

**SOIL AND MAIZE RESPONSE TO COMPACTION,
SLOPE STEEPNESS AND NITROGEN FERTILIZATION
IN COARSE TEXTURED SOIL**

Dissertation

**Submitted to the Punjab Agricultural University
in partial fulfillment of the requirements
for the degree of**

**DOCTORATE OF PHILOSOPHY
in
SOIL SCIENCE
(Minor Subject: Soil and Water Engineering)**

By

**Jagdish Singh
(L-2010-A-43-D)**

**Department of Soil Science
College of Agriculture
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CERTIFICATE I

This is to certify that the thesis/dissertation entitled, “**SOIL AND MAIZE RESPONSE TO COMPACTION, SLOPE STEEPNESS AND NITROGEN FERTILIZATION IN COARSE TEXTURED SOIL**” submitted for the degree Ph.D., in the subject of **SOIL SCIENCE** (Minor subject: **SOIL AND WATER ENGINEERING**) of the Punjab Agricultural University, Ludhiana, is a bonafide research work carried out by **Mr. Jagdish Singh (L-2010-A-43-D)** under my supervision and that no part of this thesis/dissertation has been submitted for any other degree.

The assistance and help received during the course of investigation have been fully acknowledged.

(Dr. M. S. Hadda)
Major Advisor
Professor of Soil Conservation

CERTIFICATE II

This is to certify that the dissertation entitled, “**SOIL AND MAIZE RESPONSE TO COMPACTION, SLOPE STEEPNESS AND NITROGEN FERTILIZATION IN COARSE TEXTURED SOIL**” submitted by **Mr. Jagdish Singh (L-2010-A-43-D)** to the Punjab Agricultural University, Ludhiana, in partial fulfillment of the requirements for the degree of **Doctor of Philosophy**, in the subject of **SOIL SCIENCE (S)** (Minor subject: **OIL AND WATER ENGINEERING**) has been approved by the Student’s Advisory Committee after an oral examination on the same.

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ABSTRACT

The continuous use of farm machinery and adoption of rice-wheat cropping sequence resulted in the formation of compacted subsoil layer at the depth of 10-40 cm. The subsoil compacted layer affects nearly all soil properties and functions, which in turn affect the growth and productivity of plants. The information on the relationships among the degree of compaction, soil physical properties, N fertilizer rates, slope steepness and annual row crop performance are limited. Thus, the experiment was carried out to quantify the N fertilizer dose in the subsurface compact soils, to evaluate the effects of subsurface compaction and N fertilization on soil physical properties, plant growth and yield of maize and to investigate the effect of subsurface compaction and slope steepness on maize yield. The present investigation was carried out at Research Farm, Department of Soil Science, Punjab Agricultural University, Ludhiana during the years, 2012 and 2013. The experiment-I comprised three subsoil compaction treatments in main plots and three nitrogen levels in sub plots laid out in split-plot design replicated thrice. While, experiment-II comprised three subsoil compaction levels in main plots and three slope steepness levels in sub plots replicated thrice. The bulk density and penetration resistance was higher under C₂ treatment, while total porosity, cumulative infiltration and infiltration rate were lower. The N fertilization did not significantly affect the soil physical properties. Plant height, LAI and dry matter accumulation were negatively affected by subsoil compaction. However N fertilization mitigated the negative effects of subsoil compaction on growth of maize. The C₂ treatment reduced heat use efficiency, delayed tasseling and silking stages, while physiological maturity was advanced under C₂ treatment than that in C₀ treatment. The N₂ treatment improved the HUE than that in N₀ treatment. The crop growth rate was significantly higher under C₀ treatment at 30, 60 DAS and at harvest than that in C₁ and C₂ treatments. The root mass density was higher in 0-15 cm soil layer under C₂ treatment at knee high and pre-tasseling stage than that in C₀ treatment. However, root density was higher in C₀ treatment than that in C₁ and C₂ at all other soil depths. The grain yield reduction of 15.5 to 23.5 % was observed under C₂ treatment as compared to C₀; however N fertilization improved the yield by 14.8 to 16.1 %. The total N uptake was 14.6 and 18.2 % higher under C₀ treatment than that in C₂ treatment, while N₂ treatment had improved the total N uptake by 18.6 and 14.9 % as compared to N₀ during the years 2012 and 2013, respectively. The N₁ fertilization level can be recommended under subsurface compacted soils as compared to N₀ and N₂ fertilization. The slope steepness improved the maize grain yield by 4.2-10.2 % and biomass yield by 17-22 %, by reducing the crop lodging and cob barrenness.

Keywords: Heat use efficiency, Nitrogen levels, Physical properties, Slope steepness, Subsurface compaction

Signature of Major Advisor

Signature of the student

ਖੋਜ ਪ੍ਰਬੰਧ ਦਾ ਸਿਰਲੇਖ	: ਹਲਕੀਆਂ ਜ਼ਮੀਨਾਂ ਵਿੱਚ ਠੋਸਤਾ, ਢਾਲਾਣ ਅਤੇ ਨਾਈਟ੍ਰੋਜਨ ਖਾਦ ਪ੍ਰਤੀ ਮਿੱਟੀ ਅਤੇ ਮੱਕੀ ਦੀ ਪ੍ਰਤੀਕਿਰਿਆ
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ਸਾਰ-ਅੰਸ਼

ਫਾਰਮ ਮਸ਼ੀਨਰੀ ਦੀ ਲਗਾਤਾਰ ਵਰਤੋਂ ਅਤੇ ਕਣਕ-ਝੋਨੇ ਦੇ ਫਸਲੀ ਚੱਕਰ ਨੂੰ ਅਪਨਾਉਣ ਕਾਰਨ ਧਰਤੀ ਦੀ 10 ਤੋਂ 40 ਸੈ.ਮੀ. ਵਾਲੀ ਸਹਿਤ ਸਖਤ ਹੋ ਜਾਂਦੀ ਹੈ। ਮਿੱਟੀ ਦੀ ਹੇਠਲੀ ਸਤਹਿ ਦਾ ਸਖਤ ਹੋਣਾ, ਮਿੱਟੀ ਦੇ ਗੁਣਾਂ ਅਤੇ ਕਾਰਗੁਜ਼ਾਰੀ ਨੂੰ ਪ੍ਰਭਾਵਿਤ ਕਰਦਾ ਹੈ ਜੋ ਕਿ ਫਸਲਾਂ ਦੇ ਵਾਧੇ ਅਤੇ ਝਾੜ ਤੇ ਅਸਰ ਪਾਉਂਦਾ ਹੈ। ਜ਼ਮੀਨ ਦੀ ਸਤਹਿ ਹੇਠਲੀ ਸਖਤਾਈ, ਮਿੱਟੀ ਦੇ ਭੌਤਿਕ ਗੁਣ, ਨਾਈਟ੍ਰੋਜਨ ਖਾਦ ਦੀ ਮਿਕਦਾਰ, ਢਲਾਣਪਣ ਅਤੇ ਸਲਾਨਾ ਫਸਲ ਕਾਰਗੁਜ਼ਾਰੀ ਦੇ ਆਪਸੀ ਸਬੰਧ ਬਾਰੇ ਜਾਣਕਾਰੀ ਦੀ ਘਾਟ ਹੈ। ਇਹ ਖੋਜ ਪੰਜਾਬ ਖੇਤੀਬਾੜੀ ਯੂਨੀਵਰਸਿਟੀ ਲੁਧਿਆਣਾ ਦੇ ਭੂਮੀ ਵਿਗਿਆਨ ਵਿਭਾਗ ਦੇ ਖੋਜ ਫਾਰਮ ਉੱਤੇ ਸਾਲ 2012 ਅਤੇ 2013 ਦੌਰਾਨ ਕੀਤੀ ਗਈ। ਇਹ ਤਜਰਬਾ ਸਤਹਿ ਹੇਠਲੀ ਸਖਤ ਪਰਤ ਵਿੱਚ ਨਾਈਟ੍ਰੋਜਨ ਖਾਦ ਦੀ ਮਿਕਦਾਰ, ਸਤਹਿ ਹੇਠਲੀ ਸਖਤ ਪਰਤ ਅਤੇ ਨਾਈਟ੍ਰੋਜਨ ਖਾਦ ਦੀ ਮਿੱਟੀ ਦੇ ਭੌਤਿਕ ਗੁਣਾਂ, ਮੱਕੀ ਦੇ ਵਾਧੇ ਅਤੇ ਝਾੜ ਦੇ ਅਸਰ ਅਤੇ ਸਤਹਿ ਹੇਠਲੀ ਸਖਤ ਪਰਤ ਅਤੇ ਢਲਾਣ ਦਾ ਮੱਕੀ ਦੀ ਪੈਦਾਵਾਰ ਉੱਤੇ ਅਸਰ ਵੇਖਣ ਲਈ ਕੀਤਾ ਗਿਆ। ਪਹਿਲੇ ਤਜਰਬੇ ਵਿੱਚ ਮੁੱਖ ਪਲਾਟਾਂ ਵਿੱਚ ਤਿੰਨ ਸਤਹਿ ਹੇਠਲੀ ਸਖਤ ਪਰਤ ਦੀ ਸਖਤਾਈ ਅਤੇ ਉਪ-ਪਲਾਟਾਂ ਵਿੱਚ ਤਿੰਨ ਨਾਈਟ੍ਰੋਜਨ ਖਾਦ ਦੀਆਂ ਮਾਤਰਾਵਾਂ ਨੂੰ ਸਪਲਿੱਟ ਪਲਾਟ ਡਿਜ਼ਾਇਨ ਵਿਧੀ ਤਹਿਤ ਤਿੰਨ ਵਾਰ ਦੁਹਰਾਇਆ ਗਿਆ। ਦੂਜੇ ਤਜਰਬੇ ਨੂੰ ਮੁੱਖ ਪਲਾਟਾਂ ਵਿੱਚ ਤਿੰਨ ਸਤਹਿ ਹੇਠਲੀ ਸਖਤ ਪਰਤ ਅਤੇ ਉਪ ਪਲਾਟਾਂ ਵਿੱਚ ਤਿੰਨ ਪ੍ਰਕਾਰ ਦੀਆਂ ਢਲਾਣਾਂ ਦੀ ਵਰਤੋਂ ਕਰਕੇ ਤਿੰਨ ਵਾਰ ਦੁਹਰਾਇਆ ਗਿਆ। ਸੀ₂ ਪਲਾਟਾਂ ਵਿੱਚ ਬਲਕ ਘਣਤਾ ਅਤੇ ਪੈਨੀਟ੍ਰੇਸ਼ਨ ਵਿਰੋਧਤਾ ਵਧ ਸਨ ਜਦਕਿ ਕੁੱਲ ਪਰੋਸਿਟੀ, ਕਮੁਲੇਟਿਵ ਇਨਫਿਲਟ੍ਰੇਸ਼ਨ ਅਤੇ ਇਨਫਿਲਟ੍ਰੇਸ਼ਨ ਦਰ ਘੱਟ ਸਨ। ਨਾਈਟ੍ਰੋਜਨ ਖਾਦ ਦੀ ਵਰਤੋਂ ਨੇ ਮਿੱਟੀ ਦੇ ਭੌਤਿਕ ਗੁਣਾਂ ਨੂੰ ਖਾਸ ਪ੍ਰਭਾਵਿਤ ਨਹੀਂ ਕੀਤਾ। ਪੌਦਿਆਂ ਦੀ ਉਚਾਈ, ਪੱਤਾ ਖੇਤਰਫਲ ਅੰਕ, ਸੁੱਕੇ ਮਾਦੇ ਨੂੰ ਜਜ਼ਬ ਕਰਨ ਦੀ ਸਮਰੱਥਾ ਉਪਰ ਮਿੱਟੀ ਦੇ ਹੇਠਲੀ ਸਖਤ ਸਤਹਿ ਦੇ ਨਕਾਰਾਤਮਕ ਪ੍ਰਭਾਵ ਵੇਖੇ ਗਏ। ਜਦੋਂਕਿ ਨਾਈਟ੍ਰੋਜਨ ਖਾਦ ਦੀ ਵਰਤੋਂ ਨੇ ਜ਼ਮੀਨ ਹੇਠਲੀ ਸਖਤ ਸਤਹਿ ਦਾ ਮੱਕੀ ਦੇ ਵਾਧੇ ਤੇ ਹੋਣ ਵਾਲੇ ਬੁਰੇ ਪ੍ਰਭਾਵ ਨੂੰ ਘਟਾਇਆ। ਸੀ₂ ਪਲਾਟਾਂ ਵਿੱਚ ਤਾਪ ਦੀ ਸੁਚੱਜੀ ਵਰਤੋਂ (ਐਚ.ਯੂ.ਈ.) ਵਿੱਚ ਕਮੀ ਆਈ ਅਤੇ ਮੱਕੀ ਦੀਆਂ ਬਾਬੂ ਝੰਡਾਂ ਤੇ ਸੂਤ ਨਿਕਲਣ ਦੀਆਂ ਅਵਸਥਾਵਾਂ ਵਿੱਚ ਦੇਰੀ ਦੇਖੀ ਗਈ ਪਰ ਫਸਲ ਦਾ ਸੰਪੂਰਨ ਪਕਾਅ ਸੀ₂ ਪਲਾਟਾਂ ਵਿੱਚ ਸੀ₀ ਪਲਾਟਾਂ ਨਾਲੋਂ ਪਹਿਲਾਂ ਵੇਖਿਆ ਗਿਆ। ਐਨ₂ ਪਲਾਟਾਂ ਦੀ ਐਨ₀ ਪਲਾਟਾਂ ਨਾਲੋਂ ਐਚ.ਯੂ.ਈ. ਵੱਧ ਪਾਈ ਗਈ। ਸੀ₀ ਵਿੱਚ ਸੀ₁ ਅਤੇ ਸੀ₂ ਪਲਾਟਾਂ ਨਾਲੋਂ ਮੱਕੀ ਦੀ ਬਿਜਾਈ ਤੋਂ 30, 60 ਦਿਨ ਬਾਅਦ ਤੇ ਫਸਲ ਕਟਾਈ ਸਮੇਂ ਫਸਲ ਵਾਧਾ ਵਧੇਰੇ ਵੇਖਿਆ ਗਿਆ। ਸੀ₂ ਪਲਾਟਾਂ ਵਿੱਚ 0-15 ਸੈ.ਮੀ. ਮਿੱਟੀ ਦੀ ਤਹਿ ਵਿੱਚ ਜੜ੍ਹ ਭਾਰ ਘਣਤਾ ਸੀ₀ ਪਲਾਟਾਂ ਨਾਲੋਂ ਬੁੱਟੇ ਦੀ ਗੋਡੇ ਤੱਕ ਦੀ ਉਚਾਈ ਅਤੇ ਬਾਬੂ ਝੰਡਾਂ ਤੋਂ ਪਹਿਲਾਂ ਦੀ ਅਵਸਥਾ ਵਿੱਚ ਵੱਧ ਵੇਖੀ ਗਈ। ਜਦੋਂਕਿ ਮਿੱਟੀ ਦੀਆਂ ਹੋਰਨਾਂ ਤਿਹਾਂ ਵਿੱਚ ਜੜ੍ਹ ਘਣਤਾ ਸੀ₀ ਵਿੱਚ ਸੀ₁ ਅਤੇ ਸੀ₂ ਪਲਾਟਾਂ ਨਾਲੋਂ ਵਧੇਰੇ ਸੀ। ਸੀ₂ ਦੇ ਮੁਕਾਬਲੇ ਸੀ₀ ਪਲਾਟਾਂ ਵਿੱਚ ਫਸਲ ਦੀ ਪੈਦਾਵਾਰ ਵਿੱਚ ਕ੍ਰਮਵਾਰ 15.5 ਅਤੇ 23.5 ਫੀਸਦੀ ਵਾਧਾ ਵੇਖਿਆ ਗਿਆ। ਪ੍ਰੰਤੂ ਨਾਈਟ੍ਰੋਜਨ ਖਾਦ ਦੀ ਵਰਤੋਂ ਰਾਹੀਂ 14.8 ਅਤੇ 16.1 ਫੀਸਦੀ ਪੈਦਾਵਾਰ ਵਧ ਗਈ। ਸੀ₀ ਵਿੱਚ ਸੀ₂ ਪਲਾਟਾਂ ਨਾਲੋਂ ਕੁੱਲ ਨਾਈਟ੍ਰੋਜਨ ਸੋਖਣ ਵਿੱਚ 14.6 ਅਤੇ 18.2 ਫੀਸਦੀ ਵਾਧਾ, ਜਦੋਂਕਿ ਐਨ₂ ਵਿੱਚ ਐਨ₀ ਪਲਾਟਾਂ ਨਾਲੋਂ ਸੰਨ 2012 ਅਤੇ 2012 ਦੌਰਾਨ ਕ੍ਰਮਵਾਰ 18.6 ਅਤੇ 14.9 ਫੀਸਦੀ ਵੱਧ ਸੋਖਣ ਪਾਇਆ ਗਿਆ। ਮਿੱਟੀ ਹੇਠਲੀ ਸਖਤ ਸਤਹਿ ਵਾਲੀ ਸਥਿਤੀ ਵਿੱਚ ਐਨ₁ ਵਾਲੇ ਪਲਾਟਾਂ ਦੀ ਖਾਦ ਮਾਤਰਾ ਐਨ₀ ਅਤੇ ਐਨ₂ ਨਾਲੋਂ ਵਧੇਰੇ ਕਾਮਯਾਬ ਮੰਨੀ ਗਈ। ਢਲਾਣਪੁਣੇ ਨਾਲ ਮੱਕੀ ਦੀ ਪੈਦਾਵਾਰ ਵਿੱਚ 4.2 ਅਤੇ 10.2 ਫੀਸਦੀ ਅਤੇ ਮੱਕੀ ਦੀ ਬਾਇਓਮਾਸ ਪੈਦਾਵਾਰ ਵਿੱਚ 17-22 ਫੀਸਦੀ ਵਾਧਾ ਦਰਜ ਕੀਤਾ ਜੋਕਿ ਮੱਕੀ ਦੇ ਨਾ ਢਹਿਣ ਅਤੇ ਛੱਲੀ ਵਿੱਚ ਦਾਣਾ ਘੱਟ ਭਰਨ ਕਾਰਨ ਸਨ। ਸਤਹਿ ਹੇਠਲੀ ਸਖਤ ਪਰਤ ਵਾਲੀ ਭੂਮੀ ਵਿੱਚ ਵੱਧ ਝਾੜ ਲੈਣ ਲਈ ਸੁਚੱਜੀਆਂ ਫਸਲ ਉਗਾਉਣ ਅਤੇ ਮਿੱਟੀ ਸੰਭਾਲ ਦੀਆਂ ਵਿਧੀਆਂ ਅਪਨਾਉਣ ਦੀ ਲੋੜ ਹੈ।

