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Response of Quality Protein Maize (*Zea mays* L.) to Nitrogen Rates and Plant Population in Ambo, Central Ethiopia

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Authors' contributions

This work was carried out in collaboration between both authors. Author GA performed the statistical analysis, wrote the protocol and wrote the whole manuscript. Author HK designed the study, performed the field experiment and generated data. Both authors read and approved the final manuscript.

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ABSTRACT

Aims: Quality protein maize (QPM) is one of the major food crops in Ethiopia. However, agronomic management practices were not properly developed for QPM production in the highland areas of Ambo, central Ethiopia.

Methodology: A field experiment was conducted at Ambo Crop Protection Research Center Farm to investigate the effects of nitrogen and plant population using hybrid QPM variety, AMH-760Q.

Study Design: The treatments consist of four nitrogen rates (0, 46, 92 and 138 kg N ha^{-1}) and four plant populations (44,444, 53,333, 66,666 and 88,888 plants ha^{-1}) arranged in split plot design with three replications.

Results: The nitrogen rates and plant population were significantly (*P* = .05) influenced most of QPM parameters. Increase in both nitrogen rates and plant population delayed days to tasseling, silking and physiological maturity, and also increased plant height, stem diameter and leaf area

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index. The application of nitrogen increased ear diameter, ear length, number of ears per plant, number of seeds per ear, thousand seed weight, straw and grain yields. Similarly, plant population at 66,666 plants ha^{-1} improved most yield components, straw and grain yields of QPM. The straw, grain and total N uptake were also increased in response to N application. The interaction of nitrogen and plant population also significantly (P = .05) affected straw and grain yields.

Conclusion: The results demonstrate that the application of 92 and 138 kg N ha^{-1} to 66,666 plants ha^{-1} resulted in higher straw and grain yields. Also if there is a need for high straw production for livestock feed, 88,888 plants ha^{-1} with 92 kg N ha^{-1} could be recommended. This implies that QPM straw and grain yields could be maximized through proper matching plant population and N fertilizer rates.

Keywords: Agronomy; fertility; food; grain; nutrition; straw.

1. INTRODUCTION

Maize (*Zea mays* L.) is the third major cereal crops in the world after wheat and rice and is used for both livestock feed and human consumption [1]. In Ethiopia, maize is the main staple food crop next to tef (*Eragrostis tef* L.) and wheat (*Triticum aestivum* L.). It ranks first in productivity and total grain production, and second in total area coverage after tef [2]. It is widely produced under rain fed, ranging from moisture stress to high rainfall areas in Ethiopia. The mass of maize produced in Ethiopia was non-quality protein maize for several decades. Nevertheless, quality protein maize (QPM) has been under development over the last two decades by collaborative engagement between Ethiopian Agricultural Research Institute and International Maize and Wheat Improvement, CIMMTY [3]. Accordingly, some improved varieties of QPM have been released for national production. Among them, AMH-760Q is the variety released for the highland agroecology of central Ethiopia.

Crop production in Sub-Saharan Africa is primarily limited by soil fertility decline and poor management practices [4]. Smallholder farmers in the major maize producing regions of Ethiopia depend on maize for their daily food throughout the year and they have limited access to protein sources such as meat, egg and milk for their daily consumption. Thus, the QPM is the potential food crop for alleviating protein malnutrition in Ethiopia, since it contains the two essential amino acids lysine and tryptophan [3]. The nutritional quality of the protein in QPM grain approaches that of protein derived from cow's milk [1]. Additionally, nutritional evaluation of QPM in various locations has proved the stability of lysine and tryptophan content within the prescribed range for QPM, in spite of quite diverse types of environmental conditions [5]. Therefore, the yield potential of maize can be realized and sustainable productivity can be achieved through the maintenance of optimum plant population and adequate N fertilizer application [6]. Thus, careful matching of plant density to prevailing levels of soil nutrient is critical in improving maize productivity.

