

1 Maize Yield Response and Nutrient Use Efficiencies under Different Fertilizer Applications 2 in Contrasting Agroecosystems 3 4 5

6 Abstract 7

8 Variability in crop response and nutrient use efficiencies to fertilizer application is quite common
9 under varying soil and climatic conditions. Understanding such variability is vital develop farm-
10 and area- specific soil nutrient management and fertilizer recommendations. Hence the
11 objectives of this study were to assess maize grain yield response to nutrient applications for
12 identifying yield-limiting nutrients, and to understand the magnitude of nutrient use efficiencies
13 under varying soil and rainfall conditions. A total of 150 on-farm nutrient omission trials (NOTs)
14 were conducted on farmers' field in high rainfall and moisture stress areas. The treatments were
15 control, PK, NK, NP, NPK and NPK+ secondary and micronutrients. Maize grain yield, nutrient
16 uptake, agronomic and recovery efficiencies of N and P differed between fertilizer treatments
17 and between the contrasting agro-ecologies. The differing parameters between the agro-ecologies
18 were related to difference in rainfall amount and not to soil factors. Grain yield response to N
19 application and agronomic efficiencies of N and P were higher in the high rainfall area than in
20 the moisture stress areas. Grain yield responded the most to nitrogen (N) application than to any
21 other nutrients at most of the experimental sites. Owing to the magnificent yield response to N
22 fertilizer in the current study, proper management of nitrogen is very essential for intensification
23 of maize productivity in most maize growing areas of Ethiopia.
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26 **Keywords:** Ethiopia; *Zea mays* L.; Nutrient omission trials; Agronomic efficiency; Apparent
27 recovery efficiency, Nutrient uptake
28

29 **Abbreviations:** AE_N , agronomic efficiency of applied N; AE_P , agronomic efficiency of applied
30 P; ARE_N , apparent recovery efficiency of applied N; ARE_P , apparent recovery efficiency of
31 applied P
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33 1. Introduction 34

35 Food insecurity is a great concern in Sub-Saharan Africa (SSA) given the ever-increasing human
36 population, changing climate and persistently low crop yields. This is particularly so in Ethiopia,
37 which is the second most populous country in Africa with an average annual population growth
38 rate of 2.4%. Maize (*Zea mays* L.) has increasingly become one of the most important staple
39 food crops in Ethiopia. Its production and consumption have grown widely across many regions.
40 However, the current average maize yield is 3944 kg ha⁻¹ [1], which is much lower than its yield
41 potential. One of the major reasons for the low maize productivity in SSA and in Ethiopia in
42 particular is poor soil nutrients status. Nitrogen (N) and phosphorus (P) were specifically
43 deficient in most parts of the country [2, 3]. The wider variability in soil fertility, climate and
44 farmers nutrient management practices further contributed to low maize productivity at national
45 level. Farmers in the maize growing region apply small amounts of fertilizers containing mainly
46 N and P [4] Moreover, the recovery fractions of the applied nutrients are often quite low due to
47 nutrient losses, unbalanced nutrient application [5] and in some regions due to limited soil

48 moisture [6]. Moreover, poor crop and nutrient management practices such as lack of weeding,
49 low plant density and use of inappropriate blanket fertilizer recommendations can also reduce
50 nutrient use efficiency and crop yields [7, 8].

51
52 In Ethiopia, regional fertilizer recommendations have been developed for maize [9], which is
53 slightly region specific than the earlier single blanket recommendation of 100 kg DAP and 200
54 kg Urea ha⁻¹. Yet cropping systems, crop management practices, soil types and fertility status,
55 climatic conditions and other factors governing yield response to nutrients, vary considerably in
56 space and time [10, 11]. Due to such localized differences in crop growing conditions and the
57 soils' indigenous nutrient supply capacity, grain yield response to fertilizer application as well as
58 nutrient use efficiencies could vary across the maize production regions of the country as
59 reported by [10] in many Sub-Sahara Africa countries, by [11] in Zimbabwe and by [9] in
60 Ethiopia. Both blanket and regional fertilizer recommendations often lead to either over-
61 fertilization or under-fertilization by individual farmers. Excessive application, especially of N
62 and P fertilizers, may result in loss of investment in fertilizer input, nutrient accumulation in the
63 soil (low nutrient use efficiency) and environmental pollution [12]. By contrast, under-
64 fertilization may lead to nutrient mining owing to the imbalance between nutrient removed by
65 the crop and the nutrient applied in the form of fertilizer. To increase nutrient use efficiencies,
66 minimize soil degradation and sustain intensification of crop productivity, more site-specific
67 nutrient management options are recommended, especially for SSA where the cropping systems
68 are highly heterogeneous [10, 13]. Several studies revealed that optimum N and P rates differed
69 for different maize growing locations [9, 14] and with different cropping system [15], suggesting
70 that the old tradition of using blanket fertilizer recommendation can no more be an appropriate
71 practice to follow. Other studies confirm that ignoring important soils nutrients, other than N and
72 P in any crop production in the country could result in significant grain yield losses at least in
73 specific locations [16, 17, 18] and hence need to be carefully handled.

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

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

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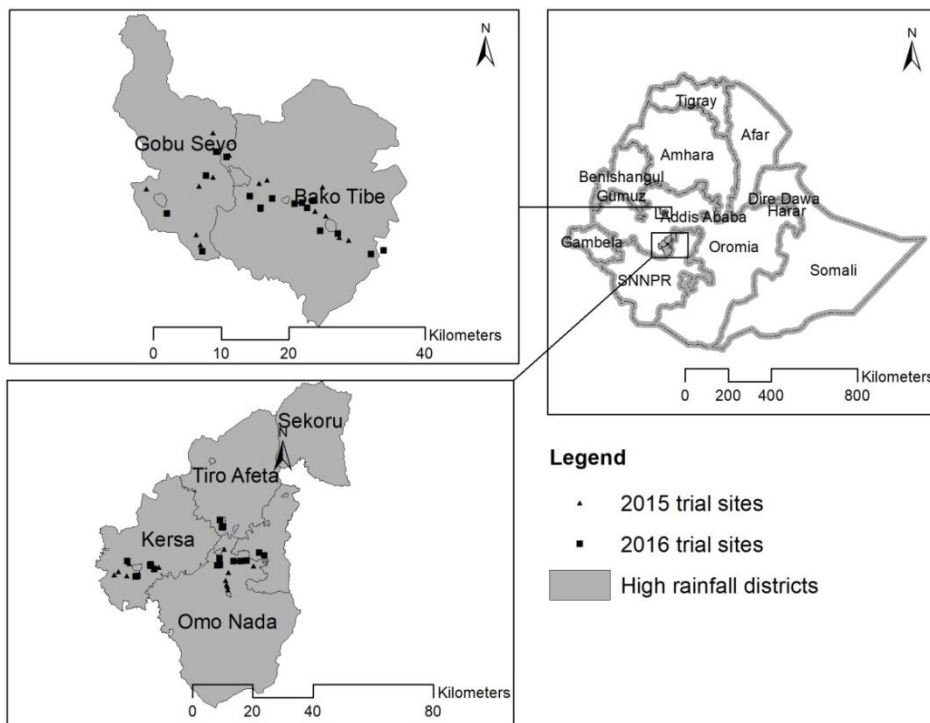
88 **2. Materials and Methods**