ਮੱਖ ਸ਼ਬਦ: ਤਾਪ ਦੀ ਸੁਚੱਜੀ ਵਰਤੋਂ, ਨਾਈਟ੍ਰੋਜਨ ਦੇ ਪੱਧਰ, ਭੌਤਿਕ ਗੁਣ, ਢਲਾਣ, ਸਤਹਿ ਹੇਠਲੀ ਠੋਸਤਾ

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CHAPTER I

INTRODUCTION

Soil compaction is the compression of soil by external forces that decrease the volume of pore space while increasing the soil density (Harris 1971). Soil compaction is a densification and reduction in porosity, associated with changes to the soil structure and an increase in strength and a reduction in hydraulic conductivity (Soane and van Ouwerkerk 1994). According to Tursic *et al* (2008), compacted layer builds up in the root zone as a consequence of poor tillage practices, primarily as a result of the farmer failing to vary the depth of intervention over several years. This problem is exacerbated by the increasing size and weight of field machinery. The extent of the soil compaction problem is a function of soil type and water content, vehicle weight, speed, ground contact pressure and number of passes, and their interactions with cropping frequency and farming practices (Larson *et al* 1994, Chamen *et al* 2003).

Abo-Abda and Hussain (1990) reported 13-42 per cent reduction in infiltration of sandy soil due to compaction while, Agrawal (1991) attributed reduction in infiltration and percolation losses of water and nutrients due to reduction in water transmitting pores. El-Kommos (1989) observed relatively low evaporation losses in compacted soil, especially when the soil water content is below field capacity mainly due to increase in microporosity. Soil characteristics such as bulk density and mechanical impedance are also affected by tillage practices, and may noticeably alter root growth and distribution (Russell 1981). Soils with high strength impede the growth, distribution, and function of roots. The magnitude of restriction is closely related to the soil water content, because of the resulting increases in soil resistance (Gupta and Allmaras 1987, Raper 2005). With these restrictions, root systems develop superficially and, as a consequence, the roots explore a smaller volume of soil and hence intercept a limited amount of water and nutrients. Barraclough and Weir (1988) reported reduction in vertical extension of wheat roots in sandy loam soil layer at 35 cm depth compacted to a bulk density of 1.8 Mg m^{-3} . Chenkual and Acharya (1990) observed restricted root growth of wheat in rice soils having hard pan below plough layer developed in consequence to puddling. Reduced oxygen content in compacted surface soils, resulting in apart from reduced porosity and soil structure degradation, can in turn affect the transport, absorption, and transformation (e.g., mineralization) of nutrients (Kemper *et al* 1971) and also restrict soil gas diffusion and water availability (Hansen *et al* 1993). Effects of soil compaction are complex and can be affected by load and tyre inflation pressure (Abu-Hamdeh *et al* 2000), weather events (Unger and Kaspar 1994), crop root reinforcement of soil (Ess *et al* 1998), and periodic chiseling and controlled traffic (Ishaq *et al* 2001). Keeping the

above points in view the compacted layer thus formed adversely affects soil-water-plant relationships, production and productivity of these soils. It therefore suggests

Compaction in the plough layer (surface soil compaction) can be alleviated by tillage and natural processes, while subsurface compaction is usually alleviated only by natural processes such as freezing-thawing, drying-wetting and biological activity (Hakansson *et al* 1987). A number of studies are available on the longevity of subsoil compaction effects. Voorhees *et al* (1986) observed subsoil compaction effects after four seasons of freeze thawing, while Blake (1976) observed such effect even after 10 seasons. Hakansson *et al* (1987) and Lowery and Schular (1991) concluded that compaction effect may persist for about 5 years depending upon clay content of soils. According to Logsdon *et al* (1992), compaction persisted for 7 years in 35-60 cm zone of clay loam soil. However, subsurface compaction may persist for a long time, and has been measured 3–11 years after heavy loading (Alakukku 1996).

A compacted subsoil layer also formed at 15-20 cm depth due to puddling practice generally done in rice (Sur *et al* 1980, Sharma and De Datta 1986). Singh (1961) defined puddling as the process of tilling the soil at high moisture content, causing shear and compression of soil particle. Puddling destroys soil aggregates and peds, creating plastic mud, and thus eliminates most macropores, which transmit water, remaining macropores are filled by dispersed fine particles (Sharma and De Datta 1986, Adachi 1990). Similar to subsoil compaction, puddling also result in non-linear reduction in water flux through soil (Sharma and Bhagat 1993). Sur *et al* (1980) reported that the saturated hydraulic conductivity of compact layer at 15-20 cm depth in rice soil was only half to that of saturated hydraulic conductivity in uncompacted soil. This hard layer formed with in as little as in a period of three years on sandy loam soil (Sharma and De Datta 1986). In a study by Aggarwal *et al* (1995) reported that hard layer develops after 3 year of rice-wheat cultivation. Puddling is done on medium to coarse textured soils, which are more vulnerable to subsoil compaction than that in fine textured soils.

Canarache *et al* (1984) reported an 18 per cent corn grain yield reduction for every 0.1 Mg m^{-3} increase in bulk density above 1.3 Mg m^{-3} in a soil with 30 to 40 per cent clay. The yield reduction was attributed to a combination, of decreased water supply in the surface 20 cm of soil and increased water supply at the 40-cm depth. Schuler and Lowery (1986) reported corn yield decreases up to 40 per cent partially due to subsoil compaction on silty clay soil. Gaultney *et al* (1982) reported about 50 per cent decrease in yield when corn was grown on subsoil compacted silt loam soil after the surface layer had first been removed and then replaced. Fausey and Dylla (1984) also reported increase in bulk density in the surface 30 cm of a silty clay loam in response to wheel traffic, but found no corn yield response if the soil had adequate nutrient and water supply. The producers attempt to compensate for lower

yields by adding extra N fertilizer for proper nutrition of crop; this may enhance, but higher rates of N fertilizer also increase the risk of nutrient loss to the environment, e.g., loss of N to groundwater through leaching and to the atmosphere by volatilization. Thus, proper management of dose of nitrogen reduces losses because of leaching and denitrification (Scharf *et al* 2002), and increased N use efficiency (NUE) and yield (Tarkalson and Payero 2008). McLaughlin *et al* (2003) found that doubling the N fertilizer rate from 150 to 300 kg ha⁻¹ on compacted clay loam soils not only increased corn yields by 0.2 Mg ha⁻¹ compared with those on non-compacted soils, where yields were increased by 0.8 Mg ha⁻¹. Hakensson (1986) also reported slight increase in grain yield of barley with application of extra dose of nitrogen under compaction affected soils, indicating that the negative effects of compaction can be marginally reduced with application of nitrogen.

In agricultural diversification efforts, maize is considered an important alternative and potential crop to rice as in Punjab and every effort should be made to introduce this crop in the state. Maize is a remarkable plant in the sense that every part of the plant is of use. Not only grains, but leaves, stalk, tassels and even the cobs are used to make hundreds of edible and inedible products (Watson 1988). The uses may be subdivided into direct human consumption, feed ingredients and forage for livestock and raw material for industries (Dowswell *et al* 1996). There has been progressive demand for maize grains for the value added products like oils, glucose, starch, soritol, dextrose and alcohol/spirit, etc. In Punjab, maize is mainly grown in kharif season on an area of about 129 thousand hectares with production of 475 thousand tonnes and average yield of 3.68 tonnes per hectare during the year 2012-13 (Anonymous 2014). The optimal yield from maize can only be realized, if physical constraints to yield are eliminated due to adoption of rice-wheat cropping system.

In advanced farming system where improved maize cultivars are used, the gap between achievable and actual yields is quite large. Major constraints in realizing the yield potential of the crop are biotic and abiotic stresses. Among different abiotic stresses root growth restricted due to subsoil compact layer and nutrition are of prime importance, because it lead to major yield losses. Maize is highly exhaustive crop and usually considered to have high soil fertility requirements to achieve maximum yield (Uribelarrea *et al* 2009). Thus, it requires large quantities of N for optimal growth and yield. Stokingher (1970) reported positive response of N fertilizer application on yield of maize. Nitrogen fertilization also known to enhance water use efficiency on nitrogen-deficient soils even when water is not limited (Al-Kaisi and Yin 2003). The information on the relationships among the degree of compaction, soil physical and chemical properties, N fertilizer rates, and annual row crop performance are limited. The information could be useful for refining economically optimal N fertilization rates or variable fertilizer rate application because soil physical constraints to crop growth may override the influence of adequate nutrients on net crop productivity.

In rainy season, maize is mainly dependent on rainfall for its water requirements. It has been observed that most of the high intensity rainstorms occur in rainy season which cause damage to crop. Crop lodging took place due to combined effect of high intensity rainfall and high wind velocity storm, as a temporary water stagnation resulted from rainfall or heavy irrigations under compact subsoil layer with low permeability and causes aeration stress. It is proposed that if a slope is provided in maize field, lodging can be reduced by draining off excess surface runoff from the field. In this field study, a broad approach was followed to evaluate the effects of subsurface compaction, soil N fertility, and slope steepness on crop growth and yield. The present investigation was planned with the following objectives:

- To optimize the N fertilizer dose in the subsurface compact soils.
- To quantify the effects of subsurface compaction and N fertilization on soil physical properties.
- To evaluate the effect of subsurface compaction and nitrogen fertilization on plant growth and yield of maize.
- To investigate the effect of subsurface compaction and slope steepness on maize yield.