Low soil fertility is one among the major factors limiting maize production and productivity in Ethiopia. It is also very common in many tropical cropping systems where fertilizer use is low and little or no agricultural residues are returned to the soil for maintaining soil fertility [7]. Thus, unless something is done to restore soil fertility, other efforts to increase crop production in this region would end up with little success. Fertilizer use is the core strategy to overcome soil fertility depletion through nutrient mining and the crop productivity decline [8]. Nitrogen is an essential nutrient for crop growth and it is a vitally important plant nutrient and is the most frequently deficient of all nutrients [9]. Nitrogen is a major plant nutrient for growth and makes up 1 to 5% of dry matter of plants. It is a component of protein and nucleic acids and when N is sub-optimal; growth is reduced. It is the most limiting nutrient for maize production especially in humid and sub-humid tropics [10], perhaps due to erosion, leaching, denitrification and volatilization loses. Nitrogen fertilizers are essential to increase crop yield, quality and production efficiency. Maize varieties or cultivars differ in grain yield response to N-fertilization [11]. It is also important to note that QPM varieties are relatively low in terms of yields than non-QPM. The optimum N fertilizer rate could be provided through site-specific fertilizer recommendation depending on the yield response of the varieties to the nutrient applied.

Plant populations affect most growth parameters of maize even under optimal growth conditions and therefore it is considered a major factor in determining the degree of competition between plants [12]. Maize is more affected by variations in plant density than other member of the grass family and hence sensitive to maximize its grain yield [13,14,15]. Maize yield differs significantly under varying plant density levels [16]. The grain yield per plant is decreased with increased plant density in response to decreasing light and other environmental resources available to each plant [14,16]. Enhanced plant-to-plant variability often results from increased competition among individual plants at progressively higher plant densities for limiting resources such as N, incident photosynthetically active radiation (IPAR), and soil moisture [17]. At higher plant population resource availability must be adequate to maintain uniform growth, development and high yield of maize [17]. Therefore, this experiment was undertaken to investigate the effects of nitrogen fertilizer rates and plant population on QPM in the highland of Ambo, central Ethiopia.

2. MATERIALS AND METHODS

2.1 Description of Study Area

The study was conducted at Ambo Plant Protection Research Center Farm, West Shewa Zone of Oromia National Regional State, Ethiopia during 2015/2016 cropping season. The center is located at 116 km^2 west of Addis Ababa and is characterized by intermediate highland agroecology having the length of growing period (LGP) of 4-5 months. The soil of the study area is characterized by black Vertisol. The center lies roughly at 8°57' N latitude and 38°07' E longitude and covers an area of 78.21 ha. The center was situated at an average elevation of 2175 m above sea level. The 10 years minimum and maximum temperature were 10.02°C and 26.89°C, respectively with annual mean temperature of 18.44°C. It receives a mono-modal rainfall, which extends from April to October, mean annual rainfall of 1018.19 mm. The mean annual relative humidity for a day is about 65%. The major crops grown in the area include maize (*Zea mays* L.), wheat (*Triticum estivum* L.), tef (*Eragostic tef*) and barley (*Hordium vulgaris* L.) [18].

2.2 Experimental Design, Treatments and Procedures

The seed bed was well prepared with traditional oxen plow. Two seeds of maize were hand planted per hill, and then after complete germination, the weak looking seedlings were thinned out to get one plant per hill.

Four N fertilizer rates (0, 46, 92 and 138 kg N ha^{-1}) and four plant populations (44,444, 53,333, 66,666 and 88,888 plants ha^{-1}) arranged in split plot design with three replications were evaluated at field condition. This plant population corresponds to 30, 25, 20 and 15 cm intra-row spacing with 75 cm inter row spacing for all populations. The seed rates that correspond to the plant population stated above are 20, 25, 30 and 39 kg ha^{-1}. The N fertilizer was assigned on the main plot while plant population was assigned on the sub-plot. The experiment was set on 4.5 m x 5.1 m = 22.95 m^2 gross plot size and 3 m x 5.1 m = 15.3 m^2 net plot size. The QPM maize variety used was AMH-760Q hybrid which was acquired from Ambo Plant Protection Research Center, Ethiopian Institute of Agricultural Research. Nitrogen fertilizer was applied to individual plants using the micro-dosing method. The N fertilizer was applied in split form by side dressing half of each dose at 45 days after sowing and the remaining half at 75 days after sowing from Urea source. An equal amount of phosphorus (46 kg P_2O_5 ha^{-1}) fertilizer was applied as tri-super phosphate to all plots. Other recommended crop management practices for maize production adhered as required.