89 90 **2.1 Study sites**

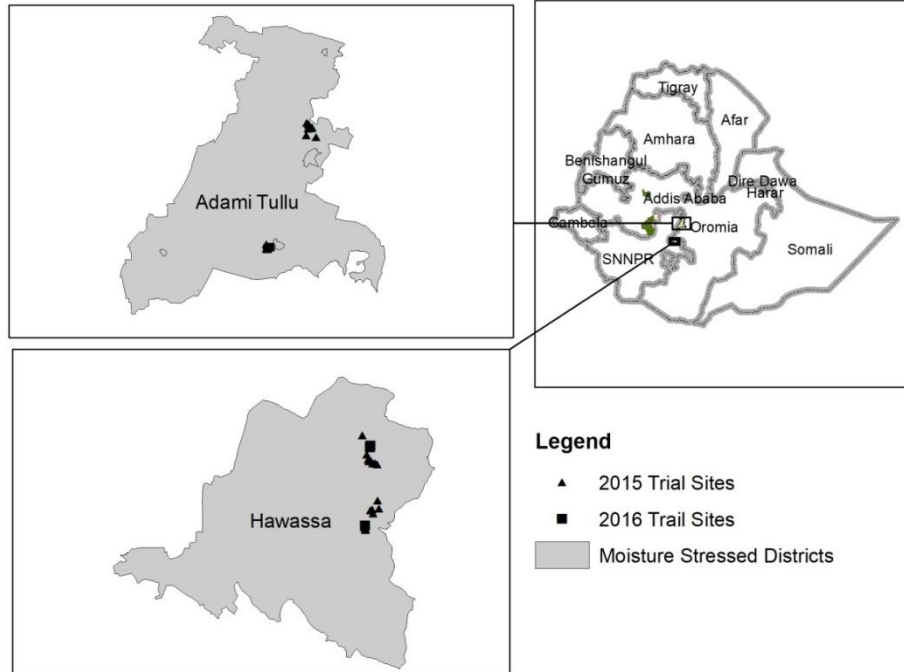
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92 Nutrient Omission Trials (NOTs) were conducted on farmers' fields in major maize production
93 areas of Ethiopia over two cropping seasons, 2015 and 2016. The NOTs study sites were
94 purposefully selected to cover a broad range of major maize growing areas in Ethiopia,

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

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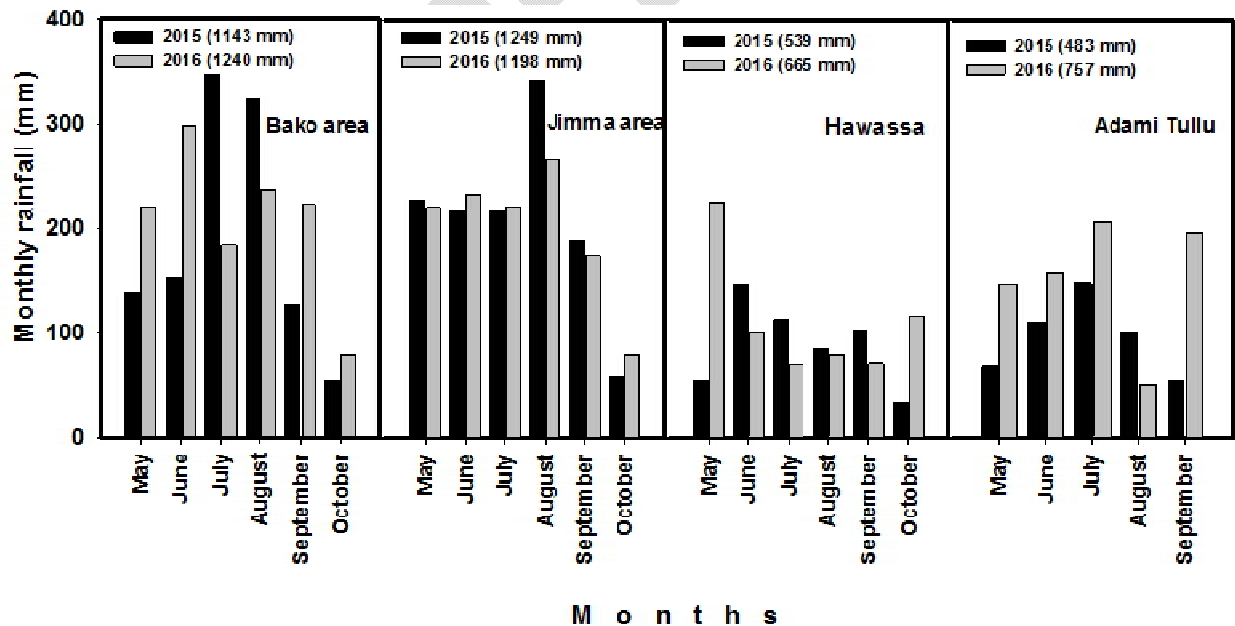


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 119 **Fig. 1:** Multi-location nutrient omission trial (NOTs) study sites located across major maize production
 120 areas in contrasting agro ecological zones in Ethiopia.

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

128
 129 **2.2 Nutrient omission trials set up and management**

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131 The nutrient omission trials (NOTs) consisted of six treatments that included: the control, PK
132 (0-40-40), NK (120-0-40), NP (120-40-0) NPK (120-40-40) and NPK + secondary (S, Ca, Mg.)
133 + micro-nutrients (B, Zn), which here after is denoted as NPK+ (Table 3). The rates of each
134 nutrient in the last treatment were 120-40-40-20-10-10-5-5 in that order. The treatments were
135 replicated across individual farmers' fields. To understand the temporal variability of yield
136 response to fertilizer application, the NOTs were repeated in 2016 cropping season in the same
137 fields used for 2015 season, using different new plots to avoid confounding effects of residual
138 nutrients.

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

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155 **2.3 Soil and plant analyses**

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157 Soil samples were collected from a depth of 0-20 cm at trial establishment before the application
158 of fertilizers. Soil samples were obtained from four points in each experimental field based on a
159 Y-frame methodology, and the four samples collected in each field were thoroughly mixed to
160 form a composite sample. The composite soil samples were analysed at IITA Laboratory in
161 Ibadan, Nigeria for major soil properties. The soil properties analysed included soil organic
162 carbon (OC) using chromic acid digestion [20], Total N using Kjeldahl digestion [21], soil pH
163 (1:2.5 soil: water suspension) according to [22], available P, Exchangeable cations and
164 micronutrients (Zn, Cu, Mn, and Fe) were determined using Mehlich 3 extraction procedure [23].