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CHAPTER II

REVIEW OF LITERATURE

The introduction of green revolution has increased the income of the farmers by the use of improved crop varieties, fertilizers, assured irrigation, improved plant protection measures and use of farm machinery. The continuous use of farm machinery and adoption of rice-wheat cropping sequence especially in Indo-Gangatic plain has resulted in formation of compacted subsoils. The literature relevant to the research problem has been reviewed under the following headings:

- Formation of subsoil compact layer
- Persistence of subsoil compact layer
- Effect of subsoil compaction on soil properties
- Impact of compaction on plant growth and yield
- Effect of subsoil compaction on root growth
- Effect of nitrogen fertilization on plant growth and yield
- Nitrogen and soil compaction
- Effect of slope steepness on soil-plant system

2.1 Formation of subsoil compact layer

Soane and van Ouwerkerk (1994) defined soil compaction as a densification and reduction in porosity, associated with changes to the soil structure and (usually) an increase in strength and a reduction in hydraulic conductivity. According to Tursic *et al* (2008) a 'thick compacted layer' builds up in the root zone as a consequence of poor tillage practices, primarily as a result of the farmer failing to vary the depth of ploughing over several years. The extent of the soil compaction problem is a function of soil type and water content, vehicle weight, speed, ground contact pressure and number of passes, and their interactions with cropping frequency and farming practices (Larson *et al* 1994, Chamen *et al* 2003). Soil compaction occurs when soil particles are pressed together, reducing pore space between them (DeJong-Hughes 2001). The existence of high plough sole density layer of 5-15 cm thick at 10-40 cm soil depth in agricultural soils was reported by Sur and Singh (1972) and particularly under soils with rice cultivation (Sidhu 1980). A compacted subsoil layer also formed at 15-20 cm depth due to puddling practice generally done in rice (Sharma and De Datta 1986). Singh (1961) defined puddling as the process of tilling soil at high moisture content, causing shear and compression of soil particle. Puddling destroys soil aggregates and peds, creating plastic mud, and thus eliminates most macropores, which transmit water, remaining macropores are filled by dispersed fine particles (Sharma and De Datta 1986; Adachi 1990). Puddling is done on medium to coarse textured soils, which are more

vulnerable to subsoil compaction over fine textured soils. The vast majority of soil compaction in modern agriculture is caused by vehicular traffic (Flowers and Lal 1998). The most common causes of soil compaction are agricultural machines such as tractors, harvesters and various other cultivation implements such as wheels travelling over moist and loose soils (Alakuku *et al* 2003). Damage from high axle loads increases when the soil is wet because wet soil has reduced strength (Kirby and Kirchhoff 1990). The degree of compaction depends on the soil strength, which is influenced by intrinsic soil properties such as texture and soil organic matter contents (Larson *et al* 1980, Hettiaratchi 1987), structure of the tilled layer at wheeling (Horn *et al* 1994) and its water content (Guerif 1984) and loading, which depends on axle load, tyre dimensions and velocity, as well as soil-tyre interaction (Lebert *et al* 1998). Arvidsson (2001) reported that, high axle load traffic (10 Mg axle load, 300 KPa inflation pressure) most often cause detectable differences in soil physical properties to around 50 cm depth on soils with clay content varying from 2 to 65 per cent. In field traffic experiments of Arvidsson *et al* (2001) with wheel loads of 8000 kg on sandy loams and loams, hydraulic conductivities of several subsoils were reduced permanently to 10 per cent over the original conductivities. Abebe *et al* (1989) concluded that the surface and the subsurface soil deformation characteristics, which were taken as indicative values of soil compactibility, strongly indicate that the maximum compaction occurred during the first three passes of a loaded wheel. Canillas and Salokhe (2001) reported that under field conditions, soil compaction is greatly influenced by the axle load and the number of tyre passes during farm operations. Raper *et al* (1998) in an experiment found that soil that was initially completely disrupted to a depth of 50 cm was re-consolidated by traffic into a soil condition similar to one that had never received a subsoiling treatment. It was also found that traffic decreased the total soil volume estimated for root growth using a 2 MPa limiting cone index value, but not the maximum rooting depth beneath the row, when an annual in-row sub-soiling practice was used. Abu-Hamdeh (2003a) revealed that the intensity of subsoil compaction occurring as vehicle tyre goes deeper with increasing axle load and tyre inflation pressure. Their results also showed that the type of tillage system also affected root density. The study showed that increasing tyre inflation pressure and axle load increased dry bulk density and cone penetration resistance. It has been estimated that over 30 per cent of ground area is trafficked by the tyres of heavy machinery even in genuine zero tillage systems (one pass at sowing) (Tullberg, 1990). Under minimum tillage (2–3 passes) it is likely to exceed 60 per cent and in conventional tillage (multiple passes) it would exceed 100 per cent during one cropping cycle (Soane *et al* 1982). Tillage and traffic using heavy machines can also induce subsoil compaction in different soil types and climatic conditions in cropped systems (Raper *et al* 1998; Mosaddeghi *et al* 2000). The degree of compaction depends on the following: soil mechanical strength, which is influenced by intrinsic soil properties such as texture and soil

organic matter contents (Larson *et al* 1980; Hettiaratchi 1987); structure of the tilled layer at wheeling (Horn *et al* 1994) and its water status (Guerif 1984); and loading, which depends on axle load, tyre dimensions and velocity, as well as soil-tyre interaction (Lebert *et al* 1998). Gildyal and Satyanarayana (1965) reported that the medium textured soils were more prone to compaction than that in light and heavier one. Ellies Sch *et al* (2000) reported that in coarse textured soils, the dominant penetration of stress was in the vertical direction, while in soil with a finer texture stress propagation was multi-directional. However, they observed that in soil with a good structure, compaction due to axle load was not so deep and strong.

2.2 Persistence of subsoil compact layer

Voorhees *et al* (1986) observed subsoil compaction even after four seasons of freezing-thawing, while Blake (1976) observed such affects even after 10 seasons. Hakansson *et al* (1987) and Lowery and Schular (1991) concluded that compaction effect may persist for about 5 years depending upon mechanical composition of soil especially clay content. According to Logsdon *et al* (1992), compaction persisted for 7 years in 35-60 cm zone of clay loam soil. However, subsurface compaction may persist for a longer time, and had been measured 3–11 years after heavy loading (Alakukku 1996). Radford *et al* (2007) concluded through their experimentation that compaction by heavy wheel traffic (10 Mg axle load) for 5 years adversely effected compaction of a wet Vertisol, that persisted for 5 years due to insufficient wet-dry cycles to swell and shrink the entire compacted layer, a no-tillage regime during the amelioration process, and low earthworm numbers in the compacted soil. Compaction of dry soil with a 6 Mg axle load had little effect, indicating that problems can be avoided by using wheel traffic only when the soil is dry. When a clay soil was already compacted, management options including tillage, deep ripping, sowing a ley pasture or crop should be considered which help in ameliorating the compacted soil. Quiroga *et al* (1999) found resistance to penetration and susceptibility to compaction to be inversely related to organic matter content and therefore higher under continuous cultivation. Hydraulic conductivity was lower in cultivated soils, especially in fine textured soils. The results showed that in sandy to loam soils, an increase of about 5 g kg⁻¹ organic matter was required to achieve a 0.06 Mg m⁻³ decrease in bulk density at the optimum proctor moisture content. The results also indicate that the loss of organic matter in the cultivated soils makes them more susceptible to compaction, which not only has adverse mechanical effects on plants growth, development and yield but also gives rise to a considerable reduction in hydraulic conductivity.

2.3 Effect of soil compaction on soil properties

One soil physical property that is always altered in response to compaction is bulk density of surface and subsurface soil. Most of the workers (Patel and Singh (1981), Ankeny *et al* (1990), Badalikova and Hruby (2006), Radford *et al* (2000)) had reported that

compaction increases bulk density by disrupting soil aggregates or by compression of soil aggregates forming restrictive layer and thus decreases soil volume by compression of soil particles closer (Chaudhary *et al* 1991). da Silva *et al* (1997) investigated the effects of tillage, wheel traffic, soil texture and organic matter content on dry bulk density and relative bulk density as an index of compactness. The dry bulk density was strongly affected by tillage, wheel traffic, soil texture and organic matter content. Verbist *et al* (2007) reported significantly higher penetration resistances between 20 and 40 cm depth, a significantly higher soil bulk density and a 14 per cent decrease in drainage pore space over the surface or top layer. Assouline *et al* (1997) in a uniaxial compressive pressure tests show that the soil at Palotina (with higher pH and CEC and lower OM content) was more compact and sensitive to the initial matric tension over the soils at Cascavel (more OM). The highest bulk density in the Palotina soil was reached for an initial matric tension of -32 kPa, which was close to the matric tension at which most agricultural practices were generally carried out.

Soil strength or penetration resistance (PR) is another property affected by compaction. Bulk density is the function of total porosity of soil but penetration resistance is the interplay of many factors or soil properties such as bulk density, water content, soil texture, soil structure and clay mineralogy, etc. Soil strength is used as a measure of soil compaction because it reflects the resistance offered by soil to root penetration (Hamza and Anderson 2003). Zhang *et al* (2006) investigated the relationships between soil water content and penetration resistance (PR), the comparison of soil compaction induced by small power tractor and the medium power tractor, the effect of tractor weight on compaction, the effect of number of tractor passes and tillage on penetration resistance, and the effect of compaction on crop yields, etc. The small powered tillage system created a more compacted plow layer over the medium powered tillage due to increased passes required with this system. Small four-wheeled tractors showed a significantly higher PR over medium power tractor in the surface soil and subsoil. The penetration resistance was significantly and negatively correlated with soil water content at time of penetration resistance measurement (Zhang *et al* 2006). After trafficking in a wheat field, the highest penetration resistance was found in the depth interval of 5 to 14 cm. The results of the study further reported that crop yield decreased with increasing numbers of tractor passes. Similar results were also reported by Balbuena *et al* (2000), who found that 10 passes significantly affect soil properties of the surface layer to 50 cm depth than that in the 1-pass and no-traffic control treatments. At high soil moisture content, the difference in soil resistance between compacted soil (with traffic) and uncompacted soil (no traffic) was low and usually less than that the value that limits root growth (>2 MPa). However, as soils get drier, soil compaction in the surface layer becomes discernible (Silva *et al* 2000). Reichert *et al* (2004) reported that penetration resistance for 6-

10 cm layer was greater than that in 2 MPa for no tillage, from 30 days after beans seeding until the end of the beans cycle.

Soil compaction considerably affects the soil permeability. Soil infiltration is directly proportional to the stability of soil structure (Tisdall and Adem 1986), pore size, volume and structure (Patel and Singh 1981, Ankeny *et al* 1990, Badalikova and Hruby 2006). Radford *et al* (2000) determined the changes in various soil properties immediately after the application of a known compaction load (10 and 2 Mg load on the front and rear axles, respectively) to a wet vertisol and found that compaction was mostly restricted to the top 20 cm of the soil where it decreases the number of pores per unit area in each of the three size ranges at soil surface and upto 10 cm depth. Ankeny *et al* (1995) found that wheel traffic reduced ponded water infiltration rates, but the impacts varied with soil type. On a silty clay loam, Ankeny *et al* (1990) found that wheel traffic reduced unsaturated water infiltration rates, but the reduction was greater in chisel-ploughed soil than that in no-tilled soil. Tarawally *et al* (2004) measured pore size distribution in a Rhodic Ferralsol in western Cuba to study the effects of three levels of soil compaction on soil moisture retention parameters. The study concluded that highest levels of soil compaction were caused at the soil water states corresponding to the field saturation and field capacity treatments. The negative effects of soil compaction on soil hydro-physical properties, denoted by an increased volume of $<0.5\mu\text{m}$ pores at the detriment of the $50\text{--}0.5$ and $>50\mu\text{m}$ pore size fractions, followed the similar trend. Marsili *et al* (1998) evaluated the change in physical properties of an arable clay soil following passage of rubber and metal-tracked tractors for ploughing on clay soil in centre-south and insular Italy in lucern. The decrease in macroporosity was greater in treatments involving the rubber-tracked tractor (from 10.6% to 4.0%) than for the metal tracked tractor (from 10.6% to 7.3%). Hydraulic conductivity decreased and the lowest values were found after one and four passes of the rubber-tracked tractor (1.5 and 0.08 mm h^{-1} , respectively).

Kayombo *et al* (1991) showed that an increase in axle load from 4 to 8 Mg reduced water infiltration rates by about 35 per cent. Similarly, on a sandy loam, Ohu *et al* (1993) reported that water infiltration decreased linearly with the increase in the number of passes (0, 5, 10, 15, and 20) of a tractor of 5 Mg by weight. Due to reduction in infiltration rates, Singh *et al* (1980) reported improved water use efficiency in rice under highly permeable soils due to reduction in percolation losses as a result of subsoil compaction. On a silt loam, Blanco-Canqui *et al* (2004) reported that wheel traffic reduced saturated hydraulic conductivity by about three times and increased bulk density by 6 per cent, averaged across various tillage systems. Canarache *et al* (1984) reported 1-3 per cent (w/w) decrease in water content in 0-20 cm soil layer with 30 tractor wheel passes over zero wheel passes in several soils of Romania. A traffic pan of 1.81 Mg m^{-3} density at a depth of 15-25 cm depth reduced water recharge by 2-3 cm in 180 cm soil profile (Sur *et al* 1980). This resulted in surface soil layer remain wet

longer at each irrigation in plots with compacted subsoil layer than that in uncompacted subsoil layer. Ghildyal and Satyanarayana (1965) reported decrease in hydraulic conductivity, non-capillary pores and void ratios of sand, sandy loam, sandy clay loam and clay soils with increase in bulk density due to compaction treatments. They further reported that hydraulic conductivity was directly related to the macropore space while micropores increased at the expense of macropores on compaction. Kirchhof *et al* (2000) reported that hydraulic conductivity underneath permanent tracks in a controlled traffic system spreaded laterally into the subsoil. Soil compaction increased bulk density and strength of the soil and thus affected the conductivity, permeability and diffusivity of water and air (Greenland 1977). Higher bulk density of subsoil has several fold reduced the saturated hydraulic conductivity and greater penetration resistance at given water content than that in layers above or below this subsoil layer (Sur *et al* 1980). It also resulted in decreased profile water storage by 2-3 cm when bulk density of subsoil layer exceeds 1.8 Mg m^{-3} from 1.55 Mg m^{-3} in sandy loam soil. The properties of subsoil layer vary with soil texture, water content, type and amount of clay and organic matter content (Singh 1986). Schwen *et al* (2011) in a study to measure water infiltration under different compaction levels and to characterize the effects of compaction on the soil's porosity and its associated water-conducting properties. The study further concluded that compaction reduced saturated hydraulic conductivity due to distortion of structural flow paths, connectivity and hydraulic effectiveness of many macropores. Compaction rearranged the pore space, resulting in more water-conducting mesopores. Ishaq *et al* (2001b) conducted a field experiment at Pakistan during 1997–1998 and 1998–1999 on a sandy clay loam soil to study subsoil compaction effects on soil physical properties and crop yield of sorghum. They observed that penetration resistance increased and total porosity and air filled porosity decreased significantly due to subsoil compaction.