2.3 Data Collection and Measurement

Field data were collected at different stages of maize growing period and after harvesting from the representative samples. These parameters include: phenology (tasseling, silking and physiological maturity), growth parameters (plant height, stem diameter, leaf area and leaf area index), yield and yield components (number of cobs per plant, number of kernels row per ear, number of kernels per row, thousand grain weight, straw yield (kg ha^{-1}), grain yield (kg ha^{-1}) and harvest index (HI). Maize tasseling days were determined as number of days from sowing to 50% tasseling. Maize silking days were determined when at least 50% of the ears have extruded silks.

2.4 Plant tissue Analyses

Stover and grain N concentration was estimated by digestion methods using Micro-Kjeldahl's apparatus. Potassium was determined using flame photometer, while phosphorous was analyzed by Olsen method.

Grain yield (kg ha^{-1}): Grain yield per plot (g plot^{-1}) was measured using electronic balance and then adjusted to 12.5% moisture contents of the seed by using digital Moisture Tester (M-3G) model and converted to hectare basis.

$$\text{Adjusted yield} = \frac{(100 - \text{actual moisture})}{(100 - \text{standard moisture})} \text{x obtained yield}$$

Harvesting index (HI): The physiological efficiency and ability of a crop for converting the total dry matter into economic yield is known as the harvest index (HI). The following formula was used: HI (%) = (Grain yield/total biological yield) x 100.

2.5 Soil Analysis

Fifteen soil samples were collected randomly from the depth of 0-30 cm across the field before planting and then bulked into one representative composite sample and analyzed for different physico-chemical characteristics. The soil samples were analyzed for organic carbon, total N, available P, exchangeable K, CEC, soil pH and soil texture at Soil and Plant Analysis Laboratory of Debre Zeit Agricultural Research Center, Ethiopia. The soil pH was measured with digital pH meter potentiometericaly in the supernatant suspension of 1:2.5 soil to distilled water ratio. Organic carbon was determined following wet digestion method [19] while Kjeldahl procedure used for the determination of total N [20]. Available P was determined following Olsen method [21]. Cation exchange capacity was measured after saturating the soil with 1N ammonium acetate (NH_4OA_C) and displacing it with 1 N $NaOA_C$ [22]. Soil texture was determined using the Bouyoucos hydrometer method [23].

2.6 Statistical Analysis

The data were analyzed using SAS version 9.0 [24] computer software package. Mean separation was computed using Least Significance Difference (LSD) at 5% probability level.

3. RESULTS AND DISCUSSION

3.1 Soil Physicochemical Properties of the Study Site

The laboratory analysis result indicated that the soil of Ambo experimental site was moderately alkaline (pH=7.23) in reaction. Total N was classified as very low (<0.1%), low (0.1-0.2%), moderate (0.2-0.5%), high (0.5–1.0%) and very high, >1% [25]. Thus, the experimental site N content was categorized as low and requires substantial amount of N fertilizer application and crop rotation with legumes for sustainable maize production. It is important to note that total N measures the total amount of nitrogen present in the soil, much of which is held in organic matter. The study soil held medium organic carbon content. Thus, organic carbon was classified as very low (<0.60%), low (0.6-1.0%), medium (1.0-1.80%), high (1.80-3.0%) and very high, >3.0% [26]. The results showed that available soil P content of the study soil was very high (Table 1). Earlier study classified Ethiopian soils available P <10 ppm as low, 11-31 ppm as medium, 32-56 ppm as high, and > 56 ppm as very high [27].

Cation exchange capacity (CEC) is the capacity of the soil to hold and exchange cations. It is an important indicator of the status of soil fertility under agricultural soils. The experimental site was rated as moderate in CEC [28] and clay in textural class (Table 1). Thus, the study suggests that organic matter application and crop rotation are quite important to improve the soil structure, water release and nutrient availability of the clay soil.

3.2 Effects of Nitrogen Rates and Plant Population on Phenology

Analyses of variance revealed that the main effects of nitrogen rates and plant population significantly (*P* = .05) influenced days to tasseling (DT), days to silking (DS), days to physiological maturity (DPM) of QPM (Table 2).

As the nitrogen rates increased, DT, DS and DPM were delayed. Mean value of the data showed that increasing nitrogen fertilizer consistently increased DT, DS and DMP. In overall, the highest nitrogen supplied (138 kg N ha^{-1}) resulted in relatively delay of most phenological parameters of QPM. These results supported the previous findings that applications of nitrogen on maize linearly delayed DT, DS and DPM [29,30,31]. The delay in phenological parameters of QPM might be due to nutrients availability in sufficient quantity that improved the photosynthesis and ultimately increased vegetative growth period.