165
166 At harvest the stover and grains samples were oven dried and ground for N and P analyses.
167 Phosphorus was determined using ascorbic acid method following a procedure described by [24],
168 while N was determined after digesting the plant samples with sulphuric acid following a
169 procedure described by [25].

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177 **Table 1:** pH, organic carbon (OC), total nitrogen (TN), available phosphorus (P) and exch. potassium (K), Calcium (Ca), magnesium (Mg), zinc
 178 (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)

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

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182 2.4 Determination of grain yield and nutrient use efficiencies

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184 Harvesting was done at physiological maturity from a net plot area of 4 m × 4.5 m (18 m²). The
185 field grain weight was recorded and the grain yield was determined after adjusted to the standard
186 12.5% moisture content. Agronomic efficiency and apparent fertilizer recovery efficiency were
187 determined using the following formulas according to [26]:

188 Agronomic efficiency (AE) was determined as:

$$189 \quad AE = \frac{GYt - GYc}{Na} \dots\dots\dots(1)$$

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

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

$$193 \quad ARE = \frac{NUt - NUc}{Na} \dots\dots\dots(2)$$

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

196 2.5 Data analysis

197 The effects of fertilizer treatments on maize grain yield, nutrient uptake, agronomic and apparent
198 recovery efficiencies were analyzed using analysis of variance (ANOVA) procedures using a
199 Statistical Analysis System (SAS), version 9.3 Software,(SAS institute INC., Cary, USA). The
200 ANOVA was computed based on PROC GLM procedure and when ANOVA showed the
201 presence of significant treatment effects, mean separation was carried out using Tukey's test at
202 $\alpha=5\%$ level of significance.

203

204 3. Results

205 3.1 Grain yield at different locations of the two agro-ecologies

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

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

221 3.2 Maize yield response to N

222

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

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

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

234 3.3 Maize yield response to P

235 During 2015, grain yield on average increased by 967 kg ha⁻¹ (range of 616 to 1574 kg ha⁻¹) in
 236 high rainfall areas and by 801 kg ha⁻¹ (range of 498 to 1104 kg ha⁻¹) in moisture stress areas due
 237 to P application across all experimental sites except at Hawassa. During 2016, grain yield on
 238 average increased by 1202 kg ha⁻¹ (range of 349 to 2056 kg ha⁻¹) in high rainfall areas and by
 239 1609 (range of 1320 to 1880 kg ha⁻¹) in moisture stress areas due to P application across all
 240 experimental sites (Table 2).

241 During 2015 season, the highest yield response to P was observed at Gobu Sayo (1574 kg ha⁻¹)
 242 and Bulbula (1104 kg ha⁻¹). During 2016 season, yield responses to P application of 2056, 1880
 243 and 1628 kg ha⁻¹ were observed at Jimma, Bulbula and Adami Tullu (Table 2).

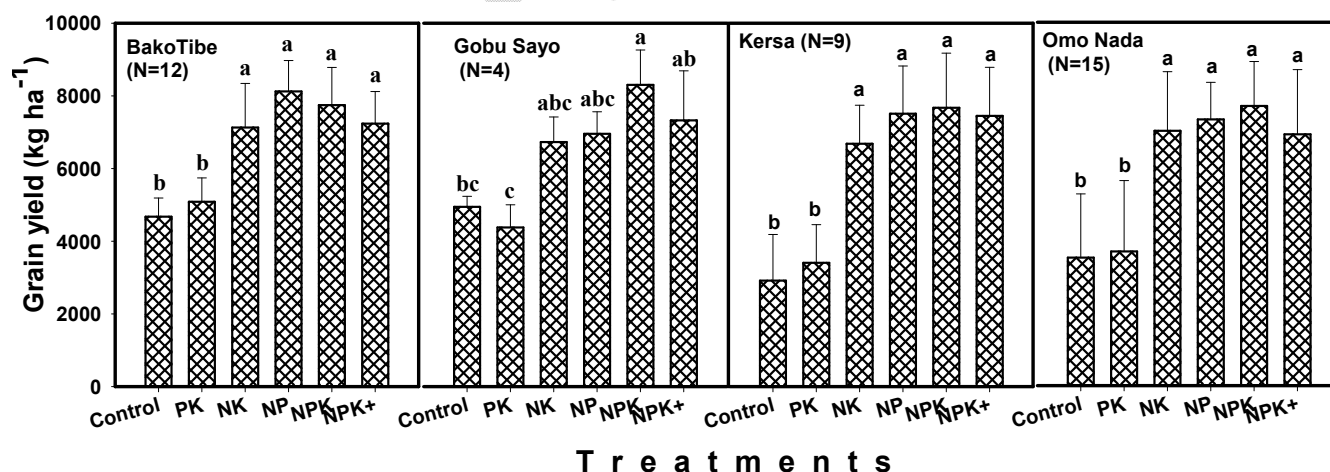
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245 3.4 Maize yield response to K and other nutrients

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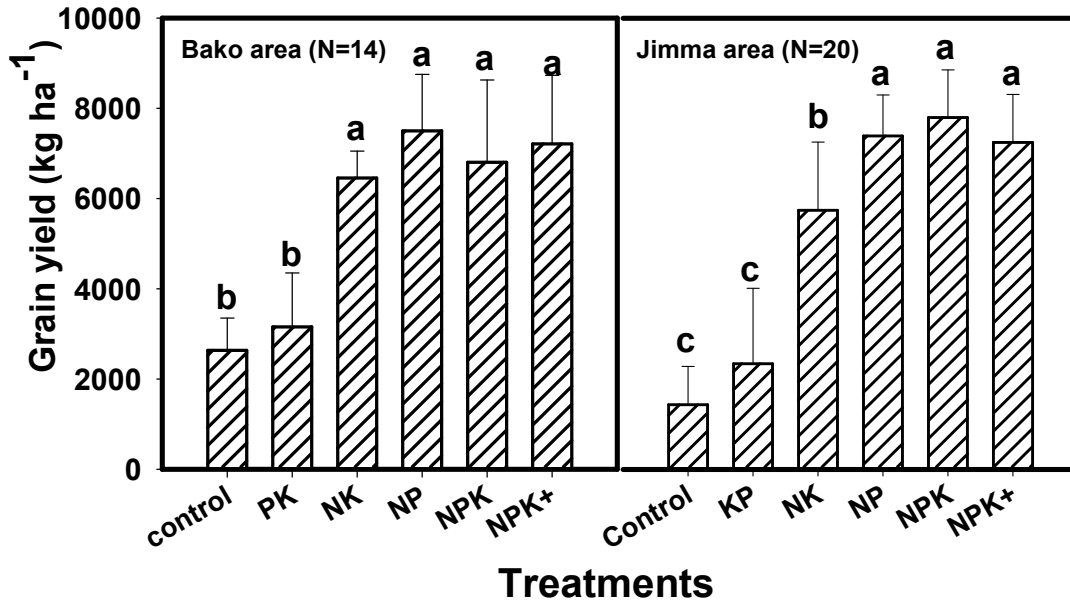
247 Overall, there was little or no yield response to all other nutrients applied (i.e. potassium, and
 248 secondary and micronutrients) (Table 2). However, maize responded to K application (1346 kg
 249 ha⁻¹) in Gobu Sayo in 2015 season and to secondary and micronutrients (1496 kg ha⁻¹) in Adami
 250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