Assouline (2006) modelled the relationship between soil bulk density and the water retention curve. He suggested that increase in the soil bulk density during compaction may influence many aspects of the soil- plant-water relations. The suggested relationships simulate a decrease in the fraction of larger pores and a resulting decrease in water retention at high capillary heads, as well as an increase in smaller pores and the related increase in water retention at relatively low capillary heads. Tobert and Wood (1992) studied the effect of soil compaction and water-filled pore space on soil microbial activity and N losses. A factorial arrangement of three bulk density levels (1.4 , 1.6 , and 1.8 Mg m^{-3}) and four water-filled pore space levels (60, 65, 70 and 75 per cent) were used. Microbial activity decreased with both increasing water-filled pore space and soil bulk density. Nitrogen loss increased with increasing bulk density from 92.8 to 334.4 g N m^{-3} soil at 60 per cent water-filled pore space, for 1.6 and 1.8 Mg m^{-3} , respectively. Shestak and Busse (2005) reported that habitable-sized pores for microorganisms (0.2 – $30 \text{ }\mu\text{m}$ diameter) increased at least 40 per cent in soils with

compaction treatment. Despite these changes, microbial measures were either unaffected by compaction or showed inconsistent increases. Pengthamkeerati *et al* (2011) determined the effect of soil compaction on soil microbiological properties related to N in a clay pan soil amended with poultry litter at Poland. Soil compaction reduced microbial biomass nitrogen and soluble N, but increased microbial C:N ratio and soil β -glucosaminidase activity. The field observation also showed that litter-amended soil had higher microbial biomass N, soil N and soil β -glucosaminidase activity compared to unamended soil in both compaction treatments, regardless of fallow and cropped plots. Whalley *et al* (1995) studied the biological impacts of soil compaction and found that soil reduces biotic activity particularly in the case of roots, earthworms and other fauna. In the case of microbial activity, the emphasis tends changed from aerobic to anaerobic activity with compaction.

Assouline *et al* (1997) concluded that soil compaction behavior was not only a function of soil texture, but also it was observed to be affected by pH, CEC, clay particle thickness, and by the presence of OM, iron oxides, and free aluminum hydroxides, which determine the nature of the resulting cohesive forces between the soil constituents. The results indicate that damages resulting from compaction, following 30 yr of intensive cultivation, were greater in the Palotina soil over the Cascavel soil. Lipiec and Stepniewski (1995) analysed that soil compaction resulting from vehicular traffic or tillage systems, affects transformations and uptake of nutrients due to changes in soil hydraulic, aeration, and diffusive properties, as well as by its effect on root growth and configuration. Nutrient uptake was reduced by soil compaction. One of the dominant factors affecting soil compaction levels in soil is soil moisture content, with change in compaction level the soil moisture content changes. Under moderate compaction, an increase in nutrient inflow rate per unit length or surface of the roots alleviates a reduction in total nutrient uptake.

2.4 Soil compaction and root growth

A significant effect of soil compaction on root growth and penetration has been reported by a number of scientists around the world. Voorhees *et al* (1976) studied compaction effects on soybean nodulation by controlling tractor wheel traffic within soybean plots. After 3 years of wheel traffic in the same inter-row areas, they concluded that, in a row cropping system, soil compaction from consistent wheel traffic could alter the vertical and horizontal distribution of nodules. Taylor and Brar (1991) reported that soil compaction can change the morphology and functioning of plant root systems by a number of mechanisms, not only physical, but also biological and chemical. Singh and Sainju (1998) reported that roots of different crop species, as well as of cultivars within species, differs considerably in their ability to penetrate through hard soil layers. Laboski *et al* (1998) in a field experiment found that a compacted soil layer confined roots almost entirely to the top 60 cm of soil because it had high soil strength and bulk density and the compacted layer, in turn, retained

more moisture for crop use. Rosolem and Takahashi (1998) reported that sub-surface compaction led to an increase in root growth in the superficial soil layer with a corresponding quadratic decrease in root growth in the compacted layer. There was no effect of subsoil compaction on total root length or surface area, soybean growth or nutrition. Soybean root growth decreased by 10 per cent when the soil penetrometer resistance was 0.52 MPa (bulk density of 1.45 Mg m^{-3}) and by 50 per cent when the soil penetrometer resistances was 1.45 MPa (bulk density of 1.69 Mg m^{-3}). Abu-Hamdeh (2003b) reported that in Okra under no-tillage and moldboard-plowed treatments had higher concentration of roots near the base of plants compared to roots of okra in the chisel-plowed treatment. Chan *et al* (2006) studied re-compaction due to tractor wheel traffic in a sodic brown clay (Vertisols) under simulated controlled traffic conditions after removal of a pre-existing subsoil pan by deep tillage. The study showed a significant reduction in canola and wheat root growth in the layer under the wheel tracks. While there was no difference in wheat yield, canola grain yield on the wheel track was only 34 per cent of that between wheel tracks, thus a potential loss in grain yield of canola observed due to compaction by tractor wheel traffic. Masle and Passioura (1987) reported that the increased mechanical impedance reduced water supply from root systems to shoots. Grzesiak (2009) conducted a pot experiment to study the different levels of soil compaction on plant growth characteristics, root biomass and root length density, leaf water status and gas exchange parameters in the seedlings of triticale and maize. Soil compaction treatments decreased leaf number, leaf area and dry matter of shoots and roots, while increasing shoot-to-root dry matter ratio. Root growth of maize was heavily restricted by the soil compaction. The results indicated that damages in photosynthesis, plant-water relation and shoot growth under soil compaction were closely related to sensitivity of root systems architecture to high mechanical impedance of soils. The presence of subsoil compacted layer affect the root amount and their distribution pattern in the soils (Sidhu 1980, Sur *et al* 1980, Sur and Sidhu, 1982). Chaudhary *et al* (1985) and Gajri and Prihar (1985) reported lesser plant water stress with deeper rooting depth as result of breakage of subsoil compacted layer with deep tillage. Aggarwal and Prihar (1975) reported that roots exert pressure when these grow and their pressure varied with crop, plant age, soil type and moisture conditions. Therefore, roots could overcome some sort of penetration resistance. Garcia *et al* (1988) reported that compaction treatments did not significantly affect total root growth, but higher N fertilization overcomes these effects. Punyawardena and Yapa (1990) studied the effect of soil compaction on root growth, K uptake, plant height and grain weight of corn at Sri Lanka. The results revealed that increase in the compaction decreased the root growth, K uptake, plant height and grain weight of corn. Reichert *et al* (2004) reported that roots concentrated mainly in the 5-15 cm layer for no tillage due to higher penetration resistance and were well distributed down to 25 cm depth for chisel tillage, while no restriction to root growth was

observed in conventional tillage. The number of days in which the crop experienced soil water outside the Least Limiting Water Range was 18 days for no-tillage, 19 days for conventional tillage, and 13 days for chisel tillage. Abu-Hamdeh (2003) reported that the plants in compacted plots had a greater concentration of roots near the base of the plants than that in the plants in the zero-load plots. Plants in the subsoiled plots had fewer roots concentrated near the base of the plant over the plants in the non-subsoiled plots for each load.

2.5 Effect of soil compaction on plant growth and yield

A wide body of literature (Table-2.1) is available on the effect soil compaction on yield of different crops. Sheikh (1976) found a linear decrease in seed germination with increasing soil bulk density (D_b). In a laboratory study (Sabir *et al* 1990), wheat germination was maximum at $1.2 \text{ Mg m}^{-3} D_b$ and minimum at soil D_b of 1.4 Mg m^{-3} . The germination was maximum (82 per cent) at 2.5 cm sowing depth with $1.2 \text{ Mg m}^{-3} D_b$ and 16 per cent soil water content. The lowest seedling emergence (17 per cent) was recorded at 5 cm deep seed placement at $1.4 \text{ Mg m}^{-3} D_b$ and 12 per cent water content. It was concluded that the tillage implements be selected to produce a D_b of 1.2 Mg m^{-3} at 16 per cent soil water content at the sowing depth of 2.5 cm to break the compacted layer had improved wheat seedling emergence. Gaultney *et al* (1980) compressed a silt loam soil to bulk densities ranging from 1.71 to 1.82 Mg m^{-3} . They positioned a 4-5 cm thick layer of this compacted soil at 20-23 cm depths. This treatment resulted in a 45 to 50 per cent reduction in corn (*Zea mays* L.) yields during the 2-yr study. In a field experiment (Adhikari 1989), wheat was grown in wheel-compacted and chiselled plots with or without FYM. Soil strength and D_b increased while the saturated hydraulic conductivity (K_s) decreased with increasing compaction but statistically remained similar with the control. Grain yields were significantly decreased by compaction while chiselling produced higher yields, possibly due to improved physical properties, particularly K_s of soil. Singh *et al* (1976) reported better and profitable utilization of stored soil moisture from the compaction treatment than that in no compaction treatment without any significant affect on the wheat yields under rainfed conditions. While, Prihar *et al* (1975) reported reduction in water use and 29 per cent yield reduction in wheat under compaction treatment in sandy loam soil. Singh *et al* (1981) reported decrease in water expense and increase in yield of rice with increase in bulk density of loamy sand soil. Similarly, Singh *et al* (1987) reported that compaction of a highly permeable soil for raising rice crop had significantly increased grain yield and reduced field water use in rice, without any deleterious effect, than that of puddling, on the yield of succeeding wheat crop. Prihar *et al* (1973) reported that the surface compaction of soil reduced the vegetative growth of the maize while grain or straw yields of wheat were unaffected by sub-surface compaction at Hissar, Haryana. Prihar *et al* (1973) found wheat yield decreased by 18-27 per cent under dense layer simulated

at 22-26 cm depth in a sandy loam soil at Hissar. Fausey and Dylla (1984) also reported increased bulk density in the surface 30-cm of a silty clay loam in response to wheel traffic, but found no corn yield response if the soil had adequate nutrient and water supply. Oussible *et al* (1992) evaluated the effect of subsurface compaction on the root and shoot growth, grain yield, and grain yield components of wheat. About 12 to 23 per cent decrease in grain yield and 9 to 20 per cent decrease in straw yield was reported due to subsurface compaction. The decrease in yield was accompanied by a consistent reduction in the number of shoots per unit area. However, plant height, leaf area, dry matter per shoot, number of kernels per spike and kernel weight remained unaffected. The decrease in shoot number was attributed to limitation in the amount of available soil N to the roots. Both root growth and distribution were markedly changed as a result of subsurface compaction. Wheat plants in compacted plots developed denser, finer and shallower root system than that in control plots. A reduction in leaf area and shoot biomass was also observed in maize plants grown on compacted soil (Ekwue and Stone 1995). Anazodo *et al* (1983) reported increased corn yield in response to moderate compaction in the surface 30-cm of a clay soil during a relatively dry year and the opposite effect during a relatively wet year. Radford *et al* (2001) studied crop responses to applied soil compaction on a Vertisols at Australia and found that annually applied axle loads of 10 and 6 Mg on wet soil (25–32 per cent soil water) tended to reduce seedling emergence, grain yield, soil water storage and crop water use efficiency (WUE). Abu-Hamdeh (2003) studied the compaction and subsoiling effects on corn growth and soil bulk density. As a result of compacting loads in 2000, corn (*Zea mays* L.) yield was reduced by 26.8 and 14.5 per cent in 2000 and 2001. However, plant height was also significantly reduced by compaction. Ishaq *et al* (2000a) reported a significant decrease in both grain and straw yields in compacted ($D_b = 1.93 \text{ Mg m}^{-3}$) than that in non-compacted ($D_b = 1.53 \text{ Mg m}^{-3}$) soils.

McLaughlin *et al* (2003) found that doubling the N fertilizer rate from 150 to 300 kg ha^{-1} on compacted clay loam soils only increased corn yields by 0.2 Mg ha^{-1} than that in non-compacted soils, where yields were increased by 0.8 Mg ha^{-1} . Canarache *et al* (1984) reported an 18 per cent decrease in corn grain yield for every 0.1 Mg m^{-3} increase in bulk density above 1.3 Mg m^{-3} in a soil with 30 to 40 per cent clay content. Radford *et al* (2001) reported that soil compaction caused by axle loads of 6–10 Mg on a wet Vertisol (25–32 per cent soil water) reduced grain yields (wheat and maize) by reducing soil water storage and crop WUE. It was concluded that trafficking the soil at low soil water contents minimizes yield decline. Ishaq *et al* (2001b) observed that fodder yield, water and nutrient use efficiencies of sorghum were reduced due to subsoil compaction. Rosolem and Takahashi (1998) studied the effects of subsurface soil compaction on root growth and nutrient uptake by soybean grown on sandy loam. They reported that sub-surface compaction led to an increase in root growth in the superficial soil layer with a corresponding quadratic decrease root growth in the compacted

layer. Soybean root growth was decreased by 10 per cent when the soil penetrometer resistance was 0.52 MPa and by 50 per cent when the soil penetrometer resistance was 1.45 MPa.

Table 2.1: Yield reduction due to soil compaction reported by various authors

Crop	Soil type	Per cent yield reduction	Reference
Wheat	Sandy loam	29	Prihar <i>et al</i> (1975)
Corn	Silt loam	45-50	Gaultney <i>et al</i> (1982)
Corn	loam	18-37	Canarache <i>et al</i> (1984)
Wheat	Vertisol	23	Radford <i>et al</i> (2001)
Sorghum		13	
Alfa alfa	Clay loam	1-35	Sander (2003)
Barley	Loam	5-31	Czyz (2004)
Lucerne	Silt loam	7-11	Glab and Gandok (2013)

Ishaq *et al* (2000b) reported reduction in nutrient uptake by wheat due to compaction was 12-35 per cent for N, 17-27 per cent for P and up to 24 per cent for K. The reduction in nutrient uptake in sorghum due to subsoil compaction was 23 per cent for N, 16 per cent for P and 12 per cent for K. the root length density of wheat below 15 cm depth was significantly reduced and was significantly correlated with soil bulk density. Oni (1991) at Nigeria investigated the effect of repeated traffic compaction by using 60 Horse power agricultural tractor on the performance of maize. The results showed that soil bulk density was significantly influenced by compaction levels. Seedling emergence, plant height and kernel yield of maize were not significant at all compaction levels.

