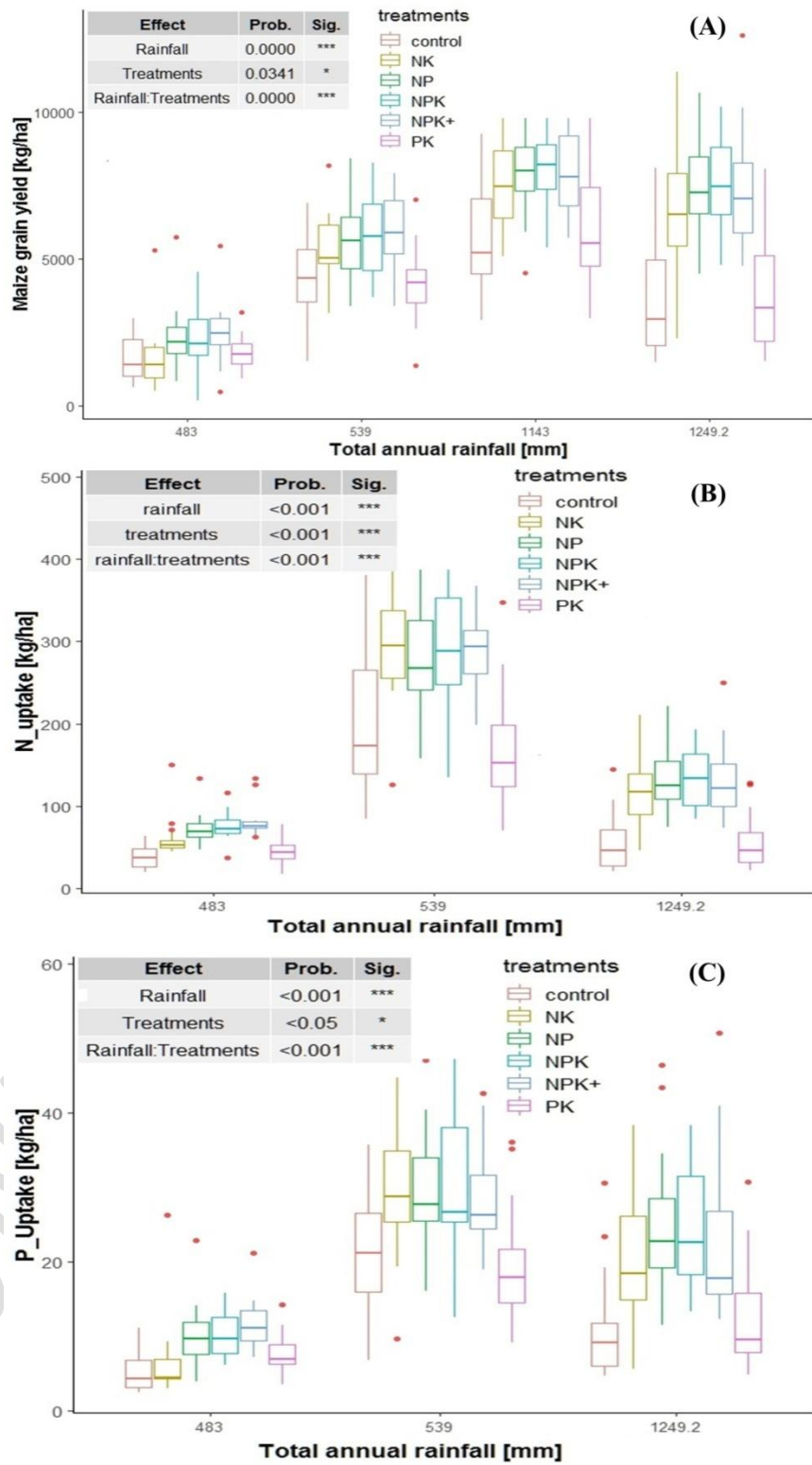
474

475 Both N and P uptakes significantly differed between locations for similar treatment and between
476 treatments for same location (Fig.6A, B). The difference in N and P uptake between locations for
477 every same treatment was attributed to difference in the rainfall amount received during growth
478 periods (Fig. 7). The N and P uptakes were higher in the high rainfall area than in the moisture
479 stress areas. The total N uptake for N applied treatments were on average more than 2-fold
480 higher than that of the control and N omitted treatments (Fig. 6A) in Jimma area, while it was
481 less than 2-fold at Adami Tullu and Bulbula suggesting that the N uptake efficiency was lower in
482 the moisture stress areas. This is further supported by the lower N recovery efficiency observed
483 for the moisture stress experimental sites (Table 4). Likewise, the total P uptake by the crop in
484 Jimma area was more than 2-fold higher than that of Adami Tullu and Bulbula. The average total
485 P uptake for the P applied treatments was only slightly higher than that of the P omitted
486 treatment but more than 2-fold higher than that of the control and N omitted treatments (Fig. 6B)
487 in Jimma area. This suggests that under favourable rainfall, the indigenous soil P can be
488 sufficient to support crop growth if N is not limiting in the soil. However, at the moisture stress
489 experimental sites (Adami Tullu and Bulbula), the average P uptake for all the P applied
490 treatments was only 1.5-fold higher than the control, N and P omitted plots. In those locations, P
491 uptake was highly constrained especially when, P fertilizer was omitted. When sufficient P is not
492 applied, the application of N fertilizer alone cannot support crop growth due to limited
493 availability of indigenous soil P in the soil solution owing to moisture stress and consequently
494 affecting P transport to the root surface for plant uptake. Thus, the P uptake efficiency becomes
495 lower in the moisture stress areas compared to the high rainfall counterparts.

496

497 The lower total N and P uptake per hectare in the moisture stress areas compared to the high
498 rainfall areas like Jimma area, is related mainly to both lower grain and biomass yields than to
499 the difference in nutrient concentration in the grain and stover, since grain N concentration was
500 even higher for the moisture stress areas than for Jimma area (data not shown). The total N and P
501 uptake by the crop (kg ha^{-1}) in the current study was lower than the N and P uptake by maize
502 under different fertilizer treatments reported by [36]. On the other hand, the total N and P uptake
503 values reported by [11] for maize was slightly lower than what was observed for the high rainfall
504 area (Jimma area) but is comparable with what is recorded for the moisture stress areas in the
505 current study. Although nutrient efficiency includes both uptake and utilization efficiency
506 components, this study focused on exploring only the uptake efficiency component specifically
507 the agronomic efficiency and apparent recovery efficiency since physiological efficiency is
508 varietal character which cannot easily be improved through agronomic intervention unlike the
509 uptake efficiency.