Table 1. Soil characteristic of Ambo experimental site at 0-30 cm soil depth

Characteristics	Value	Character	Value
Soil pH-H_2O (1:2.5)	7.23	Sand	67%
Available P (ppm)	70.63	Silt	18%
Total N (%)	0.10	Clay	15%
OC (%)	1.16	Textural class	Clay
CEC (meq 100 g^{-1} soil)	19.80	-	-
Exc. K (meq 100 g^{-1} soil)	1.49	-	-

CEC= cation exchange capacity; OC= organic carbon; Exc.K= exchangeable potassium.

Plant population increase from the lowest (44,444) plants ha^{-1} to the highest (88,888) plants ha^{-1} delayed DT, DS and DPM (Table 2). The highest number of DT (67.5) was recorded with plant population of 88,888 ha^{-1} while the lowest DT (60.6) was recorded with the lowest plant population (44,444 ha^{-1}). These results are in line with those who reported that an increase in plant densities delayed numbers of DT, DS and DMP as compared to lower plant density [32, 33,34]. Higher plant densities, enhanced competition between crop plants for different growth resources especially moisture and nutrients that might have slowed the pace of phenological development that ultimately delayed tasseling emergence [35,36,37].

3.3 Effects of Nitrogen Rates and Plant Population on Growth Parameters

Analyses of variance revealed that N fertilizer application significantly (*P* = .05) affected plant height (PH), stem diameter (SD) and leaf area (LA), but did not significantly affect leaf area index (Table 2; Fig. 1). Interaction of N rates by plant population was non-significant in affecting plant height (Data not shown). The PH, SD and LA increased with increasing rates of nitrogen fertilizer (Table 2). Similar results were reported by many researchers [29,31,38], which stated that the increase in PH due to more N may be attributed to better vegetative development that resulted in increased mutual shading and internodal extension. A similar study suggested that higher N application increased cell division, cell elongation, nucleus formation as well as green foliage production [39]. Maize yield is strongly depended on leaf efficiency for absorption of solar radiation for photosynthesis process [40,41].

Plant population significantly (*P* =.05) affected LAI, but did not significantly affect effect PH and LA. The LAI was increased as plant population density was increased. The highest leaf area index (5.53) was recorded with a plant population of 88,888 ha^{-1} whereas the lowest LAI was obtained with 44,444 ha^{-1} plant population. These results are in confirmation with those of Kandil [42] who concluded that plots maintained a thicker density of 100,000 plants ha^{-1} gave the higher LAI than the plots maintained at lower plant density.

Fig. 1. Effect of nitrogen fertilizer application to densely populated QPM hybrid variety at Ambo, central Ethiopia

Table 2. Effects of nitrogen rates and plant population on tasseling, silking, physiological maturity, plant height, leaf area and leaf area index of QPM hybrid variety, AMH760Q at Ambo, central Ethiopia

Treatment	DT	DS	DPM	PH (cm)	SD (mm)	LA (cm^2)	LAI
N (kg ha^{-1})							
0	59.8^d	66.3^d	172.2^c	266.7^b	26.05^b	6217.2^{ab}	3.9
46	62.0^c	68.2^c	176.6^b	273.9^a	25.51^b	6589.6^a	4.1
92	66.9^b	74.3^b	181.3^a	275.2^a	26.24^{ab}	5973.3^b	3.8
138	68.3^a	77.1^a	181.7^a	279.7^a	27.53^a	6301.8^{ab}	4.0
LSD (5%)	1.1	1.3	3.5	0.9	1.3	519.2	0.4
CV (%)	12.3	8.1	2.3	5.3	7.9	9.3	12.3
Plant population ha^{-1}							
44,444	60.6^d	67.1^d	173.9^c	273.0	24.91^b	6350.8	2.83^d
53,333	63.3^c	70.7^c	176.6^b	272.3	26.74^a	6298.2	3.36^c
66,666	65.6^b	73.3^b	179.8^a	275.0	26.45^a	6217.2	4.15^b
88,888	67.5^a	74.9^a	181.3^a	275.1	27.23^a	6215.7	5.53^a
LSD (5%)	1.3	1.2	1.7	3.3	1.5	150.6	0.4
CV (%)	2.35	2.04	1.14	2.6	6.7	10.7	11.8