Tubeileh *et al* (2003) studied the effect of soil compaction on photosynthesis and carbon partitioning within a maize-soil system at France and observed that soil compaction reduced root and shoot growth and increased carbon input into the soil and soil microbial biomass. The results showed that compaction effects persisted upto tassel initiation. Crop yields may decrease because plants grown at high soil bulk density might not be able to compensate for the delay in plant growth. Lowery and Schuler (1991) reported in an experiment to determine the duration and effect of subsoil compaction on soil strength and corn (*Zea mays* L.) growth found that the plant heights, at physiological maturity were reduced by 13 and 26 per cent on the 8 and 12.5 Mg compaction treatments, respectively, over the control.

2.6 Effect of nitrogen fertilization of plant growth and yield

Two year field study at Kadawa in Sudan Savanna of Nigeria was conducted to evaluate to the effect of nitrogen levels on yield and yield components of maize. Application of nitrogen upto 80 kg ha⁻¹ increased the cob length, cob diameter; cob weight and grain yield

significantly while further application did not affect the cob diameter and grain yield (Namakka *et al* 2008). In Sudan Savana of Nigeria Application of 120 kg N ha⁻¹ produced significantly higher dry matter per plant (g), plant height (cm), leaf area index and growth rate (g/m²/week) than that in other nitrogen rates (Hussaini *et al* 2001). Khot and Umrani (1992) conducted a field trial at Rahuri, Maharashtra to study the effect of different levels of nitrogen on yield and quality of 'African Tall' maize and observed that there was successive increase in yield up to 160 kg N ha⁻¹. Further increase in N reduced the seed yield significantly probably due to the law of diminishing returns. Significant differences in yield between 45, 90 and 135 kg N ha⁻¹ and the highest grain yield was obtained at highest dose (135 kg) of N at Chhindwara (Paradkar and Sharma 1993). Application of 120 kg N ha⁻¹ gave higher grain yield than that in 0 and 60 kg N ha⁻¹, whereas fertilizer use efficiency was higher with application of 60 kg N ha⁻¹ at Ludhiana (Kapur and Rana 1980). Brar and Cheema (1988) at Ludhiana recorded highest grain yield, 1000 grain weight, dry matter per plant and N uptake with the application of 120 kg N ha⁻¹ than 80 kg N ha⁻¹. Singh *et al* (1992) reported that grain yield of maize increased significantly with increase in nitrogen level up to 180 kg ha⁻¹ due to increase in number of grains per cob, cob length and 1000-grain weight.

2.7 Nitrogen and soil compaction

Gregorich *et al* (2011) evaluated the effects of compaction, N fertilization, and soil texture on corn (*Zea mays* L.) growth and yield at Canada. They observed that yields were reduced by up to 2.7 Mg ha⁻¹ (33%) and dry matter by 4.1 Mg ha⁻¹ (26%) in compacted soils. The soil response to compaction was more evident than the crop response, because a carryover compaction effect was observed on increasing the soil strength near the bottom of plow layer. A relatively large amount of post harvest soil N in compacted soil was observed, that increases the risk of N loss to the environment by denitrification, volatilization or leaching. However, Lowery and Schuler (1991) reported that nitrogen and potassium uptake was reduced by compaction while yields reduced by 4 to 14 per cent under different compaction levels relative to the control. Garcia *et al* (1988) conducted a greenhouse experiment to study the effects of horizontally and vertically oriented compaction zones and nitrogen fertilizer placement on corn (*Zea mays* L.) root growth patterns, soil water depletion, and nitrogen fertilizer uptake. Compaction treatments did not significantly affect total root growth, but higher N fertilization tended to decrease it. Root growth compensation, both enhancement in zones of favorable nutrient supply and redirection of growth to zones of more favorable physical conditions, was observed. Nitrogen placement had a greater impact on N uptake when compaction zones were present than that in uncompacted zones. Water extraction from a given zone was directly related to root density in that zone. Lipiec and Stepniewski (1995) studied the nitrogen economy of the soil that was adversely influenced by compaction as it caused lower accessibility of nitrogen for plants and greater denitrification.

Consequently, in compacted soil, nitrogen losses to the ground water and to the atmosphere were greater over uncompacted soil. Lowery and Schuler (1991) studied effects of subsoil compaction on nutrient uptake by maize (*Zea mays* L.) and reported a severe deficiency of N and K in plants grown on compacted soil.

2.8 Effect of slope steepness on soil-plant system

Steeper slopes resulted in greater runoff, as well as greater translocation of surface materials downslope through surface erosion and movement of the soil mass (Hall 1983). Verbist *et al* (2007) investigated relation of subsoil compaction due to conventional tillage techniques to subsurface flow and runoff on a sloped field in Belgium. They found significantly higher penetration resistances between 20 and 40 cm depth, a significantly higher soil bulk density and a 14 per cent decrease in drainage pore space compared to the top layer. In Nigeria, Lal (1983) observed increased soil erosion with increase in slope length and steepness. Fan and Wu (2001) studied relationship between slope steepness, soil properties, rainfall intensity and interrill soil erosion rates. The results revealed that increase in slope steepness increases runoff, while increased soil strength also increased runoff. Spratt and McIver (1972) found that the addition of N and P fertilizers did not increase crop yields at upslope positions to levels equal to those at lower slope position. Nazmi *et al* (2012) found yield reduction with increasing slope gradient and with changing slope positions from down slope to upslope. The accumulation of transported OC and fine particles from the up slopes by erosion were found to be responsible for yield increase under lower slopes. The yield components of barley were significantly higher in the lower slope positions than in the upper slopes. While, McConky *et al* (1997) during their study on slope gradient and subsoiling reported wheat yield decrease with increase in slope steepness, however subsoiling was not found beneficial for increasing the grain yield due to higher soil erosion under high slope steepness.

Conclusively, the most researchers pointed out that soil compaction affects soil properties contrastically, either positively or negatively (Soane and Ouwerkerk 1994 and Hakansson *et al* 1995). In Punjab, use of heavy machines like tractors, tillers, puddler, manure spreader, harvesters, etc. in rice-wheat cropping sequence resulted in formation of compacted soil or subsoil layer. In addition puddling is done to reduce percolation of water in rice under coarse textured soils which build up hard pan below the root zone, especially in rice-wheat cropping sequence. The formation of compact layer at any depth resists the penetration of roots and also affects physical, chemical and biological properties of soils, strongly affects soil-plant-water relations and yield of crops. In rainy season, maize is mainly dependent on rainfall for its water requirements. It has been seen that most of high intensity rainstorms arise in rainy season which cause damage to crop. Crop lodging took place due to combined effect of high intensity rainfall and high wind velocity storms, as a temporary waterlogging resulted

from rainfall or heavy irrigations under compact subsoil layer with low permeability. It is proposed that if a slope is provided in maize fields, lodging can be reduced by draining of excess surface runoff from the field. However, knowledge gap exists on interactive effect of subsoil compaction and nitrogen fertilization on physical properties of soil and on plant growth and yields under Indian conditions. The effect of subsoil compaction and slope steepness on the yield of maize crop during the moonson season also not known on varying soil conditions in India.

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CHAPTER III

SUBMITTED/ACCEPTED/PUBLISHED RESEARCH ARTICLES

The present investigation entitled “Soil and maize response to compaction, slope steepness and nitrogen fertilization in coarse textured soil” was carried out during the year 2012 and 2013. Following research articles have been submitted/accepted in the various journals.

S. No	Published/accepted/submitted articles	Journal	Rating	Status
1	Phenology and thermal indices of maize (<i>Zea mays</i> L.) influenced by subsoil compaction and nitrogen fertilization under semi-arid irrigated conditions	Journal of Applied and Natural Science	5.08 (NAAS)	Accepted
2	Maize (<i>Zea mays</i> L.) response to subsoil compaction and nitrogen fertilization under semi-arid irrigated conditions	Journal of Applied and Natural Science	5.08 (NAAS)	Submitted
3	Physiological growth indices of maize under semi-arid irrigated condition as influenced by subsoil compaction and nitrogen fertilization	Proceeding National Academy of Science, India. Sect: B Biological Sciences	6.00 (NAAS)	Revision submitted
4	Water use and water productivity of maize as influenced by subsoil compaction and nitrogen fertilization under semi-arid irrigated conditions	International Symposium on New-Dimensions in Agrometeorology for Sustainable Agriculture		Submitted
5	Soil physical properties, root mass density and yield of maize influenced by subsoil compaction and N fertilization under sandy loam soil			To be submitted
6	Soil and plant response to subsoil compaction and slope steepness under semi-arid irrigated condition	International Journal of Food, Agriculture and Veterinary Science	5.38 (ICV)	Accepted

Research Article: 1

Phenology and thermal indices of maize (*Zea mays* L.) influenced by subsoil compaction and nitrogen fertilization under semi-arid irrigated conditions

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Abstract: The magnitude of yield reduction due to soil compaction is variable and depends on the soil type, fertility status and other soil and environmental factors. The present investigation was carried out at the research farm, Department of Soil Science, Punjab Agricultural University, Ludhiana. The experiment was conducted to evaluate the effect of different levels of subsoil compaction and nitrogen fertilization on maize phenology, yield and heat use efficiency. The C₂ (subsoil bulk density (D_b) = >1.8 Mg m⁻³) treatment reduced yield by 15.5 and 24.3 percent and heat use efficiency (HUE) by 15.2 and 20.9 percent than that in C₀ (subsoil D_b = 1.55-1.65 Mg m⁻³) treatment during the year 2012 and 2013, respectively. The tasseling and silking stage was delayed, while physiological maturity was advanced under C₂ subsoil compaction treatment than that in C₀ treatment. The N₂ treatment improved the yield by 14.9 and 13.9 percent and HUE by 15.2 and 14.3 percent than that in N₀ treatment during the year 2012 and 2013, respectively. Maize took more days to reach physiological maturity under N₂ treatment as compared to N₀ treatment. Phenothermal index (PTI) showed that crop reached different stages earlier under C₁ and C₂ than that of C₀. The data emphasized the need to take care of soil strength and soil temperature related parameters along with weather conditions for better yield prediction using thermal time.

Keywords: Accumulated growing degree days (AGDD), Heat use efficiency (HUE), Nitrogen levels, Phenology, Phenothermal index (PTI), Subsoil compaction.

INTRODUCTION

The continuous use of heavy equipment for agricultural cultivation (ploughing/puddling, leveling, sowing, harvesting, etc.) throughout the world has resulted in increased soil compaction on agricultural land affecting crop production (Abu-Hamdeh, 2003). Flowers and Lal (1998) reported that the depth of compaction varies from 10 to 60 cm due to vehicular traffic over the field, but the ill effects on crop growth are more pronounced when compact layer formed just below the plough layer. An increase in soil bulk density (Sur *et al.*, 1980) and decrease in total porosity and the proportion of larger pores to smaller pores (Motavalli *et al.*, 2003) are some of the detrimental effects of soil compaction. These changes in physical properties of soils lead to reduced plant growth and production mainly by restricting root growth, decreased soil water and nutrient availability and lower soil aeration (Domzal *et al.*,

1991). The restrictive effect of soil compaction can be physical and physiological, affecting plant growth and yield (Iijima *et al.*, 1991).

Nitrogen (N) fertilization plays a significant role in improving soil fertility (Habtegebrial *et al.*, 2007), and results in increased vegetative growth and biomass of maize (Ogola *et al.*, 2002). Nitrogen is most yield limiting nutrient, its stress reduces grain yield by delaying plant growth and development. Maize is usually considered to have a high soil fertility requirement to achieve maximum yield (Uribelarrea *et al.*, 2009). Thus, it requires large quantities of N for optimal growth and yield. Shafi *et al.*, (2007) also reported increased maize yield with the application of N fertilizer. Maize starts to take up N rapidly at the middle of vegetative growth period and maximum N uptake occurs near silking stage (Hanway, 1963). N deficiencies at such stages reduce maize growth and, consequently, biomass yield (Uhart and Andrade, 1995). To overcome the ill effects of compaction farmers over fertilize the crop with high analysis fertilizer such as Urea.

Characterizing and understanding crop phenology is vital for crop management practices such as fertilization and irrigation scheduling (Streck *et al.*, 2008). It is useful to assess if the most critical stages of growth occur during periods of favorable weather and soil fertility conditions. Air temperature based agrometeorological indices viz., growing degree days (GDD) and phenothermal index (PTI) have been used to describe changes in phenological behaviour and growth parameters (Streck *et al.*, 2008; Kumar *et al.*, 2010). Crop phenology is primarily affected by the air temperature and secondarily by the soil temperature. Some studies (Stone *et al.*, 1999) reported that maize development is controlled by the temperature of the meristem, which lies underground. It was assumed to be affected by soil bulk density and soil temperature which are altered by soil compaction. A little information is available on the consequences of compact subsurface layer on the crop growth and development. Thus, the present study was initiated with the objective to assess the effect of subsoil compaction and nitrogen fertilization on the phenology, yield and heat use efficiency of maize.

MATERIAL AND METHODS

Site description, experimental design, and treatments

The present experiment was conducted at research farm of Department of Soil Science, Punjab Agricultural University, Ludhiana during the summer season of 2012 and 2013. The site is situated at 30°54' N latitude and 75°48' E longitude with an altitude of 247 metres above the mean sea level, in the central plain region of Punjab under Trans-Gangetic agro-climatic zone of India. It represents sub-tropical and 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. About 75 percent of

the average annual rainfall is received during July to September months. The soil was classified as alluvial, sandy loam in texture, calcareous, Typic Haplustept. The physico-chemical properties of soil are given in table 1.

The treatments were arranged in a split-plot design with three blocks. Three subsoil compaction levels were kept in main plot treatments while three doses of N were kept under subplot treatment. The subsoil compaction treatments were given 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 desired bulk density, surface soil was put back on the place. The subsoil compaction treatments were C₀- Control (bulk density, Db = 1.55-1.65 Mg m⁻³), C₁- Moderate compaction, (Db = 1.70-1.75 Mg m⁻³) and C₂- High compaction (Db >1.80 Mg m⁻³) at 15-30 cm depth. The nitrogen treatments were N₀-155 kg N ha⁻¹, N₁-195 kg N ha⁻¹ and N₂-235 kg N ha⁻¹.

Cultural practices

The maize 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 sowing and remaining N was applied in two equal splits i.e. at knee high and at pre-tasselling stages (Anonymous, 2012). Irrigation was applied at regular intervals as per the crop demand to avoid water stress at any stage. Recommended cultural practices were employed to ensure proper weed, insect and pest control (Anonymous, 2012).