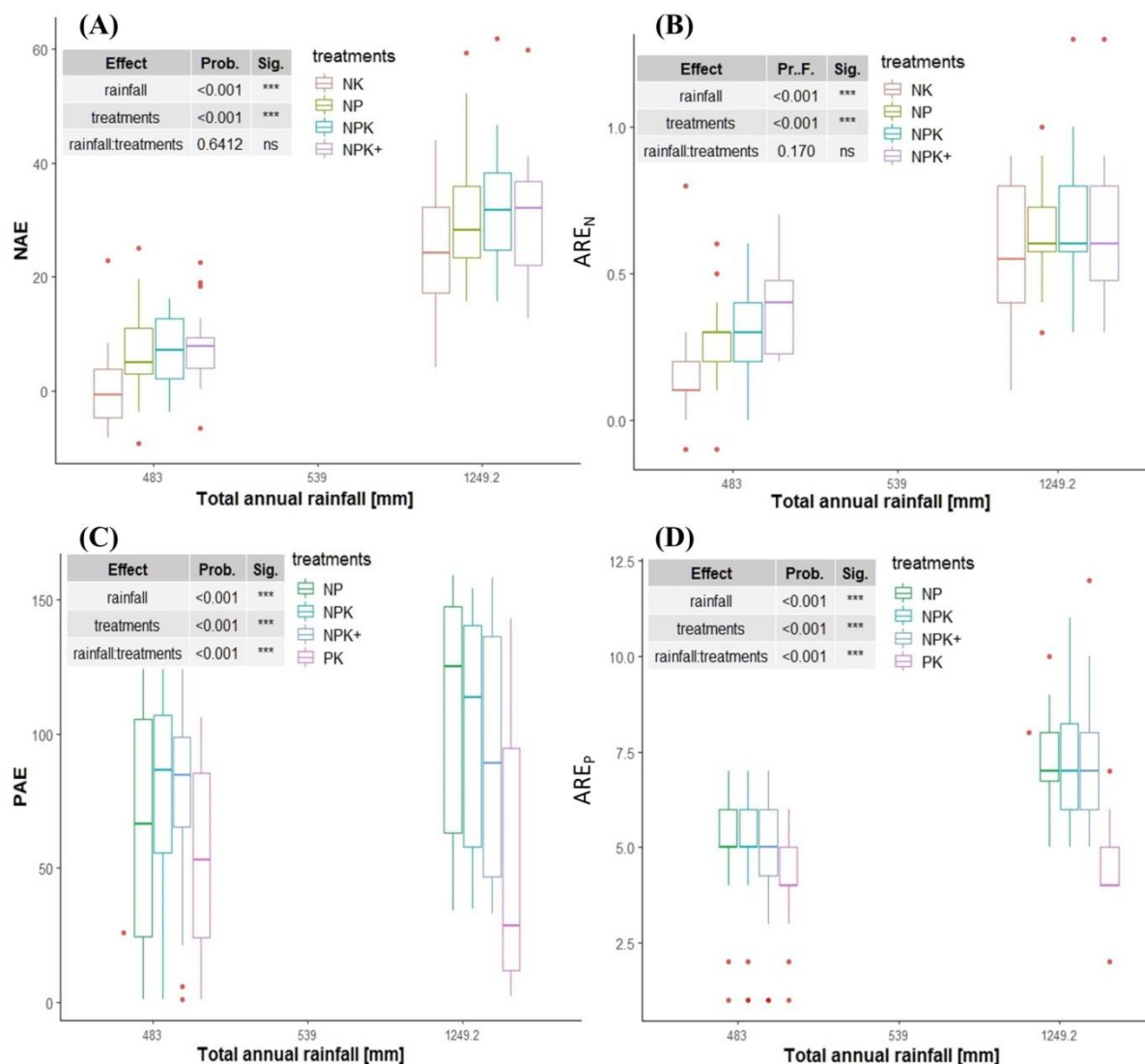
510



511

512 **Fig 7:** Relationship between total growing season rainfall, grain yield and total N and P uptake

513



514
515 **Fig 8:** Relationship between total growing season rainfall, Agronomic efficiency of N and P and Apparent
516 recovery fraction of N and P.

517 **4.6 Agronomic efficiency of N and P**

518
519 The agronomic efficiency of nitrogen (AE_N) highly contrasted between the high rainfall and
520 moisture stress areas. Significantly higher AE_N was observed for the high rainfall area than for
521 the moisture stress areas for every same treatment (Table 3). For instance, the agronomic
522 efficiency of N for the same treatment was 4-fold higher in Jimma area than Adami
523 Tullu/Bulbula. The agronomic efficiency of N reported in the current study for the NPK
524 treatment for high rainfall area is very close to the agronomic efficiency of N reported by [11],
525 which was 29-35 kg grain kg^{-1} N for the NPS applied treatment and 31-36 kg grain kg^{-1} N for the
526 NPKS applied treatments for different field types.

527
528 A similar trend to AE_N was observed with the agronomic efficiency of phosphorus (AE_P), in that
529 AE_P also significantly differed between high rainfall and moisture stress areas (Table 3). In the
530 high rainfall area, the maximum agronomic efficiency of P was 100.8 kg grain kg^{-1} of P (for

531 NPK treatment), while in the moisture stress areas, it was lower (27.6 kg grain kg⁻¹ P) for NPK
532 treatment at Bulbula and for NPK+ at Adami Tullu (Table 3). On average, AE_P was more than
533 3.5-fold higher for the high rainfall area compared to moisture stress areas. The agronomic
534 efficiency of P also varied between treatments at both contrasting agro-ecologies but with
535 different magnitude. Omission of N (i.e. PK treatment) highly reduced AE_P, suggesting that P
