Journal of Applied and Natural Science 7 (1) : 493 – 500 (2015)

JANS

Maize (*Zea mays* L.) response to subsoil compaction and nitrogen fertilization under semi-arid irrigated conditions

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Received: June 11, 2014; Revised received: March 29, 2015; Accepted: June 20, 2015

Abstract: The present investigation was carried out to access the optimal N dose and its impact on growth, yield and yield attributes of hybrid maize (*Zea mays*. L) under subsoil compaction condition. The experiment was conducted at Research Farm, Department of Soil Science, Punjab Agricultural University, Ludhiana during the summer seasons of the year 2012 and 2013. The experiment comprised three subsoil compaction treatments in main plots and three nitrogen levels in sub plots following split-plot design with three replications. Plant height, leaf area index and dry matter accumulation were negatively affected by subsoil compaction. However nitrogen fertilization mitigates the negative effect of subsoil compaction on growth of maize. Cob length was recorded lower with higher cob barrenness under higher degree of subsoil compaction. The grain yield was reduced by 13-16 per cent and biomass yield by 10-17 per cent due to subsoil compaction. The total N uptake was 14.6 and 18.2 per cent higher under C_0 treatment than that in highly compacted subsoil (C_2), while N_2 treatment had improved the total N uptake by 18.6 and 14.9 per cent as compared to N_0 treatment during the year 2012 and 2013, respectively. The results revealed that N_1 fertilization level can be recommended under subsurface compacted soils as compared to N_0 and N_2 rates. This study further suggests the management option should be explored in addition to deep tillage to maximize yield of maize.

Keywords: Dry matter, Subsoil compaction, Maize, N uptake, Nitrogen, Yield, Yield attributes

INTRODUCTION

Maize is the third most important cereal grain crop after wheat and rice, produced worldwide for its food, feed and other industrial purposes. Environmental and soil factors such as air temperature, precipitation, atmospheric CO_2 concentration, and nutrient availability affect crop phenology, growth and development. Inherent soil nutrient status and nutrient fertilization (i.e, location and cultivar specific) limits the maize yield (Azeez *et al.*, 2006). Nitrogen is one of the most important nutrients required by maize plants in large quantities for completion of its life cycle. A significant effect of N fertilization had been reported on number of grains per cob, 1000-grain weight (Fedotkin and Kravtsov, 2001) and also improves yield and yield components of maize (Torbert *et al.*, 2001). Deficiency of N at critical crop growth stages adversely affects crop phenology, limits growth and yield of maize. Crop respond to N up to an optimum level beyond which the crop does not response to N input, as additional N application negatively affect the crop growth (Hennessy, 2009) and environment. Judicious N management interventions not only optimize grain yield but also reduces the potential N leaching losses beyond the root zone of the crop (Worku *et al.*, 2007; Yousra *et al.*, 2013) and N_2O emissions from field. Maximum nitrogen use efficiency of about 50 per cent had been reported under optimal N level, however it varied from 30-40 per cent under poor N management (Patel *et al.*, 2006) in maize.

In addition to plant nutrition, soil environment plays a significant role in crop establishment, growth and yield. Tillage systems are sequences of operations that manipulate soil to prepare good seed bed and facilitate favorable soil environment for better crop production. Intensive tillage operations (sowing to harvesting) results in the formation of compact subsoil layer below the soil surface with the increase in number of passages of machines (Williamson and Neilsen 2000). High soil strength and low porosity of subsurface compact layer restricts crop roots in the top layer and reduces the volume of soil to be explored by the plants for nutrients and water (Lipiec *et al.*, 2003). Due to compact subsoil layer, volume of soil explored by root is reduced, which lessens the availability of soil N to roots, resulting in reduced shoot growth (Sakai *et al.*, 2008). Farmers apply more N fertilizers to get higher yield under such conditions, which increases the cost of production and also lead to higher greenhouse gases emission and leaching losses of N (Cassman, 2002). Thus, it is essential to optimize nitrogen application for getting a higher crop yield so that maximum benefits could be achieved under subsoil compacted soils. Thus, the present study was conducted to evaluate the effect of different levels of subsoil compaction and nitrogen on the growth, yield

ISSN : 0974-9411 (Print), 2231-5209 (Online)

and yield attributes of maize (*Zea mays* L.).