Crop and weather measurements

The time of emergence was considered as the date when the coleoptiles of 50% of planted seeds were emerged from above the soil surface. Days taken to tasselling and silking were recorded as the number of days taken from planting to the date when the tassels and silks were emerged on 50 per cent of plants in the plot. The dough stage was recorded when 50 per cent of plants in the plot had whitish yellow to yellow kernels and fingernail impression was retained on them. Number of days taken to physiological maturity was recorded from the date of planting to the date when 50 per cent plants showed browning or drying of ear husk.

Growing degree days (GDD) as a measure of thermal time, were calculated by simple arithmetic accumulation of daily mean temperature above the base temperature value of 10°C considered for the maize crop. The growing degree days for each stage were calculated as (Nuttonson, 1955):

$$\text{Growing degree days (°C days)} = \sum_{i=1}^n T_i - T_b \quad (1)$$

Where, i is the i th day from sowing, T_i is mean temperature for that day, n is the number of days in the growing season (Ellis *et al.*, 1990) and T_b is Base temperature and was taken equal to 10°C. The heat use efficiency (HUE) was calculated using the following formula:

$$\text{HUE (kg ha}^{-1} \text{ }^{\circ}\text{C days}^{-1}) = \frac{\text{Grain or dry matter yield (kg/ha)}}{\text{AGDD (}^{\circ}\text{C day)}} \quad (2)$$

AGDD is accumulated growing degree days ($^{\circ}\text{C day}$) is sum of GDD acquired by crop during life cycle. Pheno thermal index (PTI) is the ability of the plant to utilize thermal heat for its development. PTI was calculated as

$$\text{PTI (}^{\circ}\text{C day day}^{-1}) = \frac{\text{GDD}}{\text{Number of day taken between two phenophases}} \quad (3)$$

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 percent moisture level and expressed in t ha^{-1} . Rainfall, evaporation, daily maximum and minimum temperatures (Figs. 1, 2) were recorded at Agrometeorological Observatory, Punjab Agricultural University, Ludhiana for the period of 21th of June to 28th of October of the year 2012 and 2013.

Statistical analysis

Statistical analysis was done as per the standard procedure given by Gomez and Gomez (1984) for the analysis of variance for split plot design. Mean separations using least significant difference (LSD) were determined for treatment effects when F-tests were significant at P values <0.05 .

RESULTS AND DISCUSSION

Effect of subsoil compaction and nitrogen fertilization on phenology of maize

The perusal of data (Table 2) shows that the higher level of subsoil compaction (C_2) significantly advanced the days taken to emergence during the year 2013. Maize crop took almost 10 days to complete germination in plot with no subsoil compaction, while germination advances by about 3 days with increased level of subsoil compaction over no subsoil compaction treatment during the year 2013. Higher soil moisture at the time of sowing during the year 2013, might be responsible for advancement of emergence during year 2013, because rainfall occurred few days prior to the sowing of crop.

The crop took 48-52 days during the year 2012 and 55-60 days during 2013 to appearance of tassel (Table 2). The subsoil compaction delays the 50 % tasseling by 4 days during 2012 and about 5 days during 2013. It had delayed the 50 % silking by about 4 days during 2012 and 2013 than that in no subsoil compaction treatment. The delaying of tasseling and silking may be attributed to the higher level of subsoil compaction which restricted the

growth and expansion of roots, thus adversely affecting the plant growth and development. Nitrogen being the most limiting nutrient to crop production significantly delayed the days to 50% tasseling and silking stage. An increase in the dose of N from 125 kg N ha⁻¹ to 190 kg N ha⁻¹ significantly advanced the tasseling and silking during both the years. The increasing in N dose resulted in advancement in the occurrence of tasseling by 3 days during 2012 and about 4 days during 2013 than that in no subsoil compaction treatment. An increasing in N dose had advanced in the occurrence of silking by about 3 days during 2012 and 2013. Our results confirms the findings of Dawadi and Sah (2012) who reported that increasing N level decreased the number of days to reach tasseling and silking. Abayomi and Adedoyin (2004) also found that application of higher dose of N significantly reduces time to tassels and silk emergence. Gajri *et al.* (1994) also reported that phenological parameters of maize were significantly affected by the amount of N fertilization and deep tillage.

The subsoil compaction advanced the dough stage by about 6 days and 4 days during the year 2012 and 2013, respectively (Table 2), than that in no subsoil compaction treatment. N application delayed dough stage by about 4 days and 3 days during the year 2012 and 2013, respectively. The delay in the dough stage with higher dose of N fertilizer is attributed to the higher vegetative growth under higher level of N application over the lower N application.

The subsoil compaction advanced the physiological maturity by about 7 days and 6 days (Table 2) during the year 2012 and 2013, respectively over no subsoil compaction treatment. The advancement in physiological maturity under higher level of subsoil compaction is attributed to lesser plant growth resulting from restricted root growth and shortened period of flowering and grain filling. N application delays physiological maturity by 3 days during 2012 and 5 days during 2013. The delay in the physiological maturity with higher dose of N application is attributed to the higher vegetative growth as compared to lower N dose. Ali *et al.*, (2012) found that increasing dose of N application in maize delays physiological maturity, because higher N level delays leaf senescence, sustain photosynthesis longer, extend duration of vegetative growth and increase succulence of plants.

Effect of subsoil compaction and N fertilization on thermal requirement for various phenophases

The concept of thermal time or Growing degree days (GDD) have been extensively used to illustrate and elucidate the effect of temperature on emergence and establishment of crops. The subsoil compaction and nitrogen levels (emergence, tasseling, silking, dough stage and maturity) had shown an increasing trend of heat unit (GDD) (Table 3). Among the subsoil compaction treatments, the C₀ treatment registered higher GDD to attain physiological maturity over C₁ and C₂ treatment. The AGDD ranged from 1847.7 to 1956.9 °C days in the year 2012, and 1774.5 to 1894.1 °C days in 2013 under different subsoil compaction levels.

The reduction in GDDs consumed by the maize to attain various phenophases under higher levels of subsoil compaction might be attributed to reduced growing period and poor rooting depth of maize. Thus it affected the uptake of growth resources specially, nutrient and water.

Among the nitrogen treatments, the N_2 treatment registered more GDD to attain physiological maturity than that of N_0 and N_1 treatment. N_2 treatment has prolonged the growth period which lead to more plant growth and crop acquired more GDD over the lower level of N fertilization. This indicates that improvement in fertility level through N fertilizer help attain crop growth stages earlier by decreasing the degree days requirement of the crop due N application, which enhances the vegetative growth. The reduction in accumulated GDD to attain maturity during the year 2013 was mainly attributed to reduction in growing period as a result of subsoil compaction and increase in minimum temperature over the year 2012.

The inference drawn indicates that crop growth is not only dependent on prevailing atmospheric temperature but also on essential plant nutrients. According to Liebig's law of minimum the crop growth is limited by the growth factors which are available in minimum. The atmospheric temperature during the crop season remained within the optimum range, therefore, the plant growth was directly proportional to subsoil compaction and N fertilization.

The subsoil compaction and N fertilization treatments had higher PTI at the early stages and gradually decreased towards the maturity stage (Table 4). Higher PTI was recorded for treatment C_2 and N_0 level. The decrease in PTI at later stage was due to the increasing growth duration at the advanced phenological stages of the maize. It was observed that the PTI gradually increased with increase in fertility level through N fertilizer for attaining silk and physiological maturity stage. However, for attaining tasseling stage, a reverse trend was observed i.e. decreased from lower fertility level to higher fertility level. Increasing level of N fertilizer lowered the PTI requirement because degree days consumed as well as number of days between two stages decreased and crop reached different stages earlier than the crop with non compacted subsoil and recommended N. Thus, it resulted in highest PTI requirement. The trend was uniform during both the years and for all growth stages.

Effect of subsoil compaction and N fertilization on Maize yield

Subsoil compaction and N fertilization significantly affected the grain yield of maize during both years of the study (Table 5). Experimental plot without subsoil compaction (C_0) recorded highest grain yield during both years of study. Higher level of subsoil compaction resulted in yield reduction that varied from 15 to 25 percent. Gaultney *et al.*, (1980) also reported 45-50 per cent yield reduction in maize due to subsoil compaction. Highest grain yield was achieved under non compacted subsoil (C_0) treatment than that in C_1 and C_2 treatments during year 2012 and 2013. The maize yield reductions under higher degree of subsoil compaction

occurred due to root growth restrictions. Allmaras *et al.*, (1988) also found lower yield as a result of root growth restrictions under subsoil compaction. In addition to this crop took less number of days to mature under higher degree of subsoil compaction and ultimately it had reduced crop yield. Muchow, (1990) had also observed reduced grain yield due to shorter grain filling period resulting from early maturity. N application significantly affects the grain yield (Table 5). The increase in N dose from 125 kg N ha⁻¹ to 190 kg N ha⁻¹ 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. Our finding confirms the finding of Inamullah *et al.*, (2011) who found increased grain yield with higher dose of nitrogen.

Effect of subsoil compaction and N fertilization on heat use efficiency

The higher levels of subsoil compaction adversely affect the HUE of maize and resulting from lower grain yield (Table 5). However, N fertilization had favorable effects on HUE due to higher grain yield and prolonged growth period. An improvement in the HUE was observed with the increase in fertility level and advancement of the crop stage as a result of N fertilization that enhanced the ability of the plant to utilize thermal heat for its development. This reduced HUE under higher level subsoil compaction was due to shortened growth period, lesser AGDD and reduced yield.

CONCLUSION

The present investigation concludes that the soil compaction adversely affect the phenology of crop resulting in yield reduction and reduced heat use efficiency. The C₂ subsoil compaction treatment had significantly delayed the occurrence of tasseling and silking stage, while, advanced the physiological maturity. Nitrogen application above the recommended dose had advanced the occurrence of tasseling and silking stage, while delayed the physiological maturity of crop, and improved crop yield and HUE. The crop acquired lesser AGDD under C₂ treatment than that in C₀ treatment leading to lower HUE. The various thermal indices used to predict crop yield are based on the canopy temperature, which could lead to serious error, if the soil strength and soil nutrition parameters are not considered. The present study revealed the need to take care of soil strength, soil temperature and soil nutrition related parameters for better yield prediction of maize using various thermal indices.

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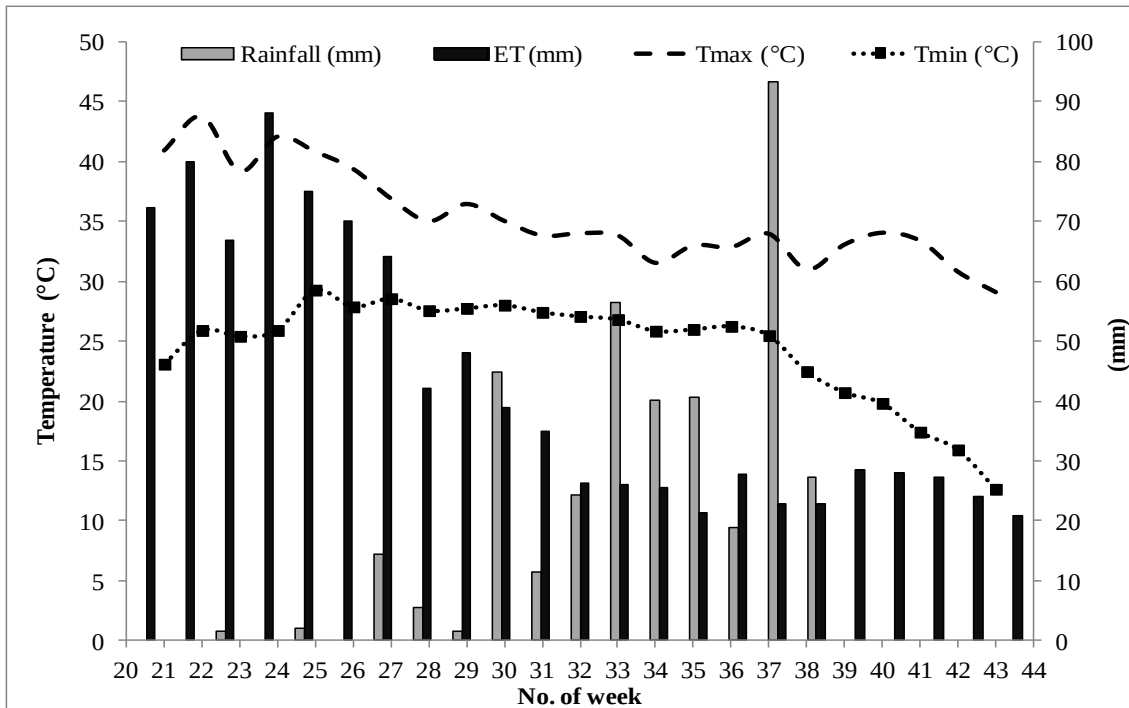


Fig.1. Weather observations from 21th of June to 28th of October of the year 2012

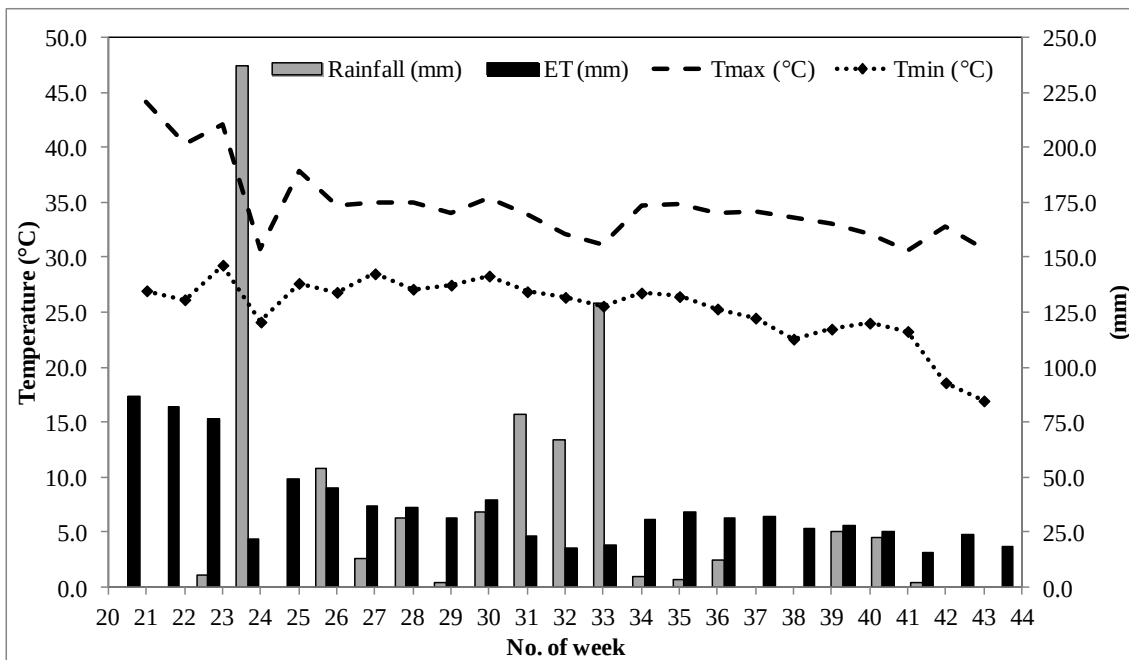


Fig. 2. Weather observations from 21th of June to 28th of October of the year 2013