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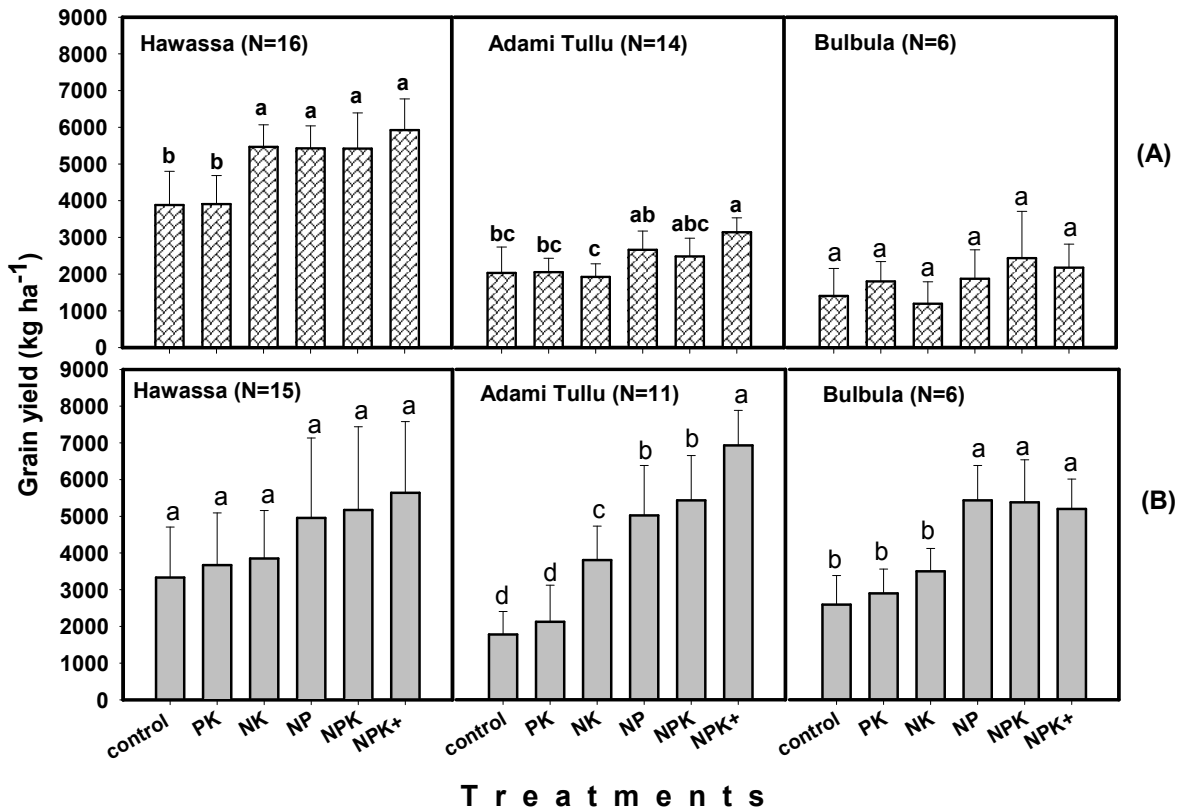
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253 **Fig. 3:** Effects of fertilizer treatments on responsive soils at Bako Tibe, Gobu Sayo, Kersa



254

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



258

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

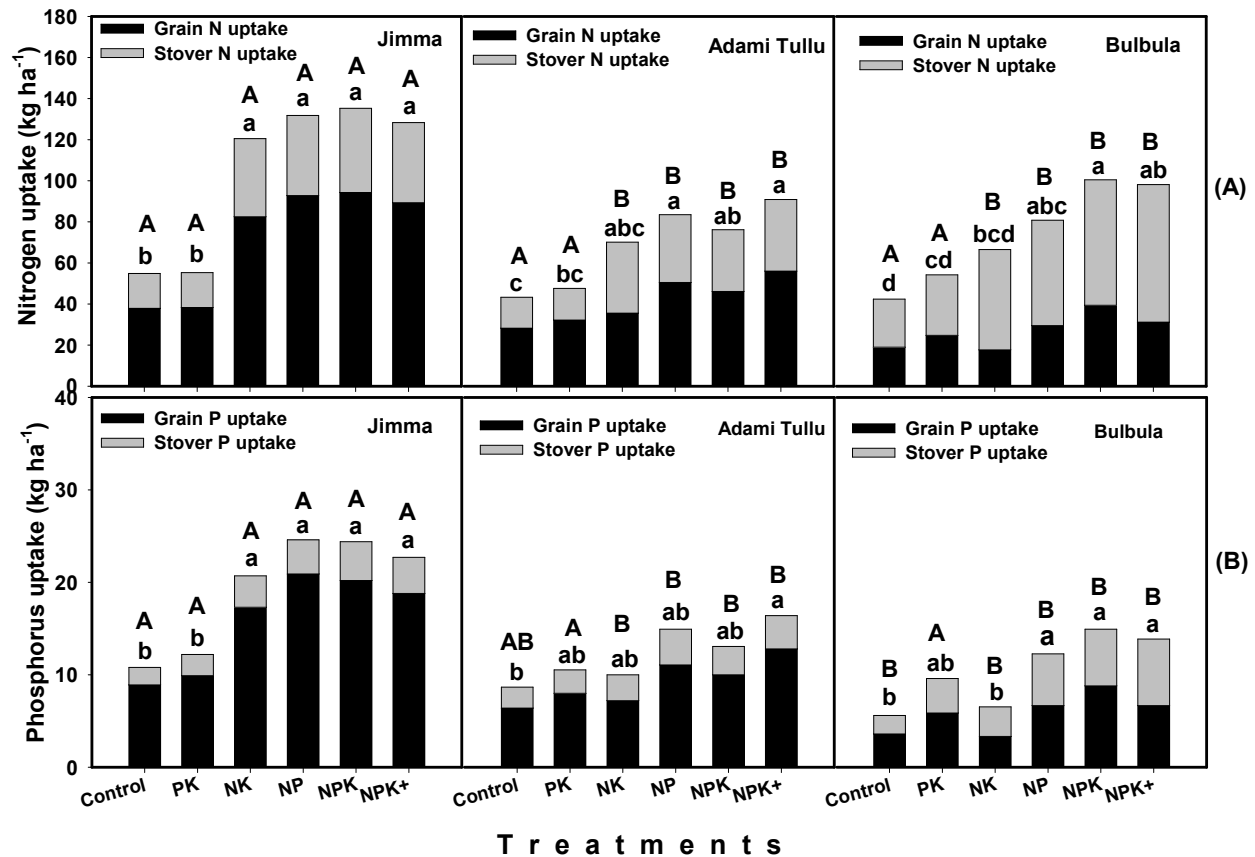
262 **Table 2:** Maize grain yield response to each nutrient applied in the nutrient omission trials
 263 (NOTs) established in 2015 and 2016 seasons