MATERIALS AND METHODS

The present experiment was carried out at Research Farm of Department of Soil Science, Punjab Agricultural University, Ludhiana during the summer season of 2012 and 2013. The site is located at 30º54′ N latitude and 75º48′ E longitude with an altitude of 247 m above the MSL (mean sea level), in the central plain region of Punjab. It represents semi-arid climate with very hot and dry summer from April to June, hot and humid conditions from July to September, cold winters from November to January and mild climate during February and March. July to September months receives 75 per cent of the average annual rainfall in the area. The soil was classified as alluvial, sandy loam in texture, calcareous, Typic Haplustept. The soil P and K of experimental site were lied in medium category, while N and Organic carbon status of soil was low. The physio-chemical properties of soils are given in Table-1.

A split-plot design was laid out with three subsoil compaction levels (main plot treatments), and three doses of N (subplot treatment) in three replications. The subsoil compaction treatments were imposed by removing the surface 15-cm soil and then compacting the sub-surface layer with passes of tractor mounted roller to achieve the desired bulk density. After achieving the desired bulk density, surface soil was put back on the place. The soil compaction treatments were C_0- Control (bulk density, D_b= 1.55-1.65 Mg m^{-3}), C_1- Moderate compaction, (D_b = 1.70-1.75 Mg m^{-3}) and C_2- High compaction (D_b >1.80 Mg m^{-3}) at 15-30 cm depth. The nitrogen treatments imposed were: N_0 -155 kg N ha^{-1}, N_1-195 kg N ha^{-1} and N_2 -235 kg N ha^{-1}

The maize variety PMH-1 was sown on June 27 during 2012 and June 22 during 2013. Sowing was done on the same day for all plots with row to row spacing of 60 cm and plant to plant spacing of 20 cm, during each year of the study. Phosphorus, potassium and zinc sulphate were applied @ 60, 30 and 25 kg ha^{-1}, respectively. Entire quantity of P, K and Zinc Sulphate with one third of N (as Urea 46 % N) was applied at the time of sowing and remaining N was applied in two equal splits i.e. at knee high and at pre-tasselling stages. The recommended cultural practices of Punjab Agricultural University, Ludhiana (Anonymous, 2012) were followed to ensure proper weed, insect and pest control.

The plant height (cm) was recorded as average from five randomly selected plants at 30 days after sowing (DAS), 60 DAS and at harvesting stage. Two plant samples for dry matter accumulation were cut from the ground level from each plot at 30 DAS, 60 DAS and at harvesting stage. These plants were sun dried and then in oven at the temperature of 60 ^{o}C till constant weight was achieved. Average weight (g dry matter accumulated plant^{-1}) for these plants was taken. Leaf area index was recorded using the Sun Scan Canopy Analyzer at 30 DAS, 60 DAS and at harvesting stage. All the ears from each net harvested plot were sun dried for three days and shelled. Moisture content of grains from each plot was determined. The grain yield was adjusted to 15 per cent moisture level and expressed in t ha^{-1}. The cob length (cm), cob bareness (%) and 1000-grain weight (g) were recorded from 10 randomly selected cobs from each plot at the time of threshing. Unfilled portion of cobs selected for length was measured with scale to calculate the percentage barrenness of the cob. The grain yield and biomass was recorded after sun drying and threshing of produce. The harvest index (HI) was calculated as the ratio of maize grain yield to the total biomass yield.