LSD is list significant difference. Means with the same letter in the columns are non-significantly different; NS= non -significant. DT= days to tasseling, DS=days to silking, DPM=days to physiological maturity, PH=plant height, SD=stem diameter, LA=leaf area and LAI=leaf area index

3.4 Effects of Nitrogen Rates and Plant Population on Yield Components

Analyses of variance revealed that nitrogen fertilizer and plant population significantly (P =.05) affected ear diameter (ED), earl length (EL), number of ears per plant (NEP), number of kernels row per ear (NKR), number of seeds per row (NSR) and thousand seed weight, TSW (Table 3). The ED, EL, NEP, NKR, NSR and TSW were increased with increase in nitrogen fertilizer rates. These results agreed with the previous findings that state maize yield components significantly increased as the rate of nitrogen fertilizer increased [29,30,38,41,43]. In general, the increase in yield components of QPM due to nitrogen fertilizer application are attributed to higher photosynthetic capacity that resulted from the functional role of nitrogen through enhancing leaf formation, cell division and vegetative growth promotion.

The plant population significantly (P = .05) affected maize ED, EL, NEP, NSR and TSW at Ambo, central Ethiopia (Table 3). All these yield components decreased as plant population density increases. The highest EL, NEP, NSP and TSW seed weight were recorded from the plot where maize was planted at 66,666 plants ha^{-1}. Similar findings were reported that ear length and number of ears per plant increase up to optimum plant population and then declined [38,44,45,46]. The increase in seed weight at intermediate plant population might be due to the availability of more resources (nutrient and water) for comparatively less number of plants which they utilized efficiently.

3.5 Nitrogen Rates and Plant Population Effect on Straw Yield

Straw yield of QPM was significantly ($p<0.05$) affected by nitrogen fertilizer rates and plant population (Table 3). The interaction of nitrogen rates and plant population was also found significant (P = .05) in influencing the straw yield (Fig. 2). All plant population density produced similar amount of straw yield at 0 and 46 kg N ha^{-1} (Fig. 2). However, 66,666 plants ha^{-1} density produced higher straw yield at the higher nitrogen doses and significantly differ from other treatments (Fig. 2). Straw yield increased significantly when the rate of nitrogen was increased from 0 to 138 kg N ha^{-1} even within the same plant population. The highest straw yield (23542.2 kg ha^{-1}) was obtained at 92 kg N ha^{-1} application while the lowest (12940.8 kg ha^{-1}) was recorded from the control treatment. The increase in straw yield with the increase in nitrogen fertilizer rates could be due to the fact that larger amount of nitrogen promoted more photosynthesis assimilates that resulted in higher vegetative growth.

The increment in plant population density positively influenced straw yield. The highest straw yield (22931.7 kg ha^{-1}) was recorded with 66,666 plant population ha^{-1} while the lowest straw yield (16875.3 kg ha^{-1}) was recorded under the lowest plant population (44,444 plants ha^{-1}). This value corresponds to 36% higher straw yield as compared to the lowest plant population density (Table 4). In general, straw yield of maize increased with increasing nitrogen fertilizer rates and plant population densities as compared to control treatment and lowest population density respectively. The increase in straw yield due to population density is related to more biomass accumulation with a higher number of plants per unit area than low number of plants. The presented findings confirmed that the biological yield increased by enhancement of nitrogen level and increasing high plant density [28]. Dry matter accumulation was much in high plant densities as compared to low plant densities. The straw yield response to nitrogen fertilizer rates was relatively higher than the response to plant population density.

Table 3. Effects of nitrogen and plant population on yield and yield components of quality protein maize variety, AMH760Q at Ambo plant protection research center