536 application in the absence of N cannot improve the agronomic efficiency of P. The absence of N
537 application reduced agronomic efficiency of P from 100.8 to 3.3 kg grain kg⁻¹ P applied in
538 Jimma area and from 16.1 to 1.4 kg grain kg⁻¹ P applied at Adami Tullu and from 17.6 to 13.5 kg
539 grain kg⁻¹ P applied at Bulbula. The maximum agronomic efficiency of P reported by [11] ranged
540 between 50 and 52 kg grain kg⁻¹ P for optimum fertilizer level and this was lower than the
541 highest AE_P we recorded for the high rainfall areas (100.8 kg grain kg⁻¹ of P) but higher than the
542 highest AE_P we recorded for the moisture stress areas (27.6 kg grain kg⁻¹ P) in the current study.
543 Improving the agronomic efficiency is a core objective of any agronomist, to enable farmers to
544 obtain higher profits. Selecting balanced fertilizer combination that confers the highest
545 agronomic efficiency of each nutrient is quite important since the findings from this study as
546 well as the findings of [11] confirm this concept. The co-application of N and P is especially
547 very important since absence of one of these nutrients remarkably reduce the agronomic
548 efficiency of the other nutrient as observed in the current study.

549

550 **4.7 Apparent Recovery Efficiency of N and P**

551

552 The apparent recovery fraction of N (ARE_N) did not significantly differ between treatments
553 except for Bulbula but differed between locations for every same treatment (Table 4). The ARE_N
554 was 1.7-fold higher for high rainfall area compared to moisture stress areas under the application
555 of balanced NPK fertilizer and this was related to sufficiency of rainfall since growing season
556 rainfall amount was the most important variable that influenced fertilizer recovery efficiency
557 between the two contrasting agro-ecologies (Figs. 8B and 8D).