Grain and straw samples were collected at harvest from each plot and appropriate amounts of the ground grain and straw material was used to determine the total N content using a modified Kjeldahl digestion method (Nelson and Somers, 1973). The grain and straw N content was used to drive total N uptake by multiplying with total grain and straw yields, respectively. Statistical analysis was done using PROC GLM (SAS software version 9.1, SAS Institute Ltd., USA) as per the standard procedure given by Gomez and Gomez (1984) for the analysis of variance (ANOVA) for split plot design. Duncan's multiple range test (DMRT) was employed to compare treatment means. PROC CORR was used for Pearson's correlation analysis between growth, yield and yield attributes.

RESULTS AND DISCUSSION

Effect of soil compaction and N fertilization on plant height, periodic dry matter accumulation and leaf area index: Plant height decreased significantly with the increase in the soil strength of subsoil layer at 30, 60 DAS (days after sowing) and at harvesting stage of maize (Table 2). Maximum plant height (267.4 and 258.75 cm) was recorded at harvesting in plots with C_0 treatment against minimum (248.33 and 223.5 cm) with C_2 treatment plots during the year 2012 and 2013 respectively. The C_2 treatment resulted in reduced plant height by 15.7 and 10.8 per cent at 30 DAS, 17.6 and 11.3 per cent at 60 DAS and 7.1 and 13.6 per cent at harvesting than that in C_0 treatment during the year 2012 and 2013 respectively. The reduced plant height in response to subsoil compaction may be attributed to restricted root growth and reduces N availability (Tan *et al.*, 2008) under higher subsoil strength. N fertilization significantly affect the plant height at 30, 60 DAS and at harvesting stage. Sweeney *et al.*, (2006) also reported reduction in plant height and LAI of soybean and sorghum due to soil compaction. Abu-Hamdeh (2003) also observed lower plant height of maize due to soil compaction. Maximum plant height at harvesting stage (265.31 and 252.84 cm) was recorded in N_0 plots against minimum (251.56 and 234.2 cm) under N_2

treatments during the year 2012 and 2013 respectively. Increased plant height in response to higher N application had also been confirmed by Akbar *et al.,* (2002) and Rasheed *et al.,* (2004). Increase in plant height with higher N application may be attributed to more vegetative development that resulted in increased mutual shading and internodal extension.

Dry matter production serves as a reliable measure of the relative influence of different treatments on plant growth and ultimately on the crop yield. Data on dry matter accumulation by crop reveals that dry matter decreased with increase in the bulk density of subsoil layer (Table 3). The crop sown under C_0 treatment achieved significantly higher dry matter than that in C_1 and C_2 treatments at 60 DAS and at harvesting during the year 2012 and 2013. Increase in bulk density of subsoil from C_0 treatment to C_1, decreased dry matter accumulation by 7.1 and 6.2 per cent, while increase in bulk density of subsoil from C_0 treatment to C_2 treatment resulted in 13.2 and 18.1 per cent decrease at the time of harvesting during the year 2012 and 2013 respectively. Similar results were also reported by Lipiec *et al.,* (1996) who found that the reduction in dry matter of maize under compacted soil conditions was mostly due to reduction in leaf area, stem diameter and plant height. N fertilization had significantly increased dry matter accumulation at 30, 60 DAS and at harvesting stage. Dry matter accumulation had shown increasing trend over the passage of time i.e. lower at 30 DAS, which increased to maximum at the time of harvesting. Increase in N dose from N_0 to N_1 increased dry matter accumulation by 12.8 and 19.4 per cent, while increase in N dose from N_0 to N_2 resulted in 28.7 and 48.5 per cent increase at the time of harvesting during the year 2012 and 2013 respectively. The enhanced dry matter

Table 1. Soil physico-chemical properties of experimental site.

Parameter	Value
Sand (%)	67.8
Silt (%)	15.9
Clay (%)	16.3
Bulk density, (Mg m^{-3})	
0-15 cm depth	1.49
15-30 cm depth	1.63
pH	7.63
E C (dS m^{-1})	0.51
Plant available water (cm/180 cm profile)	21.8
Saturated Hydraulic conductivity (cm hr^{-1})	
0-15 cm depth	5.87
15-30 cm depth	1.95

Table 2. Plant height (cm) of maize under different subsoil compaction and nitrogen fertilization levels. Different letters in each column of experimental factors show significant differences at < 0.05 probability level.