Table 1. Soil physico-chemical properties of experimental site

Parameter	Value
Sand (%)	64.8
Silt (%)	18.9
Clay (%)	16.3
Bulk density, (Mg m ⁻³)	
0-15 cm depth	1.49
15-30 cm depth	1.67
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. Effect of subsoil compaction and nitrogen fertilization on phenology of maize during 2012 and 2013

Treatments	Emergence		50 % Tasseling		50% Silking		Dough stage		Physiological maturity	
	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013
Subsoil compaction levels										
C ₀	7.4	10.1	48.8	55.4	54.8	60	81.3	75.9	97.2	91.67
C ₁	7.2	7.2	51.4	57.7	56.6	63.5	77.6	74.3	94.4	89.0
C ₂	7.0	7.0	52.8	60.4	59.1	64.6	74.7	71.3	90.8	85.0
LSD- C	ns	1.5	3.01	3.49	2.9	3.61	4.29	3.46	2.77	4.87
Nitrogen levels										
N ₀	7.1	8.0	52.3	59.4	58.2	64.3	76.0	72.1	92.3	86.6
N ₁	7.3	8.0	51.1	57.5	56.8	62.6	78.0	73.8	94.2	88.0
N ₂	7.2	8.3	49.6	56.6	55.4	61.2	79.7	75.8	95.9	91.0
LSD- N	ns	ns	1.32	2.01	1.16	2.14	2.16	2.73	1.59	2.52
LSD C×N (P=0.05)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Table 3. Growing degree days (°C days) taken by the maize crop under different levels of subsoil compaction and nitrogen fertilization

Treatments	Emergence		50% Tasseling		50% Silking		Dough stage		Physiological maturity	
	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013
Subsoil compaction levels										
C ₀	195.8	245.8	1067.6	1182.1	1181.6	1268.7	1688.4	1596.7	1956.9	1894.1
C ₁	191.7	186.4	1119.2	1223.4	1216.0	1339.2	1627.2	1564.5	1909.5	1844
C ₂	187.6	182.0	1143.2	1276.8	1261.0	1362.7	1573.3	1501.8	1847.7	1774.5
Mean	191.7	204.7	1110.0	1227.4	1219.5	1323.5	1629.6	1554.3	1904.7	1837.5
Nitrogen levels										
N ₀	189.6	204.3	1134.5	1256.1	1245.3	1356.2	1598.6	1518.6	1873.0	1804.0
N ₁	193.7	204.3	1114.1	1219.6	1219.7	1320.4	1634.6	1554.2	1906.0	1826.8
N ₂	191.7	209.8	1084.3	1203.6	1193.3	1292.8	1661.6	1594.7	1935.2	1881.3
Mean	191.6	206.1	1110.9	1226.4	1219.4	1323.1	1631.6	1555.8	1904.7	1837.3

Table 4. Phenothermal Index (PTI) taken by the maize crop under different levels of subsoil compaction and nitrogen fertilization

Treatments	Emergence		50 % Tasseling		50% Silking		Dough stage		Physiological maturity	
	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013
Subsoil compaction levels										
C ₀	26.46	24.34	20.58	20.36	19.00	18.83	19.12	20.63	16.89	18.86
C ₁	26.63	25.89	20.29	20.07	18.62	19.97	19.58	20.86	16.80	19.01
C ₂	26.80	26.00	20.04	20.00	18.70	20.45	20.02	20.76	17.04	19.91
Mean	26.63	25.41	20.31	20.14	18.77	19.75	19.57	20.75	16.91	19.26
Nitrogen levels										
N ₀	26.70	25.54	20.14	20.01	18.78	20.43	19.85	20.82	16.83	19.68
N ₁	26.53	25.54	20.35	20.10	18.53	19.76	19.57	20.88	16.75	19.20
N ₂	26.63	25.28	20.50	20.17	18.79	19.39	19.27	20.68	16.89	18.86
Mean	26.62	25.45	20.33	20.09	18.70	19.86	19.56	20.79	16.83	19.25

Table 5. Effect of subsoil compaction and nitrogen fertilization on grain yield and heat use efficiency of maize

Treatment	Grain yield (t ha ⁻¹)		Heat use efficiency (kg ha ⁻¹ °C days ⁻¹)	
	2012	2013	2012	2013
Subsoil compaction levels				
C ₀	6.307	5.494	3.21	2.92
C ₁	5.738	4.391	2.99	2.40
C ₂	5.326	4.158	2.72	2.31
LSD – C	0.67	0.87	0.35	0.46
Nitrogen levels				
N ₀	5.400	4.346	2.75	2.38
N ₁	5.763	4.646	3.00	2.53
N ₂	6.209	5.049	3.17	2.72
LSD- N	0.47	0.52	0.22	0.25
LSD C×N (P=0.05)	ns	ns	ns	ns

Research Article: 2

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

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ABSTRACT

Intensive tillage operations for cultivation of land results in the formation of compact subsoil layer of high strength and low porosity, which restricts crop roots and reduces the volume of soil explored by the plant roots for nutrients and water, ultimately reduces crop yield. Farmers apply more fertilizer N to get higher yield under such soil conditions, which not only increases the cost of production but also affect the environment. Thus, an experiment was carried out to find the optimal N dose under subsoil compaction conditions and also to assess the impact of subsoil compaction and nitrogen management on growth characters, yield attributes and yield of hybrid maize by conducting two year field study. The present investigation was carried out at Research Farm, Department of Soil Science, Punjab Agricultural University, Ludhiana during the *kharif* season of 2012 and 2013. The experiment comprised three subsoil compaction treatments in main plots and three nitrogen levels in sub plots following split-plot design. Plant height, LAI and dry matter accumulation were negatively affected by subsoil compaction. However N 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 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 C₀ treatment than that in highly compacted subsoil (C₂), while N₂ treatment had improved the total N uptake by 18.6 and 14.9 per cent as compared to N₀ treatment during the year 2012 and 2013, respectively. The results reveal that N₁ fertilization level can be recommended under subsurface compacted soils as compared to N₀ and N₂ rates. This study further suggests the management option should be explored in addition to deep tillage to maximize yield of maize.

KEYWORDS: Subsoil compaction, Nitrogen, Yield, Dry matter accumulation, Yield attributes, N uptake.

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 CO₂ concentration, and nutrient availability affect crop phenology, growth and development. Maize yield depends on inherent soil nutrient status and fertilization, however these are location and variety specific (Shanti *et al.*, 1997). 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, that 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 (Yousra *et al.*, 2013) and N₂O 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 results in the formation of compact subsoil layer below the soil surface (Flowers and Lal, 1998). 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 to be explored by root is reduced, which reduce the availability of soil N to roots, resulting in reduced shoot growth. Farmer apply more of N 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. 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 characters, yield attributes and yield of maize.

MATERIAL 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 30°54' N latitude and 75°48' 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, K and soil organic carbon content of experimental site were lied in medium category. The physio-chemical properties of soils are given in Table-1.

A split-plot design was laid out in three blocks with three subsoil compaction levels (main plot treatments) and three doses of N (subplot treatment). 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 C₀- Control (bulk density, Db= 1.55-1.65 g/cm³), C₁- Moderate compaction, (Db= 1.70-1.75 g/cm³) and C₂- High compaction (Db>1.80 g/cm³) at 15-30 cm depth. The nitrogen treatments were N₀-62.5 Kg N ha⁻¹, N₁-78.5 Kg N ha⁻¹ and N₂-94.0 Kg N ha⁻¹.

The maize 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 PAU (Anonymous, 2012) were followed to ensure proper weed, insect and pest control.

The plant height (cm) was recorded as average from randomly selected five plants at 30 DAS, 60 DAS and at harvesting stage. Two plant samples for dry matter accumulation were cut from the ground level from each plot. These plants were sun dried and then in oven at the temperature of 60 °C till constant weight was achieved. Average weight (g dry matter accumulated plant⁻¹) for these plants was taken. Periodic leaf area index was recorded using the Sun Scan Canopy Analyzer. 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) and cob bareness (%) and 1000-grain weight (g) were recorded at the time of threshing. Unfilled portion of cobs selected for length was measured with scale and noted as 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 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.

Statistical analysis was done using PROC GLM (SAS software 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 employed for correlation analysis between 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 (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 under higher subsoil strength. N fertilization significantly affect the plant height at 30, 60 DAS and at harvesting stage. 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 Gee-Clough *et al.*, (1990) who found reduction in dry matter yield by 16% under higher degree of compaction as compared to uncompacted soil. 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 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 as also reported by Bangarwa *et al.*, (1988).

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. 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) have reported more leaf elongation and less leaf senescence with higher nitrogen supply. Prasad *et al.*, (1990) also reported increased LAI 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 treatment. 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 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 barrenness under C_2 treatment may be attributed to poor dry matter accumulation and

translocation of photosynthates. In general, cob barrenness decreased with increase in nitrogen dose. 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 its 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.

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). Gaultney *et al.*, (1980) also reported 45-50 per cent yield reduction in maize due to subsoil compaction. Siemens and Peterson (1997) reported an average yield reduction of 13 per cent due to compaction resulting from vehicular traffic. The maize yield reductions under higher degree of subsoil compaction occurred due to root growth restrictions. Allmaras *et al.*, (1988) reported lower yield due to root growth restrictions under higher subsoil compaction. Crop 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 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.*, (2011) who reported an increase in 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 .

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.*, (2011) also reported improvement in biomass yield 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.*, (2011) also reported positive correlations of cob length with 1000 grain weight and grain yield.

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 C₂ subsoil compaction treatment and N₂ level of N fertilization during the years 2012 and 2013. Xi *et al.*, (2009) also reported that the N concentration in constituent organs of maize experiencing root growth restriction remain similar to that of control plants.

Grain and straw N uptake was significantly higher under C₀ treatment than that in C₁ and C₂ during the year 2012 and 2013. The grain N uptake in C₀ treatment was 15.5 and 27.1 per cent higher than that in C₂ subsoil compaction level during the year 2012 and 2013, respectively (Table-6). The application of higher N rate improved the grain N uptake in N₂ treatment by 15.7 and 16.8 per cent over the N₀ level. The straw N uptake was 13.5 and 10.6 per cent higher in C₀ treatment than that in C₂ treatment during the year 2012 and 2013, respectively. The N₂ treatment had improved the straw N uptake by 21.4 and 13.0 per cent as compared to N₀ 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 (C₀) than that in highly compacted subsoil (C₂) during the year 2012 and 2013, respectively. The higher soil strength under C₂ treatment might have restricted the crop 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 N₂ treatment had improved the total N uptake by 18.6 and 14.9 per cent as compared to N₀ 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 C₀ treatment was 15.5 and 27.1 per cent higher than that in C₂ subsoil compaction level, while application of higher N rate improved the grain N uptake by 14-18 per cent. The N₁ 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. Further studies are needed to access the fate of excess N application in relation to soil and environment health.

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

Parameter	Value
Sand (%)	64.8
Silt (%)	18.9
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
<i>p-value C</i>	0.0006	0.047	<0.0001	<0.0001	0.003	<0.0001
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
<i>p-value N</i>	0.039	0.056	0.0034	0.046	0.023	0.002
<i>p-value C X N</i>	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
<i>p-value</i>	0.0006	0.0038	0.0008	0.0021	0.0001	<0.0001
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
<i>p-value-N</i>	0.0003	0.0002	<0.0001	<0.0001	<0.0001	<0.0001
<i>p-value C X N</i>	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
<i>p-value C</i>	0.004	<0.0001	0.0003	0.0006	<0.0001	0.005
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
<i>p-value N</i>	0.0001	<0.0001	0.0004	0.0014	<0.0001	0.0016
<i>p-value C X N</i>	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 (%)		Test weight (g)		Harvest index	
	2012	2013	2012	2013	2012	2013	2012	2013
Subsoil compaction levels								
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
<i>p-value C</i>	0.037	0.0046	0.05	0.03	0.0059	0.076	0.82	0.0016
Nitrogen levels								
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
<i>p-value N</i>	0.029	0.05	0.007	0.0016	0.0031	0.21	0.51	0.41
<i>p-value C X N</i>	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
<i>p-value C</i>	0.21	0.076	0.63	0.33	0.0002	0.0007	0.04	0.006	0.001	0.001
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
<i>p-value N</i>	0.63	0.94	0.12	0.51	0.0002	0.03	0.002	0.0017	0.0002	0.006
<i>p-value C X N</i>	0.92	0.85	0.71	0.74	0.41	0.94	0.99	0.14	0.94	0.75

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
<i>p-value</i> C	<0.01	<0.001	<0.016	<0.001
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
<i>p-value</i> N	0.01	<0.038	<0.01	<0.01
<i>p-value</i> C X N	0.65	0.99	0.96	0.44

Table-8. Correlation matrix for plant growth, yield and yield attributes of maize

	Dry matter per plant at harvest	Plant height at harvest	LAI at harvest	Test 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**	-0.355**	-0.557**	-0.118	-0.630**	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**	-0.456**	1

* Significant at $P > 0.05$, ** Significant at $P > 0.01$

Research Article: 3

Physiological growth indices of maize under semi-arid irrigated condition as influenced by subsoil compaction and nitrogen fertilization

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Abstract

The study was initiated to access the effect of subsoil compaction and nitrogen fertilization on various growth indices of maize, at research farm, Department of Soil Science, Punjab Agricultural University, Ludhiana. The split plot design was employed with three levels of subsoil compaction (main plot), three levels of N fertilization (subplot) and three replications. The dry matter accumulation, leaf area and growth indices were significantly lower under higher level of subsoil compaction. The crop growth rate was significantly higher under C₀ treatment at 30 DAS, 60 DAS and at harvest than that in C₁ and C₂ treatment. Higher root mass density was observed in the surface soil under C₂ treatment, while a reverse trend was recorded at 15-30 and 30-60 cm soil depth, where higher root mass density was observed under C₀ treatment than that in C₁ and C₂ treatment. Application of higher dose of N resulted in higher dry matter, leaf area index and growth indices than that in lower N application. A positive exponential relationship was observed between grain yield-crop growth rate and biomass yield-crop growth rate. The total N uptake was lower under C₂ subsoil compaction level, while higher N rates found to improve N uptake. The N fertilization resulted in favourable nutrient regime and thereby improved maize growth, development and yield formation under higher subsoil compaction levels. Further studies could be to access the environmental and soil health risks associated with higher N application under compacted subsoil conditions.