Treatment	ED	EL	NEP	NKR	NSR	TSW	SY	GY	HI
N (kg ha^{-1})									
0	34.1^{c}	11.8^{d}	1.1^{b}	12.40^{b}	25.4^{d}	234.7^{c}	13940.8^{c}	3343.5^{c}	24.2^{c}
46	41.9^{b}	16.0^{c}	1.3^{ab}	13.10^{a}	33.3^{c}	289.9^{b}	19175.9^{b}	5837.0^{b}	31.0^{a}
92	48.0^{a}	17.5^{b}	1.4^{a}	13.27^{a}	38.0	409.7^{a}	23542.2^{a}	6345.2^{a}	27.7^{b}
138	47.4^{a}	20.1^{a}	1.3^{ab}	13.22^{a}	40.5^{a}	402.9^{a}	22979.0^{a}	6554.2^{a}	29.7^{ab}
LSD (5%)	1.6	0.5	0.2	0.4	1.2	13.8	1422.5	350.2	3.2
CV(%)	6.7	10.9	3.5	6.3	12.6	19.2	17.3	19.2	5.3
Plant population ha^{-1}									
44,444	43.4^{a}	16.4^{b}	1.2^{b}	13.0^{b}	33.9^{b}	320.1^{c}	16875.3^{d}	6161.1^{a}	36.8^{a}
53,333	42.9^{ab}	16.0^{b}	1.1^{b}	13.2^{a}	34.0^{b}	336.3^{b}	18360.1^{c}	5594.4^{b}	30.1^{b}
66,666	43.6^{a}	17.6^{a}	1.5^{a}	12.9^{b}	36.5^{a}	351.6^{a}	22931.7^{a}	5917.7^{ab}	25.4^{c}
88,888	41.5^{b}	15.5^{c}	1.2^{b}	13.0^{a}	32.8^{b}	329.3^{bc}	21470.7^{b}	4406.8^{c}	20.3^{d}
LSD(5%)	1.6	0.5	0.2	NS	1.2	13.9	1422.5	385.0	3.2
CV(%)	4.4	3.7	20.2	4.2	4.2	4.9	8.5	7.5	13.5

ED= Ear diameter, EL=ear Length, NEP= numbers of ears per plant, NKRE= number of kernels row per ear; NSR=number of seeds per row, TSW=thousand seed weight; GY= grain yield and HI= harvest index. Means with the same letter in the column are non-significantly different

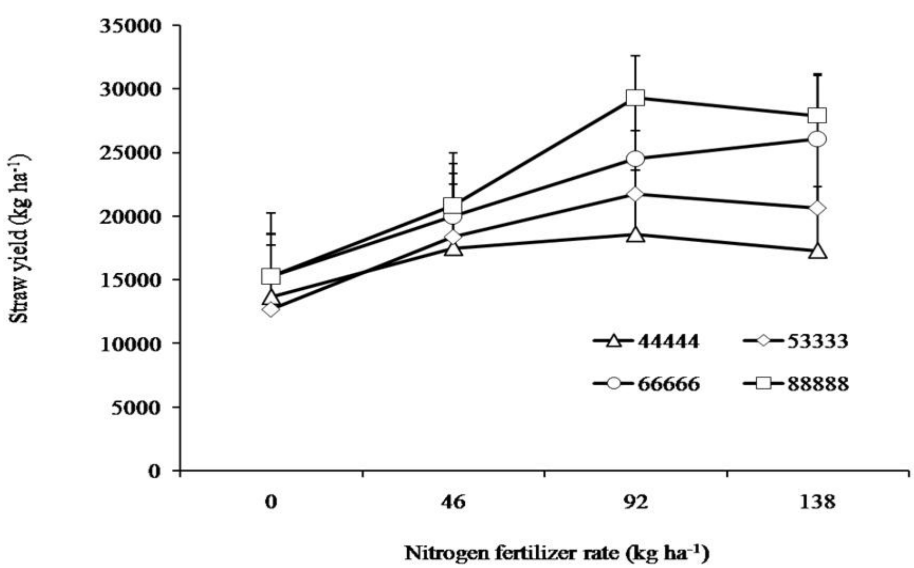

Fig. 2. Interaction effect of nitrogen x plant population density on straw yield at Ambo, central Ethiopia

3.6 Nitrogen Rates and Plant Population Effect on Grain Yield

The main effects of nitrogen rates and plant population significantly (*P* =.05) affected grain yield of maize (Table 3). Yield can be considered to be the results of the interaction of genotype, management, and environmental factors [47]. The application of 92 and 138 kg N ha^{-1} improved the grain yield of QPM by 90 and 96%, respectively over control plot (Table 3). The increase in grain yield with an increase in nitrogen rate might be attributed to better crop growth rate (plant height, yield components and straw yield (Table 3). These results confirmed the report that stated grain yield was increased as nitrogen levels increased [35]. Higher grain yield at higher nitrogen levels might be due to the lower competition for a nutrient that allows the plants to accumulate more biomass with higher capacity to convert more photosynthesis into sink resulting in more grains yield.