Treatments	30 DAS		60 DAS		At harvesting	
	2012	2013	2012	2013	2012	2013
C_0	66.84a	57.77a	225.00a	202.07a	267.39a	258.75a
C_1	60.76b	55.67ab	216.67a	182.52b	256.33b	244.83b
C_2	56.33c	52.11b	199.56b	169.90c	248.32b	223.50c
p-value C	<0.001	0.047	<0.001	<0.001	0.003	<0.001
N_0	58.39b	52.22b	206.56b	178.26b	251.56b	234.20b
N_1	61.38ab	55.67ab	211.67b	185.62ab	255.18b	240.04b
N_2	64.15a	57.67a	223.00a	190.61a	265.31a	252.84a
p-value N	0.039	0.056	0.0034	0.046	0.023	0.002
p-value C X N	0.91	0.99	0.45	0.80	0.053	0.40

Table 3. Dry matter (g $plant^{-1}$) of maize under different subsoil compaction and nitrogen treatments. Different letters in each column of experimental factors show significant differences at < 0.05 probability level.

Treatments	30 DAS		60 DAS		At harvesting	
	2012	2013	2012	2013	2012	2013
C_0	27.06a	16.24a	144.61a	128.38a	266.12a	241.06a
C_1	25.78a	15.49a	133.65b	119.13a	247.06b	227.81b
C_2	22.55b	13.47b	121.05c	101.79b	230.75c	201.63c
p-value	<0.001	<0.01	<0.001	<0.01	<0.001	<0.001
N_0	22.61c	13.00c	113.19c	100.41b	217.78c	186.48c
N_1	25.05b	15.14b	131.04b	110.67b	245.74b	222.87b
N_2	27.72a	17.05a	155.05a	138.23a	280.41a	261.14a
p-value-N	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
p-value C X N	0.60	0.48	0.55	0.20	0.69	0.18

Table 4. Periodic leaf area index maize under different subsoil compaction and nitrogen treatments. Different letters in each column of experimental factors show significant differences at < 0.05 probability level.

Treatments	30 DAS		60 DAS		At harvesting	
	2012	2013	2012	2013	2012	2013
C_0	1.01a	0.93a	3.19a	3.03a	2.38a	2.21a
C_1	0.95b	0.87b	3.08b	2.89b	2.24b	2.07b
C_2	0.92b	0.86b	2.97c	2.76c	2.14c	2.00b
p-value C	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
N_0	0.89c	0.84c	2.96c	2.77c	2.12c	1.97c
N_1	0.96b	0.89b	3.08b	2.90b	2.28b	2.10b
N_2	1.02a	0.94a	3.19a	3.01a	2.36a	2.22a
p-value N	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
p-value C X N	0.96	0.61	0.89	0.071	0.50	0.12

Table 5. Yield attributing characters and Harvest Index of maize under different subsoil compaction and nitrogen treatment. Different letters in each column of experimental factors show significant differences at < 0.05 probability level.

Treatments	Cob length (cm)		Cob barrenness (%)		1000-grain weight (g)		Harvest index	
	2012	2013	2012	2013	2012	2013	2012	2013
C_0	17.08a	17.74a	10.83b	9.78b	268.3a	241.6a	0.389a	0.36a
C_1	16.28ab	17.19a	11.31b	11.93ab	253.2ab	238.2a	0.375a	0.31b
C_2	15.39b	15.26b	14.62a	13.62a	239.3b	226.2a	0.383a	0.32b
p-value C	0.037	<0.01	0.05	0.03	<0.01	0.076	0.82	<0.01
N_0	15.44b	15.94b	14.45a	14.86a	249.3b	229.4a	0.39a	0.32a
N_1	16.12ab	16.58ab	11.58b	11.80b	271.1a	235.1a	0.37a	0.33a
N_2	17.19a	17.67a	10.72b	8.67c	240.4b	241.5a	0.37a	0.34a
p-value N	0.029	0.05	<0.01	<0.01	<0.01	0.21	0.51	0.41
p-value C X N	0.99	0.87	0.69	0.91	0.55	0.99	0.54	0.78

Table 6. Effect of subsoil compaction and N fertilization on grain and yield N content during the year 2012 and 2013. Different letters in each column of experimental factors show significant differences at < 0.05 probability level.