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

264
 265 *Yield response was calculated considering yield from NPK plot as maximum yield and subtracting the*
 266 *yield obtained from missing nutrient (e.g Yield from NPK plot –Yield from PK plot =Yield response due*
 267 *to N)*

268
 269 **3.5 N and P Uptake**

270
 271 Total N uptake significantly differed between the high rainfall and moisture stress areas for every
 272 same treatment (except for control and PK) as well as between treatments of every same location
 273 (Fig. 6A). The total N uptake for every same treatment (except for control and PK) was
 274 significantly higher in high rainfall area (Jimma) than in moisture stress areas (Adami Tullu and
 275 Bulbula) (Fig. 6A). Total N uptake, however did not significantly differ between the two
 276 moisture stress locations. The average N uptake (for all treatments) by the crop is 1.7-fold higher
 277 at high rainfall compared to the moisture stress area. The total N uptake was significantly lower
 278 for the control and N omitted treatments compared to other treatments at all experimental sites.
 279 At Jimma, the total N uptake ranged from 55 kg ha⁻¹ (for the control and N omitted treatments)
 280 to 135 kg ha⁻¹ (for the NPK treatment). At Adami Tullu and Bulbula, the total N uptake ranged
 281 from 38.5 (for control) to 82 kg ha⁻¹ (for NPK treatment), and from 40.1 (for control) to 89.2 kg
 282 ha⁻¹, (for NPK treatment), respectively. At Jimma and Adami Tullu, a higher proportion of the
 283 total N was taken up by the grain than the stover, while at Bulbula a higher proportion of total N
 284 was taken up by the stover than by the grain (Fig. 6A).



285
 286 (Different small letters denote significant difference between treatments at each location whereas;
 287 different capital letters denote significant difference between locations for similar treatment).

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

289
 290 Similar to total N uptake, the total P uptake also significantly differed between the high rainfall
 291 and moisture stress areas for every same treatment (except PK) as well as between treatments of
 292 same location (Fig. 6B). The total P uptake for every same treatment (except PK) was
 293 significantly higher in high rainfall area (Jimma) than in moisture stress areas (Adami Tullu and
 294 Bulbula) (Fig. 6B). The average P uptake (for all treatments) by the crop is 2.3-fold higher at
 295 high rainfall compared to the moisture stress areas. The total P uptake for NP, NPK and NPK+
 296 treatments were significantly higher than for the control, N and P omitted plots, especially at
 297 Jimma and Bulbula. The total P uptake was generally lower for the control and N omitted
 298 treatments at Jimma and for the control and P omitted plots at Bulbula (Fig.6B). At Jimma, the P
 299 uptake ranged from 10.8 kg ha⁻¹ (for the control) to 24 kg ha⁻¹ (for NP and NPK treatments).
 300 However, at the moisture stress areas, P uptake was lower ranging from 6.5 kg ha⁻¹ to 12.5 kg ha⁻¹
 301 at Adami Tullu and from 4.3 to 11.0 kg ha⁻¹ at Bulbula. Conversely to the grain and stover N
 302 uptake, the grain P uptake was consistently higher than the stover P uptake for all the three
 303 locations (Fig. 6B).

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307 **3.6 Agronomic efficiency of N and P**

308
 309 The agronomic efficiency of nitrogen (AE_N) did not vary between treatments at Jimma but varied
 310 at the moisture stress areas. It also varied between locations for the same treatment (Table 3).
 311 The AE_N ranged from 24.8 to 32.5 kg grain kg^{-1} N at Jimma. At the moisture stress areas it
 312 ranged from 1.0 kg grain kg^{-1} N (NK treatment) to 10.2 kg grain kg^{-1} N (NPK treatment) at
 313 Adami Tullu and from 0.1 kg grain kg^{-1} N (NK treatment) to 8.3 kg grain kg^{-1} N (NPK
 314 treatment) at Bulbula. The AE_N was significantly lower for the NK treatment compared to the
 315 rest of the treatments both at Adami Tullu and Bulbula. On the other hand, for every same
 316 treatment, the AE_N was significantly higher for the high rainfall than low rainfall areas (Table 3).

317
 318 The agronomic efficiency of phosphorus (AE_P) varied between treatments at all experimental
 319 sites. In Jimma area, the agronomic efficiency of phosphorus (AE_P) ranged from 3.3 kg grain kg^{-1}
 320 1 of P (N omitted plot) to 100.8 kg grain kg^{-1} of P (NPK treatment). Compared to the high
 321 rainfall area, the AE_P in the moisture stress areas was remarkably lower and ranged from 1.4 to
 322 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
 323 Bulbula, respectively (Table 3). The AE_P was significantly lower when N was omitted for Jimma
 324 and Adami Tullu. For every same treatment the AE_P was also significantly higher for the high
 325 rainfall area than for the moisture stress areas, except for the PK treatment where there was no
 326 significant difference in AE_P (Table 3).

327
 328 **3.7 Apparent recovery efficiency of N and P**

329
 330 The apparent recovery fraction of N (ARE_N) did not differ between treatments at the other two
 331 locations except at Bulbula but differed between locations for every same treatment (Table 4). At
 332 Bulbula, the ARE_N ranged from 0.16 (NK treatment) to 0.41 kg N kg^{-1} applied N (NPK
 333 treatment) (Table 4). For every same treatment, the ARE_N was significantly higher at the high
 334 rainfall area compared to moisture stress areas. However, the ARE_N did not differ between the
 335 two moisture stress areas.

336
 337 The apparent recovery fraction of P (ARE_P) significantly varied between treatments at all
 338 locations and also between high rainfall and moisture stress areas for every same treatment
 339 except for the PK treatment (Table 4). However, the ARE_P did not differ between the two
 340 moisture stress areas. At Jimma, the P recovery fraction ranged from 0.04 kg P kg^{-1} of applied P
 341 (for PK treatment) to 0.35 kg P kg^{-1} of applied P (for NP treatment). At the moisture stress areas,
 342 it ranged from 0.03 kg P kg^{-1} applied P (for PK) to 0.15 kg P kg^{-1} applied P (for NPK+
 343 treatment) at Adami Tullu and from 0.07 kg P kg^{-1} of applied P (for PK treatment) to 0.15 kg P
 344 kg^{-1} of applied P (NPK) at Bulbula.