558

559 Our study showed that with the application of balanced NPK fertilizer, up to 67% of the applied
560 N fertilizer could be recovered by maize crop in the high rainfall area while only up to 37/ 41%
561 of the applied N fertilizer could be recovered by maize crop in the two moisture stress areas,
562 Adami Tullu/Bulbula (Table 4). [11] also observed different recovery efficiencies of N at
563 different locations, which was also affected by fertilizer treatments, unlike our finding. They
564 observed higher N recovery fraction of 0.79 and 0.83 kg N kg⁻¹ of applied N, with the application
565 of balanced NPS and NPKS nutrients, respectively compared to the application of NK alone,
566 where the ARE_N was only 0.44, at similar locations. Thus, their finding supports the findings we
567 observed in the current study.

568

569 The apparent P recovery efficiency (ARE_P) significantly differed between locations for every
570 same treatment as well as between treatments for the same locations (Table 4). In the high
571 rainfall area, the maximum ARE_P observed was 0.35 kg P kg⁻¹ of applied P (NP and NPK
572 treatments) (Table 4). However, the maximum possible ARE_P was only 0.17 kg P kg⁻¹ of applied
573 P (for NPK treatment) and 0.15 kg P kg⁻¹ of applied P (for NPK+) at the moisture stress locations
574 (Bulbula and Adami Tullu, respectively). Thus, in the moisture stress areas maize crop could
575 only recover up to 17% of the P fertilizer applied (only half the amount recovered in the high
576 rainfall area), while maize crops in the moisture sufficient areas could recover up to 35% of the P

577 fertilizer applied under balanced NPK fertilization. The low P recovery efficiency in the moisture
578 stress areas can be related to insufficient soil moisture which brings about low P diffusion rate to
579 the root surface [28] than to the soil pH, which also usually affects P recovery efficiency. The P
580 recovery efficiency was very low for the treatments where N was missing in the current study
581 (Table 4). This indicates that the co-application of N with other nutrients enhances the P
582 recovery efficiency, as was also reported by [11]. The P recovery efficiency reported by [11] was
583 equivalent to the P recovery efficiency observed for the moisture stress areas but lower than that
584 of the high rainfall areas. In a nutshell, the lower agronomic as well as apparent recovery
585 efficiencies of both N and P, in the moisture stress areas compared to the moisture sufficient
586 areas was mainly related to difference in the amount of total growing season rainfall in the two
587 agro-ecosystems as can be realized from the strong positive effect of growing season rainfall on
588 both Agronomic and apparent recovery efficiencies of N and P (Figs. 8A, B, C, D).

590 5. Conclusions

591
592 High degree of variability in maize response to fertilizer application was observed between the
593 different study sites denoted as contrasting agro-ecologies (i.e high rainfall and moisture stress
594 areas). Response to fertilizer application in terms grain yield, nutrient uptake, agronomic and
595 apparent recovery efficiencies of N and P was higher in high rainfall than low rainfall areas, as
596 growing season rainfall amount was the determinant of the variability. Nitrogen was the most
597 yields limiting in almost all study sites while P was the second most yield limiting in some study
598 sites. The responses of maize to potassium and secondary and micronutrients were highly
599 localized; potassium was important at Gobu Sayo while micronutrients were important at Adami
600 Tullu. Thus, application of potassium fertilizer and micronutrients blended fertilizers would be
601 important in such areas as Gobu Sayo and Adami Tullu, respectively. The wide variability in
602 maize yield response to application of different nutrients observed in this study suggests that site-
603 specific nutrient management is fundamental to intensify maize production and productivity.
604 This study has demonstrated that balanced application of nutrients, especially NP and NPK
605 significantly improved nutrient uptake by crop, agronomic and fertilizer recovery efficiencies,
606 regardless of the study sites. The remarkable difference in N and P uptake, N and P agronomic as
607 well as recovery efficiencies between the high rainfall and moisture stress areas implies that soil
608 moisture play a key role in improving nutrient availability in the soil rhizosphere thereby
609 enhancing the agronomic and recovery efficiencies of nutrients through enhancing nutrients
610 concentration in the soil solution as well as their transport to the root surface. Ensuring moisture
611 availability during both side dressing and top dressing of fertilizers is, therefore, very important
612 to optimize the recovery of applied nutrients and minimize nutrient losses to the environment.
613 Mechanisms of improving nutrient efficiencies such as moisture conservation options through
614 tide-ridging, practicing supplementary irrigation when possible should be sought in moisture
615 stress areas. Proper management of N fertilizer is vital for increasing maize yields. Thus, policies
616 that promote farmers' access to N fertilizers are critical for intensification of maize productivity
617 in Ethiopia.

618
619

620 **Conflict of Interest:** The authors state that they have no conflict of interest.

621

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