	Grain (%)		Straw (%)		N uptake grain (kg ha^{-1})		N uptake straw (kg ha^{-1})		Total N uptake (kg ha^{-1})	
	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013
C_0	1.673a	1.697b	0.635a	0.638a	105.64a	93.17a	108.09a	95.7a	213.75a	188.87a
C_1	1.702a	1.723ab	0.639a	0.649a	97.52b	75.93b	102.18ab	89.9b	199.70b	165.83b
C_2	1.713a	1.764a	0.646a	0.658a	91.14c	73.25b	95.26b	86.5b	186.39c	159.75b
p-value C	0.21	0.076	0.63	0.33	<0.01	<0.01	0.04	<0.01	<0.01	<0.01
N_0	1.694a	1.723a	0.625a	0.640a	91.46c	74.78b	91.19b	85.08c	182.65c	159.86b
N_1	1.686a	1.731a	0.645a	0.649a	97.00b	80.231ab	103.45a	90.78b	200.45b	171.02ab
N_2	1.707a	1.731a	0.649a	0.656a	105.8a	87.34a	110.89a	96.23a	216.74a	183.57a
p-value N	0.63	0.94	0.12	0.51	<0.01	0.03	<0.01	<0.01	<0.01	<0.01
p-value C X N	0.92	0.85	0.71	0.74	0.41	0.94	0.99	0.14	0.94	0.75

accumulation per plant with N application, obviously appear to be a direct consequence of increased N availability for growth and development of plant. The increased N supply expanded the leaf area (reflected in leaf area index) which might have accelerated the photosynthetic rate, thereby increasing the supply of carbohydrates to plants. Significantly higher amounts of dry matter accumulated with increase in N-level, that was due to the cumulative effect of higher plant height and higher leaf area index under higher N application over the lower N application was also reported by Shivay and Singh (2000). While, Tan *et*

Table 7. Grain and biomass yield of maize under different subsoil compaction and nitrogen treatments. Different letters in each column of experimental factors show significant differences at < 0.05 probability level.

	Grain yield (t ha^{-1})		Biomass yield (t ha^{-1})	
	2012	**2013**	**2012**	**2013**
C_0 N_0	5.86	5.22	16.00	14.78
C_0 N_1	6.38	5.43	17.05	14.80
C_0 N_2	6.68	5.84	17.94	15.43
C_1 N_0	5.21	3.99	14.59	12.94
C_1 N_1	5.61	4.35	16.30	14.06
C_1 N_2	6.40	4.84	17.01	14.52
C_2 N_0	5.13	3.84	13.00	12.14
C_2 N_1	5.30	4.17	15.02	13.07
C_2 N_2	5.55	4.47	16.05	14.20
	2012	**2013**	**2012**	**2013**
C_0	6.307a	5.494a	16.99a	15.00a
C_1	5.738b	4.391b	15.96ab	13.83b
C_2	5.326b	4.158b	14.69b	13.13b
p-value C	<0.01	<0.01	<0.016	<0.01
N_0	5.400a	4.346b	14.53b	13.28b
N_1	5.763ab	4.646ab	16.12a	13.98b
N_2	6.208a	5.049a	17.00a	14.72a
p-value N	0.01	<0.038	<0.01	<0.01
p-value C X N	0.65	0.99	0.96	0.44

Table 8. Pearson Correlation Matrix for plant growth, yield and yield attributes of maize.