345 **Table 3:** Agronomic efficiency of nitrogen (N) and phosphorus (P) as affected by fertilizer
 346 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

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

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Table 4: Apparent recover fraction of applied N and P fertilizer as affected by fertilizer 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

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

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4. Discussion

355

4.1 Grain yield response to N application

356

357 Grain yield response to nitrogen (N) application was much higher than the response to any other
358 nutrients at all study sites. This clearly shows that N is the most limiting essential plant nutrient
359 for maize intensification in major maize growing areas of Ethiopia and hence needs special
360 attention. The magnitude of yield response to the application of 120 kg N ha⁻¹ was more
361 magnificent in the high rainfall areas than in the moisture stress areas. This can explain the fact
362 that application of high dose of N fertilizer in moisture stress areas only slightly improve maize
363 productivity, since soil moisture being the medium of nutrient transport to the absorbing root,
364 plays a key role in influencing crop response to fertilizer application. Integrating soil moisture
365 conservation with fertilizer management could, therefore, be one of the vital strategies to
366 improve maize productivity in moisture stress areas. The more magnificent grain yield response
367 to N application in the high rainfall area compared to the moisture stress areas is in agreement
368 with the findings of [27], who also reported higher magnitude of yield response to nitrogen
369 application under favourable rainfall conditions than unfavourable conditions. The higher grain
370 yield response under favourable rainfall could be attributed to the availability of more available
371 N forms in the soil solutions owing to sufficient soil moisture as well as to the high water flux,
372 both of which increase the mass flow of nitrogen ions to the root surface enhancing N uptake

373 since mass flow rate is a function of both water flux in the root rhizosphere and nutrient
374 concentration in the soil solution [28].

375 At Gobu Sayo, only 14% of the fields had a soil total N content that is rated as low while at Bako
376 Tibe 66% of the fields had a soil total N content that is rated as low, and yet the yield response to
377 nitrogen application was higher at Gobu Sayo (3922 kg ha⁻¹) than at Bako Tibe (2657 kg ha⁻¹).
378 This suggests that total N content of soil might not necessarily reflect availability of nitrogen for
379 plant uptake. However, at Omo Nada, where 87% of fields had a soil total N that is rated as low,
380 the yield response to N application during 2015 was also correspondingly very high (4005 kg ha⁻¹).
381).

382 **4.2 Grain yield response to P application**

383 Yield response to P was significantly large at Gobu Sayo (1574 kg ha⁻¹) and Bulbula (1104 kg
384 ha⁻¹) during 2015 season and at Jimma (2056 kg ha⁻¹), Bulbula (1880 kg ha⁻¹) and Adami Tullu
385 (1628 kg ha⁻¹) in 2016 season (Table 2). The yield response to P was quite small although not nil
386 at Bako Tibe and inconsistent between years at Hawassa. The yield response to P during both
387 years was, however, not as high as the yield response to N application and such lesser yield
388 response to P application can be attributed to P fixing nature of the weathered nitisols and
389 calcareous soils of the high and low rainfall areas, respectively. It may also be due to the
390 carryover effects of previous P fertilizer application, especially in some sites where the available
391 P before planting was already in the high range (Table 1).

392 Grain yield response to application of 40 kg ha⁻¹ P was remarkably higher at Gobu Sayo and
393 Bulbula compared to the other experimental sites during 2015, while the response was higher for
394 all experimental sites except for Bako Tibe during 2016. This differential yield response to P
395 application across the experimental sites may only partly and not fully be explained by the
396 difference in the levels of available soil P across the locations. In the high rainfall areas such as
397 Gobu Sayo, none of the fields (Table 1) had available soil P that is above the critical P for maize
398 (12-17 mg kg⁻¹ soil) suggested by [29], which can explain the higher yield response to P
399 application (Table 2). At Bako Tibe, however, only 19% of the fields had available soil P content
400 that was greater than the critical soil P of 12-17 mg kg⁻¹ soil [29] and yet yield response to P
401 application was lower (Table 2) perhaps due to the P fixation as a result of acidity. At Omo Nada
402 and Kersa, 40% and 44% of the fields had available soil P content that was greater than the
403 critical soil P of 12-17 mg kg⁻¹ soil [29] and consequently the yield response to P application was
404 lower compared to Gobu Sayo (Table 2) perhaps due to the carryover effect of previously
405 applied P in most farms.

406 However, in the moisture stress areas such as Bulbula, Hawassa and Adami Tullu, the soil
407 available P were above the critical level of 12-17 mg kg⁻¹ soil in almost all the fields, and yet
408 there was a grain yield response to P application. Thus, under these conditions, the amount of
409 available P in the soil in relation to the critical level cannot explain the yield response to P
410 application. In those moisture stress areas, rather only a small fraction of the available P goes to
411 the soil solution and hence transport to the root surface via diffusion is highly constrained due to
412 both limited water availability and lower nutrient concentration in the soil solution since the rate
413 of diffusion depends on both water availability in the root rhizosphere and the concentration of
414 the nutrient ions in the soil solution [28]. Thus, more P needs to be applied to compensate for the
415 soil water limitation.

416

417 **4.3 Grain yield response to K application**

418 Crop response to K application was limited to few sites unlike the response to N and P
419 application. No response to K application was observed at Bako Tibe, Omo Nada, and Adami
420 Tullu, while grain yield increased due to application of 40 kg K ha⁻¹ at Gobu Sayo. At Gobu
421 Sayo, only one field had a soil K content that was less than the critical soil K level (234 to 312
422 mg kg⁻¹ soil) suggested by [30], for maize production and yet there was an average grain yield
423 response of 1346 kg ha⁻¹ to potassium application (Table 2). At Omo Nada and Kersa, all the
424 fields had soil potassium content above the critical level suggested by [30] for maize and
425 consequently there was no remarkable grain yield response to K application at these
426 experimental sites. Surprisingly, at Hawassa, nearly all the fields (94%) had soil K content that
427 were below the critical soil K content for maize production and yet there was no yield response
428 to K application. This could probably be due to dependency of the critical K levels on soil types
429 [31] and thus Hawassa could have lower critical K level than the critical level described by [10]
430 [30] for soils in Nigeria. Even within the same country, critical nutrient levels for a crop could
431 vary with locations/regions [31, 32]. At Bulbula, 83% of the fields had a soil K contents that
432 were below the critical K of 234 -312 mg kg⁻¹ soil for maize production and consequently, there
433 was a grain yield response of 498 kg ha⁻¹ to the application of 40 kg ha⁻¹ K (Table 2). Unlike
434 2015 season, where there was no yield response to K application in most sites, except at Gobu
435 Sayo and Bulbula, there was a tendency of yield response to K application in the other sites as
436 well during 2016 season. However, the magnitude of increase in grain yield due to the
437 application of 40 kg K ha⁻¹ was smaller ranging only from 213 to 411 kg ha⁻¹.