Also, plant population significantly affected grain yield. The maximum grain yield (6161 kg ha^{-1}) was obtained from the population density of 44,444 plants ha^{-1} while the minimum grain yield (4406.8 kg ha^{-1}) was recorded from the highest plant population density (88,888 plants ha^{-1}). The N x plant population density interaction showed that the highest plant density produced low grain yield across the N fertilizer rates tested, while the lowest plant density relatively produced higher grain yield. Nevertheless, the intermediate plant density (66,666 plants ha^{-1}) produced lower amount of grain at lower N rates and higher amount of grain at higher N rates tested (Fig. 3). At the higher plant densities, application of nitrogen at an increased rate is essential for obtaining maximum grain yield [48]. This result was also consistent with the finding of Thakur et al. [38] in which maximum grain yield of 4000 kg ha^{-1} was attained in response to the nitrogen application at the rate of 160 kg ha^{-1}. Application of different nitrogen fertilizer rates to a constant level of plant population density, increased grain yield of maize consistently in all levels (Fig. 3) implying that N nutrition is the vital limiting factor for maize production. The interaction of nitrogen rates and plant population were also found significant (*P* =.05) in influencing grain yield. At control and 46 kg N ha^{-1} application higher grain yield was recorded at 44,444 plant population ha^{-1}, but at higher N application (92 and 138 kg N ha^{-1}) higher grain yield was recorded at 66,666 plant population ha^{-1} (Fig. 3). This implies the importance of proper matching of plant population with nitrogen fertilizer rates.

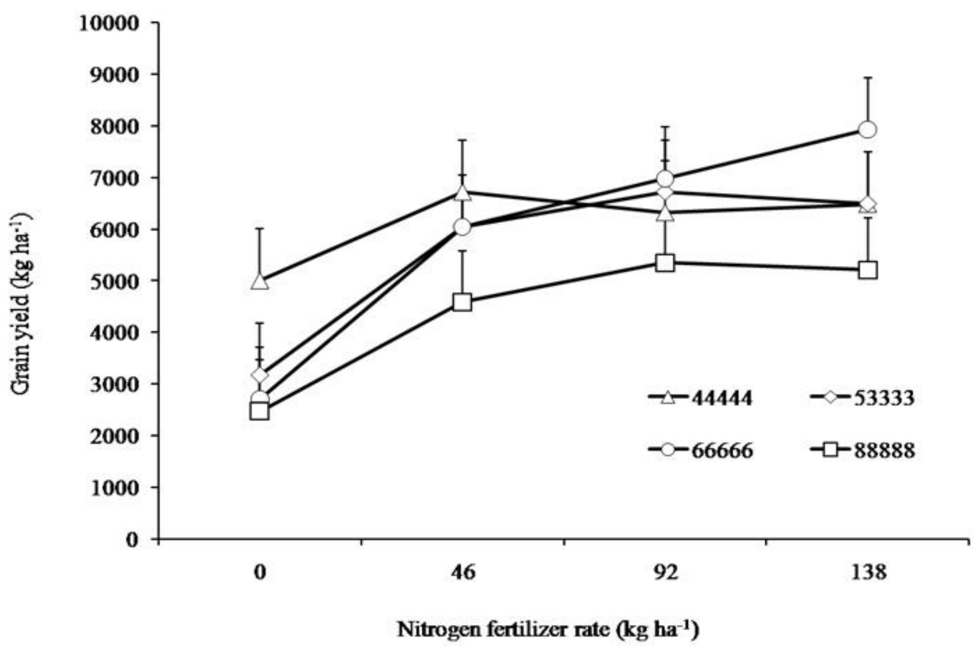

Fig. 3. Interaction effects of nitrogen fertilizer rates x plant population on grain yield of hybrid QPM variety, AMH760Q at Ambo, central Ethiopia