	Dry matter per plant at harvest	**Plant height at harvest**	**LAI at harvest**	**1000-grain weight**	**Cob length**	**Cob barrenness**	**Grain yield**	**Biomass yield**	**Harvest index**
Dry matter per plant at harvest	1								
Plant height at harvest	0.512**	1							
LAI at harvest	0.717**	0.489**	1						
1000-grain weight	0.225	0.446**	0.285*	1					
Cob length	0.477**	0.185	0.346*	0.137	1				
Cob barrenness	-0.643**	-.355**	-.557**	-0.118	-.630**	1			
Grain yield	0.59**	0.69**	0.52**	0.54**	0.21**	-0.247	1		
Biomass yield	0.46**	0.31*	0.262	0.41**	0.41**	-0.207	0.63**	1	
Harvest index	0.147	0.40**	0.30*	0.102	-0.252	-0.010	0.36**	-.456**	1

* significant at P>0.05, ** significant at P>0.01

al., (2008) also reported reduced N availability due to soil compaction might be affecting dry matter accumulation and plant height.

Leaf area index (LAI) is an important parameter to characterize the yield potential photosynthetically. LAI increases as the plant height increases and is considered to be important index strengthening the source-sink relationships. LAI increased upto 60 DAS and thereafter declined due to senescence (Table-4). A clear and significant effect of subsoil compaction was observed on the leaf area index of maize. LAI was significantly higher under C_0 treatment as compared to C_2 at 30 DAS, 60 DAS and at harvesting during the year 2012 and 2013. Similarly, Sweeney *et al.,* (2006) also reported reduction in LAI of sorghum due to soil compaction. Application of higher dose of N resulted in significant increase in LAI over control at 30 DAS, 60 DAS and at harvesting stage. LAI of maize in N_2 treatment increased by 7.7 and 8.6 per cent over N_0 at 60 DAS during the year 2012 and 2013, respectively. Similarly increase of LAI under N_2 treatment was 11.3 and 12.6 per cent higher over N_0 treatment at harvesting during the year 2012 and 2013, respectively. Highest LAI values were observed at 60 DAS under different levels of N application as compared to 30 DAS and at harvest stage. The increase in LAI due to N application might be attributed to its functional role in cell elongation and cell multiplication, thereby resulting in enhanced leaf area per plant. The increase in LAI with increasing nitrogen level might be due to lesser senescence and longer leaf retention period with higher nitrogen application. Uhart and Andrade (1995) reported more leaf elongation and less leaf senescence with higher nitrogen supply in maize. Prasad *et al.,* (1990) also reported increased LAI in maize with application of higher dose of N.

All the interaction effects of subsoil compaction and N application on plant height, dry matter accumulation and leaf area index were non-significant during the year 2012 and 2013.

Effect of soil compaction and N fertilization on yield attributes: Cob length is considered an indicator of total number of grain which could be considered as desirable yield component of maize. The cob length was significantly higher under C_0 treatment (17.08 cm and 17.74 cm) than that in C_2 treatment during the year 2012 and 2013 respectively (Table-5). However, cob length was statistically at par under C_0 and C_1 subsoil compaction treatments. Higher dose of N fertilizer significantly improves the cob length. N_2 treatment resulted in 11.3 and 10.8 per cent increase in cob length than that in N_0 treatment during the year 2012 and 2013 respectively.

The cob barrenness was highest (14.63 and 13.62 per cent) under C_2 treatment during the year 2012 and 2013, respectively. Cob barrenness was 33 and 39 per cent higher under C_2 treatment over C_1 treatment during the year 2012 and 2013, respectively. The higher cob barrenness under C_2 treatment may be attributed to poor dry matter accumulation and translocation of photosynthates. The Cob barrenness in N_2 was significantly higher than that in N_0 and N_1 during the year 2013. The cob barrenness was lower by 25.6 and 41.6 per cent during the year 2012 and 2013, respectively under N_2 than that in N_0. The reduced cob barrenness might be attributed to the higher vegetative growth and dry matter accumulation and it role in reproductive system of plant. Similarly, Shivay and Singh (2000) and Kumar (2009) also reported reduced barrenness with increased N application in maize crop.