438 **4.4 Grain yield response to secondary (S, Mg, Ca) and micronutrients (Zn, B)**

439 The application of secondary (S, Ca, Mg) and micronutrients (Zn, B) during 2015 season
440 remarkably enhanced grain yield at Adami Tullu (1496 kg ha⁻¹) and slightly enhanced grain
441 yield at Bako (407 kg ha⁻¹) and Hawassa areas (469 kg ha⁻¹) but resulted in no grain yield
442 response at Jimma and Bulbula (Table 2). Grain yield response was consistent across years for
443 Hawassa and Adami Tullu but not for Bako area. The remarkable increase in grain yield at
444 Adami Tullu, however, cannot be attributed to any single nutrient effect as they were applied to
445 the plots altogether. However, analysis of the pre-planting soil samples taken from the
446 experimental fields showed that the soil S content (data not shown) were above the critical soil
447 sulphur level of 10 mg kg⁻¹ soil for all fields at Adami Tullu, which may confirm that the grain
448 yield response is less likely due to S application. The soil Ca and Mg content in these two
449 experimental sites were in the sufficient range of 151-350 mg kg⁻¹ soil according to rating by
450 [33] for Mg and 1200-2500 mg kg⁻¹ soil for Ca, suggesting that the grain yield response might
451 not be related to the application of Ca and Mg containing fertilizers. Moreover, [34], reported
452 that maize grain yields remained unaffected under a wide range of Mg levels with a Ca/Mg ratio
453 ranging between 1.8 to 36.9, suggesting that grain yield response cannot be expected due to Mg
454 application with the narrow Ca/Mg ratio ranging between 6.8 (at Bulbula) and 13.0 (at Hawassa).
455 Thus, the grain yield response could be due to Zn and B application since the Zn contents of all
456 NOTs fields at Bulbula, Hawassa and Adami Tullu were below the critical level of 5-10 mg kg⁻¹
457 soil suggested by [30] or 1.5 mg kg⁻¹ soil suggested by [35] and [33] for maize production. The
458 Zn contents of all NOTs fields in the high rainfall areas were, however, in the high to very high
459 range (Table 1) according to [33] rating and thus response could not be expected. The grain yield
460 response could also be due to B, besides Zn. However there is need for a further study to

461 understand the impact of each of the secondary and micro-nutrients on maize productivity in
462 those locations where response to combined application of these nutrients were noticed.

463

464 **4.5 N and P uptake**

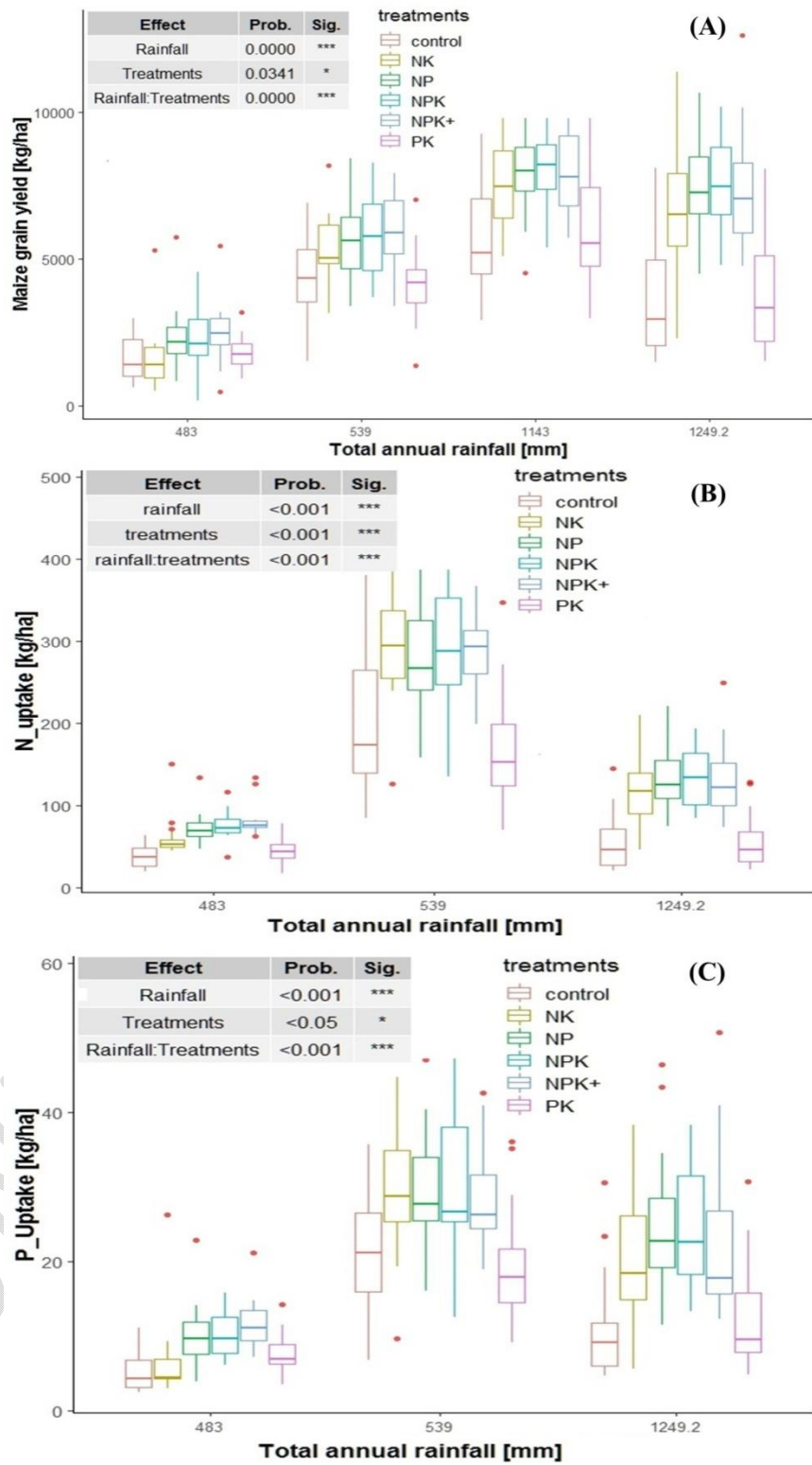
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466 Both N and P uptakes significantly differed between locations for similar treatment and between
467 treatments for same location (Fig.6A, B). The difference in N and P uptake between locations for
468 every same treatment was attributed to difference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