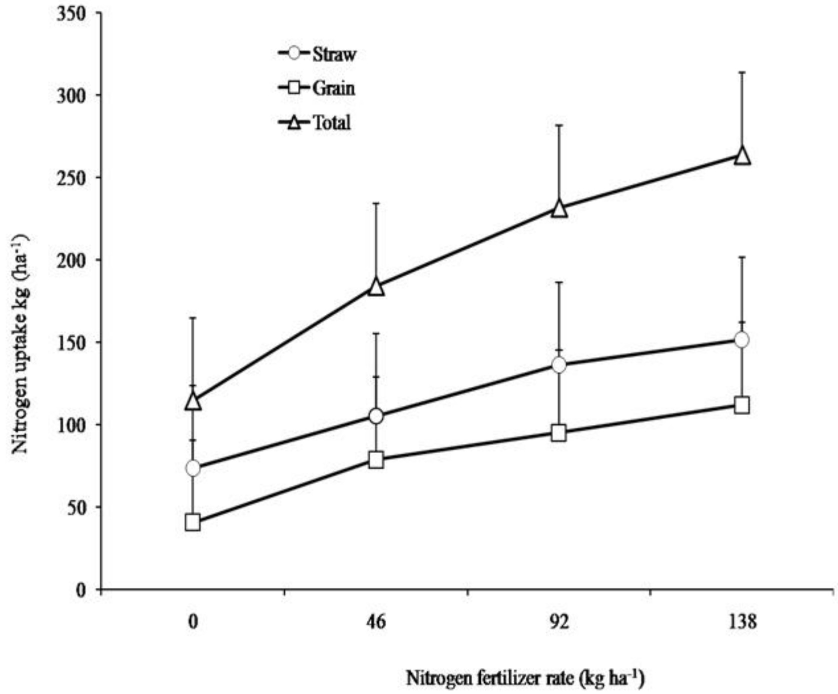

Fig. 4. N uptake of hybrid QPM variety, AMH760Q in response to N fertilizer application at Ambo, central Ethiopia

3.7 Harvest Index

Nitrogen fertilizer rates and plant population significantly ($p<0.05$) influenced the harvest index of quality protein maize (Table 3). Harvest index did not show clear trend with increasing nitrogen fertilizer rates from 0 to 138 kg N ha^{-1}. It is essential to note that harvest index (HI) show the potential physiological efficiency of plants to convert the fraction of photoassimilation rates to high grain yield. However, the HI of the present experiment was relatively low than previously reported values elswehere [49]. Ealier reports from different parts of the world indicated HI of maize as high as 50%; this could be largely attributed to the genetic potentail of the crop varieties.

Plant population density also affected harvest index (HI). Mean values of the data showed that decreasing trends of harvest index with increment in plant population density. In this case, the highest HI (36.8%) was recorded from 44,444 plants ha^{-1} while the minimum (20.2%) HI registered from the highest plant population (88,888 ha^{-1}). This result is similar with the previous finding who stated that HI decreased with increase in plant population density [48,49].

3.8 Nitrogen Uptake in Straw and Grain of QPM

The N uptake of QPM was significantly increased in response to N fertilizer application irrespective of plant population (Fig. 4). Similarly, straw and grain N uptake exhibited increasing trends in response to N application. This implies that N fertilizer application improved the protein content of QPM in the straw and grain.

4. CONCLUSION

Crop production in Sub-Saharan Africa is primarily limited by soil fertility decline and poor crop management practices. The sustainable production of quality protein maize (QPM) in the highland of Ethiopia can be achieved through optimum N fertilizer management and maintenance of optimum plant population. The results revealed that nitrogen fertilizer application improved straw yield of QPM by 37.6 to 68.9% over the control. Similarly, nitrogen fertilizer application improved grain yield of QPM by 74.6 to 96%. The straw, grain and total N uptake were also increased in response to N application. Generally, plant population at 66,666 ha^{-1} improved most yield components, straw and grain yields of QPM. Plant population increase from 44,444 to 53,333, 66,666 and 88,888 ha^{-1} improved straw yield by 8.8, 35.9 and 27.2%, respectively. In contrast, plant population increase from 44,444 to 53,333, 66,666 and 88,888 ha^{-1} resulted in reduction of grain yield by 10.1, 4.1 and 39.8%, respectively. Thus, the highest grain yield was recorded at the lowest plant population. Nitrogen fertilizer by plant population interaction revealed that matching the optimum fertilizer with plant population is very important for both higher straw and grain yields. Accordingly, we recommend the application of 46, 92 and 138 kg N ha^{-1} to 44,444, 53,333 and 66,666 plant population ha^{-1} for sustainable QPM production in the highland of Ambo, central Ethiopia. Thus, further study of nitrogen fertilizer rates and plant population may be crucial over wider locations with different QPM varieties.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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