Test weight (1000-grain weight) was not statistically affected by the subsoil compaction and N fertilization during the year 2012 and 2013. The test weight was numerically higher in C_0 treatment than that in C_1 and C_2 treatment. Fedotkin and Kravtsov, (2001) found positive effect of N fertilization on number of grains per cob and 1000-grain weight of maize.

Harvest index (HI) is an indicator of efficiency of crop plants to translocate manufactured food material at source level to the sink or grains. Harvest Index was significantly higher under C_0 treatment than that in C_1 and C_2 treatment during the year 2013. However, HI was not significantly affected by subsoil compaction during 2012. Harvest Index wasn't significantly affected by N fertilization during the year 2012 and 2013.

Effect of soil compaction and N fertilization on Grain yield, biomass yield and harvest index: The highest grain yield was achieved under C_0 treatment than that in C_1 and C_2 treatments. Higher levels of subsoil compaction resulted in yield reduction of 15 to 25 per cent (Table-7). Voorhees (2000), Radford *et al.,* (2001), Ishaq *et al.,* (2001) and Abu-Hamdeh (2003) reported a maize yield reduction of 15 to 50 % due to subsoil compaction. The maize yield reductions under higher degree of subsoil compaction occurred due to root growth restrictions. Lipiec *et al.,* (2003) reported crop yield (cereal and root crops) reduction due to root growth restrictions under higher subsoil compaction. Crop also took less number of days to mature under higher degree of subsoil compaction (Jagdish-Singh and Hadda, 2014) might be responsible for reduced crop yields due to lesser production and translocation of photosynthates. Muchow (1990) also observed maize grain yield reduction due to shorter grain filling period due to early maturity of crop. N application significantly affects the grain yield (Table-7). The increase in N dose from N_0 to N_2 resulted in 14.8 and 16.1 per cent increase in grain yield during the year 2012 and 2013, respectively. An increase in grain yield is attributed to higher plant growth in response to higher level of N fertilization over the recommended dose of N. The study supports the finding of Inamullah *et al.,* (2011a) who reported an increase in maize grain yield with higher dose of N application.

The grain yield recorded was in the order of $C_0N_2>C_1N_2>C_0N_1>C_0N_0>C_1N_1>C_2N_2>C_2N_1>C_1N_0>C_2N_0$ under different levels of subsoil compaction and N fertilization levels. The highest yield was recorded under N_2 level under C_0 subsoil compaction while lowest grain yield was observed under N_0 level under C_2 treatment. The addition of N above the N_1 dose had not significantly affected the grain yield of maize, while grain yield from N_2 level was statistically at par with N_1 level. Thus, N_1 level could be recommended under subsurface compacted soils, which not only improves grain yield but also reduces cost of fertilization as compared to N_2. Hakansson and Lipiec (2000) also reported that that negative effects of excessive soil compaction on crop yield can only be marginally reduced by increased nitrogen fertilization.

Biomass yield was significantly higher under C_0 than that in C_1 and C_2 (Table-7). The biomass yield from treatments C_1 and C_2 were statistically at par among themselves during the year 2012 and 2013. The higher biomass yield under C_0 treatment may be attributed to higher plant height and dry matter accumulation that was also reflected on biomass yield. Unger and Kaspar (1994) reported reduced plant growth, grain yield and biomass yield as a result of compaction due to its effect on water infiltration, aeration and disease pressure. The N_2 treatment resulted in 17 and 10.8 per cent higher in biomass yield over N_0 during the year 2012 and 2013, respectively.

Application of higher dose of N had resulted in increased vegetative growth (plant height and dry matter accumulation) which had improved the biomass yield. Inamullah *et al.,* (2011a) also reported improvement in biomass yield of maize with higher N application.

Grain and biomass yield were not significantly affected by the interaction of subsoil compaction and N fertilization.