487

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

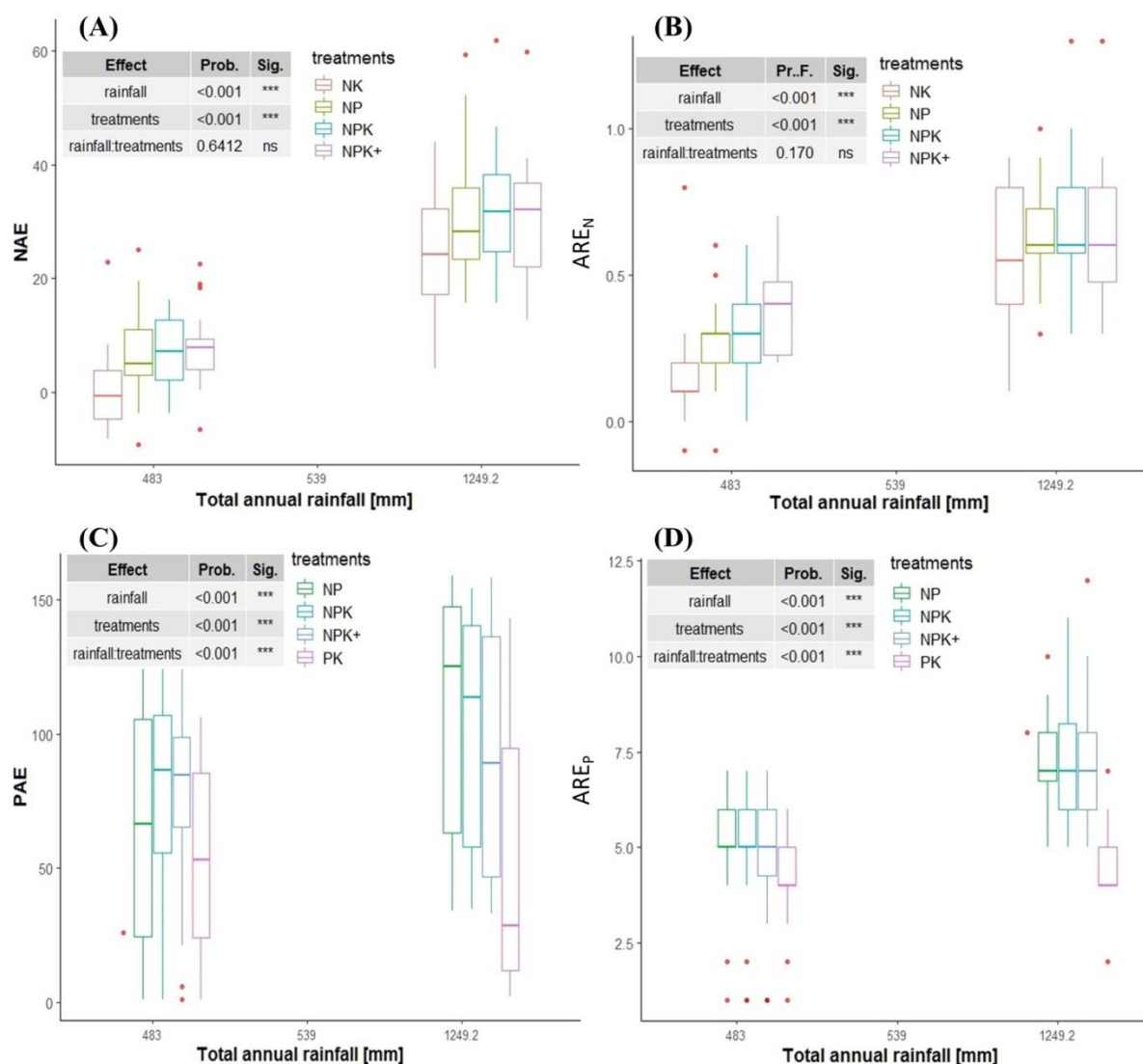
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501

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

503



504
505 **Fig 8:** Relationship between total growing season rainfall, Agronomic efficiency of N and P and Apparent
506 recovery fraction of N and P.

507 **4.6 Agronomic efficiency of N and P**

508
509 The agronomic efficiency of nitrogen (AE_N) highly contrasted between the high rainfall and
510 moisture stress areas. Significantly higher AE_N was observed for the high rainfall area than for
511 the moisture stress areas for every same treatment (Table 3). For instance, the agronomic
512 efficiency of N for the same treatment was 4-fold higher at Jimma than Adami Tullu/Bulbula.
513 The agronomic efficiency of N reported in the current study for the NPK treatment for high
514 rainfall area is very close to the agronomic efficiency of N reported by [11], which was 29-35 kg
515 grain kg^{-1} N for the NPS applied treatment and 31-36 kg grain kg^{-1} N for the NPKS applied
516 treatments for different field types.

517
518 A similar trend to AE_N was observed with the agronomic efficiency of phosphorus (AE_P), in that
519 AE_P also significantly differed between high rainfall and moisture stress areas (Table 3). In the
520 high rainfall area, the maximum agronomic efficiency of P was 100.8 kg grain kg^{-1} of P (for

521 NPK treatment), while in the moisture stress areas, it was lower (27.6 kg grain kg⁻¹ P) for NPK
522 treatment at Bulbula and for NPK+ at Adami Tullu (Table 3). On average, AE_P was more than
523 3.5-fold higher for the high rainfall area compared to moisture stress areas. The agronomic
524 efficiency of P also varied between treatments at both contrasting agro-ecologies but with
525 different magnitude. Omission of N (i.e. PK treatment) highly reduced AE_P, suggesting that P
526 application in the absence of N cannot improve the agronomic efficiency of P. The absence of N
527 application reduced agronomic efficiency of P from 100.8 to 3.3 kg grain kg⁻¹ P applied at
528 Jimma; and from 16.1 to 1.4 kg grain kg⁻¹ P applied at Adami Tullu and from 17.6 to 13.5 kg
529 grain kg⁻¹ P applied at Bulbula. The maximum agronomic efficiency of P reported by [11] ranged
530 between 50 and 52 kg grain kg⁻¹ P for optimum fertilizer level and this was lower than the
531 highest AE_P we recorded for the high rainfall areas (100.8 kg grain kg⁻¹ of P) but higher than the
532 highest AE_P we recorded for the moisture stress areas (27.6 kg grain kg⁻¹ P) in the current study.
533 Improving the agronomic efficiency is a core objective of any agronomist, to enable farmers to
534 obtain higher profits. Selecting balanced fertilizer combination that confers the highest
535 agronomic efficiency of each nutrient is quite important since the findings from this study as
536 well as the findings of [11] confirm this concept. The co-application of N and P is especially
537 very important since absence of one of these nutrients remarkably reduce the agronomic
538 efficiency of the other nutrient as observed in the current study.

539

540 **4.7 Apparent Recovery Efficiency of N and P**

541

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

548

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

558

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

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

579

580 **5. Conclusions**

581

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

608

609

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

611

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