Correlation among plant, yield and yield attributes of maize: Maize grain yield showed positive and significant correlation with Dry matter per plant at harvest (0.59), plant height (0.69), LAI (0.52), 1000- grain weight (0.54) and Cob length (0.41) while negative and non-significant correlation with harvest index (0.45) was observed (Table-8). Above ground biomass yield showed positive and significant association with Dry matter per plant at harvest (0.46), plant height (0.31), 1000- grain weight (0.41), Cob length (0.21), biomass yield (0.63) and harvest index (0.36), while negative and non-significant correlation with cob barenness. Cob length showed positive and significant correlation with dry matter per plant at harvest (0.47), LAI (0.36), grain yield (0.21) and above ground biomass yield (0.41), however 1000 grain weight, plant height and Harvest index were not significantly associated with cob length. Rafique *et al.,* (2004) and Inamullah *et al.,* (2011b) also reported positive correlations of cob length with 1000 grain weight and grain yield of maize.

Effect of soil compaction and N fertilization on N uptake: The perusal of data (Table-6) showed that grain and straw N concentration was not significantly affected by subsoil compaction and nitrogen fertilization. However N uptake was numerically higher under C_2 subsoil compaction treatment and N_2 level of N fertilization during the years 2012 and 2013. Xu *et al.,* (2009) also reported that the N concentration in constituent organs of maize (*Zea mays* L.) experiencing root growth restriction remain similar to that of control plants.

Grain and straw N uptake was significantly higher under C_0 treatment than that in C_1 and C_2 during the year 2012 and 2013. The grain N uptake in C_0 treatment was 15.5 and 27.1 per cent higher than that in C_2 subsoil compaction level during the year 2012 and 2013, respectively (Table-6). The application of higher N rate improved the grain N uptake in N_2 treatment by 15.7 and 16.8 per cent over the N_0 level. The straw N uptake was 13.5 and 10.6 per cent higher in C_0 treatment than that in C_2 treatment during the year 2012 and 2013, respectively. The N_2 treatment had improved the straw N uptake by 21.4 and 13.0 per cent as compared to N_0 treatment during the year 2012 and 2013, respectively. The total N uptake was 14.6 and 18.2 per cent higher under uncompacted subsoil condition (C_0) than that in highly compacted subsoil (C_2) during the year 2012 and 2013, respectively. Sweeney *et al.,* (2006) also found 5–25 % reduction in N uptake of sorghum due to poor plant growth under higher soil compaction. The higher soil strength under C_2 treatment might had restricted the maize roots leading to lower root density and N uptake. Kage and Ehlers (1996) also found lower N uptake due to reduction in root density. The N_2 treatment had improved the total N uptake by 18.6 and 14.9 per cent as compared to N_0 treatment during the year 2012 and 2013, respectively.

Conclusion

Adverse effects of subsoil compaction on maize yield reduction had been reported worldwide. A compact layer formed below the soil surface as a result of vehicular traffic, which restricts the plant growth. Farmers apply more fertilizer N to achieve higher yield under such conditions, which lead to increased production cost and deteriorate soil and environment health. The present study shows that plant height, LAI and dry matter accumulation were negatively affected by subsoil compaction. However, the N fertilization mitigates the negative effect of subsoil compaction on growth of maize. Cob length was lower under higher degree of subsoil compaction, but had higher cob barrenness. The subsoil compaction reduced the grain yield by 13–16 per cent and biomass yield by 10–17 per cent. Harvest index remained unaffected under higher dose of N fertilizer, but it was significantly higher under no-subsoil compaction level during the year of 2013. The grain N uptake in C_0 treatment was 15.5 and 27.1 per cent higher than that in C_2 subsoil compaction level, while application of higher N rate improved the grain N uptake by 14-18 per cent. The N_1 level could be recommended under subsurface compacted soils to achieve higher grain and biomass yield. The study emphasizes the need to adopt deep tillage practices to achieve higher grain yields from the subsurface compact soils.

ACKNOWLEDGEMENT

The present work is the part of Ph.D dissertation of first author, submitted at Punjab Agricultural University, Ludhiana. Authors are thankful to the University for providing funds and facility for field and laboratory work. Authors are thankful for the comments and suggestion given by anonymous reviewers for the improvement of the manuscript.

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