Keywords

Nitrogen fertilization, Subsoil compaction, Dry matter accumulation, Crop growth rate, Net assimilation rate

Introduction

Tillage improved the physical condition of soil for better crop establishment, growth and yield, but a compacted subsurface layer formed at the depth of 10-40 cm as a result of heavy agricultural machinery [4]. Subsurface hard pan below also developed due to puddling for cultivation of paddy, especially under rice-wheat cropping sequence [24,23]. The soil physical environment degradation occurred due to compaction, affected root as well as shoot growth and development. Soil compaction increased mechanical impedance, resulted unfavorable growing conditions for roots and limit oxygen, water and nutrients supply [3,6]. High soil strength and low porosity of subsoil layer, confined the roots in the top layer and reduced the volume of soil exploited by the plants for nutrients and water [11]. Due to compaction, availability of nitrogen from soils to roots is also reduced considerably, which decreased overall plant biomass.

Nitrogen is one of the most abundant elements on earth and also most critical growth limiting nutrient, [20] because of its low availability in soil due to various form of losses such as denitrification, volatilization, leaching, etc. [19]. Nitrogen fertilization played a considerable role in improving soil fertility and increasing crop productivity [8], and resulted in enhanced biomass and grain yield of maize [12]. Maize requires high soil fertility to achieve maximum yields and thus, require N in hefty amounts for optimal growth and yield [26, 27]. The bioavailability of soil nitrogen depends on the equilibrium between the rates of mineralization, nitrification, and

denitrification. These processes are determined by a number of factors including soil physical conditions and composition, microbial activity, aeration, soil temperature, and soil water status [21]. Maize take up N rapidly till the middle of vegetative growth period and maximum N uptake occur near silking stage [9]. Biomass production of a crop depends on the function of leaf area development and consequential photosynthetic activity. Photosynthetic rate can substantially be increased with N-fertilization, to increase grain yield and quality of maize [15].

Physiological growth indices (crop growth rate and net assimilation rate) are used to assess plant response to different environmental conditions during plant life. Physiological growth indices such as crop growth rate, net assimilation rate, dry matter assimilation and partition are affected by soil, water and nutrient regimes. Although, a large body of literature [2, 8, 12, 13, 14, 15] is available on the effect of N fertilization on physiological indices of maize, however insufficient information is available to understand physiological responses under varying soil physical environments. Better perception and understanding of effects of subsoil compaction on crop growth and yield can provide better insight of yield variability and productive responses of maize due to optimal growth and productivity. Thus, the experiment was, planned to access the effect of subsoil compaction and nitrogen fertilization on various growth indices of maize under semi-arid irrigated conditions of Ludhiana, Punjab, India.

Material and methods

The experiment was conducted at research farm, Department of Soil Science, Punjab Agricultural University, Ludhiana during the summer season of 2012 and 2013. The experimental site has semi-arid climate with very hot and dry summers 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. About 75 per cent of the average annual rainfall is received in monsoon season (July to September months). The information on rainfall, pan evaporation (PE), maximum temperature (T_{max}) and minimum temperature (T_{min}) has been presented in Fig 1 & 2. The soil was classified as alluvial, sandy loam in texture (sand 64.8%, silt-18.9% and clay 16.3%) calcareous, Typic Haplustept. The soil had pH 7.63, EC 0.51 dS m⁻¹, Organic carbon and plant available N were low and plant available water in soil profile (180 cm depth) was 21.8 cm.

The treatments were arranged in Split plot design with three levels of subsoil compaction (main plot), three levels of N fertilization (subplot) and three replications. The sub-soil compaction treatments employed were C₀- normal/uncompacted (bulk density, $D_b = 1.55-1.65$ g/cm³), C₁- moderate compaction, ($D_b = 1.70-1.75$ g/cm³) and C₂- high compaction ($D_b > 1.80$ g/cm³) at 15-30 cm depth. The subsoil compaction treatments were imposed by removing the surface 0-15 cm soil and then compacting the subsurface layer with tractor mounted stone roller of 700 kg in sandy loam soil. The tractor mounted roller was passed over the soil, till the desired bulk density was achieved for a particular treatment. After achieving the desired bulk density, the surface soil was put on the place. The nitrogen treatments applied were N₀-155 kg N ha⁻¹, N₁-195 kg N ha⁻¹ and N₂-235 kg N ha⁻¹.

The maize variety PMH-1 was planted (on June 27 during 2012 and June 22 during 2013) with row to row spacing of 60 cm and plant to plant spacing of 20 cm. Phosphorus, potassium and zinc

sulphate were applied @ 60, 30 and 25 kg ha⁻¹, respectively. Entire quantity of P, K and Zn 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 PAU were followed to ensure proper weed, insect and pest control. Hand weeding was done to ensure that weeds did not affect growth and development or depress yields.

Two plants for dry matter accumulation were cut from the ground level from each plot at 30, 60 days after sowing (DAS) and at harvest. These plants were sun dried and kept in oven at the temperature of 60 °C till constant weight was achieved. Average weight (g dry matter accumulated plant⁻¹) for these plants was taken. Periodic leaf area index was recorded using the Sun Scan Canopy Analyzer.

Crop growth rate was calculated at 30, 60 DAS and at harvest by using formula given by Hunt [10] and was expressed as g plant⁻¹d⁻¹.

$$CGR = \frac{(W_2 - W_1)}{(t_2 - t_1)}$$

Where, W₂ and W₁ are dry matter (g plant⁻¹) at time t₂ and t₁, respectively.

The net assimilation rate [10] as the index of production efficiency of plant leaf calculated in relation to total leaf area at 30, 60 DAS and at harvest and expressed as g cm⁻²d⁻¹

$$NAR = \frac{(W_2 - W_1)}{(t_2 - t_1)} \times \frac{(\ln LA_2 - \ln LA_1)}{(LA_2 - LA_1)}$$

Where, LA₂ and LA₁ are leaf area (cm²), W₂ and W₁ are dry matter (g plant⁻¹) at time t₂ and t₁, respectively.

The maize crop was harvested on October 11 during 2012 and October 3 during 2013. All the ears from each net harvested plot were sun dried for three days and shelled. The grain yield was adjusted to 15 per cent moisture level and expressed in t ha⁻¹. The biomass yield was recorded by weighing the dried total above ground biomass left after grain harvest. Grain and straw samples were collected at harvest and appropriate amounts of the ground grain and straw material were used to determine the total N content using a modified Kjeldahl digestion method [18].

Soil samples were collected with core sampler from 0-15 and 15-30 cm depth for determination of bulk density [28]. Penetration resistance as an indicator of soil strength was measured using hand penetrometer. Soil core samples were taken from 0-15, 15-30 and 30-60 cm depth with the help of root sampling pipe having internal diameter of 7 cm. The samples were taken at pre- tasselling stage by keeping the plant base in the centre of the core in each experimental plot. The collected soil samples were kept over 1.0 mm sieve under running water for washing and separating roots. The washed roots were picked up and then dried at 60°C in an oven to constant weight. The root density was expressed as weight of roots per unit volume of soil and calculated as follows:

$$\text{Root density (kg m}^{-3} \text{ of soil)} = \frac{\text{Total root weight (kg)}}{\text{Total volume of soil from which roots were collected (m}^3\text{)}}$$

The analysis of variance (ANOVA) for split plot design was employed as per the standard procedure given by Gomez and Gomez [7]. The least significant difference (LSD) was used for mean separations of treatment effects when F-tests was significant at P values <0.05.

Results and discussion

Meteorological conditions varied considerably during the period of study, as shown in figures 1 & 2. Minimum temperature remained higher than the normal minimum temperature during both the year of the study and maximum temperature during the year 2012 was more than the normal maximum temperature. Pan evaporation during the year 2012 was higher than normal pan evaporation till the vegetative period of the crop, later it was lower than the normal pan evaporation. Rainfall was lower than the average normal rainfall for the experimental site during the year 2012 and 2013.

The bulk density and penetration resistance of soil was higher at 15-30 cm soil depth under C_2 treatment as compared to C_0 treatment (Table-1). The penetration resistance at this depth under C_2 treatment reached critical value affecting the root penetration into deeper layers, thus restricted root growth and development. The use of heavy machinery for cultivation also resulted in higher bulk density and soil strength at 10-40 cm depth [4, 30].

Leaf area (LA) increases as the plant height and number of leaves per plant increases and is considered to be an important index strengthening the source-sink relationships. LA increased upto 60 DAS and thereafter declined due to rapid senescence (Fig- 3a & 3b). There was an increase in leaf area with the advance in crop age, reaching the highest value at anthesis stage of the growth cycle and thereafter declined toward grain filling stage. The LA under C_0 treatment was significantly higher than that in C_2 at 30 DAS, 60 DAS and at harvesting stage during the year 2012 and 2013. The reduction in leaf area under C_2 treatments might be attributed to root growth restrictions resulted from higher soil strength. Application of higher dose of N resulted in significant increase in LA over N_0 treatment at 30 DAS, 60 DAS and at harvesting stage. LA of maize at 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 LA 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 LA values were observed at 60 DAS under different levels of N application. The increase in LA due to high N application might be attributed to functional role of N in cell elongation and cell multiplication, thereby resulting in more leaves per plant, thus enhanced leaf area per plant. More leaf elongation and less senescence under higher nitrogen regimes were recorded by Uhart and Andrade [16]. Prasad et al. [13] observed increased LA with application of higher dose of N. Amanullah et al. [29] also found remarkable increase in leaf area, leaf area plant⁻¹, plant height and biomass yield with increasing N rate over recommended N dose due to adequate supply of N.

Dry matter production serves as a reliable measure of the relative influence of different treatments on plant growth, yield and transfer of assimilates to the sink resulting in higher yield. 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 harvest. 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 (Fig. 4a & 4b). Gee-Clough et al. [5] also found reduction in dry matter yield by 16 per cent under higher degree of compaction than that in uncompacted soils. The N fertilization had significantly increased dry matter accumulation at 30 DAS, 60 DAS and at

harvesting stage. 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 accumulation per plant with higher N application appeared to be a direct consequence of increased N availability for growth and development of plant. The increased N supply expanded the leaf area which might have improved the photosynthetic rate, thereby increased the supply of photosynthates to plants. Significantly higher amounts of dry matter accumulated with increase in N-level, might also be due to the cumulative effect of higher plant height and higher leaf area index under higher N application over the lower N application. These results supports the findings of Bangarwa et al [2] who also found higher plant height and leaf area index under higher N application.

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

In 0-15 cm soil layer root mass density at pre-tasseling stage was significantly higher under C_2 treatment than that in C_0 and C_1 treatment during the year 2012 and 2013 (Fig- 6a & 6b). Rosolem and Takahashi [22] also reported that sub-surface compaction led to an increase in root growth in the superficial soil layer with a corresponding quadratic decrease in the compacted layer. However a reverse trend in root mass density was observed for 15-30 and 30-60 cm soil depth, where root mass density was higher in C_0 treatment than that in C_1 and C_2 treatment. Root growth restriction under C_2 treatment was due to its higher subsoil bulk density and penetration resistance (Table-1) had resulted in higher root mass in 0-15 cm soil layer. However, higher root mass density in 15-60 cm soil depths was higher in C_0 treatment due to lower penetration resistance of subsoil layer. Grzesiak [25] found that the root growth of maize was heavily restricted by the soil compaction due to its higher penetration resistance and bulk density. Sur et al. [24] and Sur and Sidhu [23] also reported that the presence of subsoil compacted layer affect the root amount and their distribution pattern in the soils. The N fertilization significantly affected the root mass density of maize at pre-tasseling stage. The root mass density was higher under N_2 treatment than that in N_0 and N_1 treatment due to higher plant growth as a result of proper nutrition of maize crop.

Healthy root and shoot growth are prerequisite for higher grain and biomass yields and higher N recovery, but restricted root growth might had affected the N recovery leading to lower biomass and grain yields. The total N uptake was higher under lower subsoil bulk density than that in higher subsoil bulk density (Fig-7a). Subsoil compaction was negatively related to the total uptake, i.e. the total N uptake by the plant decreased with the increase in the bulk density of subsoil. The restricted root growth resulted in the lower grain and biomass yield that lead to lower total N uptake under higher sub-surface compacted soils. Total N uptake and N rates were positively correlated, total N uptake of maize increased with application of higher N rate. The N fertilization had improved the N uptake due to higher grain and biomass yield under higher dose of N application (Fig-7b). Kage and Ehlers [31] indicated that reduction in root density drastically reduces the N uptake, because it is plant N demand that limit N uptake not the N supply.

Crop growth rate (CGR) increased progressively with time, reached peak at 60 DAS and thereafter declined till maturity of the crop (Table. 2). Reduction in growth rate with plant age was probably due to cessation of vegetative growth, loss of leaves and rapid senescence. The CGR was significantly higher in C_0 treatment than that in C_1 and C_2 treatment. The root growth restriction due to higher soil strength might be responsible for lower CGR and dry matter accumulation under C_2 subsoil compaction level. Ogawa et al [32] also reported close relationship between root growth and supply of photosynthates.

With increasing N dose, crop growth rate (CGR) was increased. The significantly higher CGR was observed in N_2 treatment at all the growth stages. The lower CGR was recorded in N_0 treatment as compared to N_1 and N_2 treatments. Increase in CGR rate with higher N was mainly attributed to higher vegetative growth and LA. This behavior agrees with the findings of Valero et al. [17]. Also, an increase in CGR at 60 DAS might be due to transformation of plant into reproductive phase or by increase in dry matter production influenced by different N treatments, which could be attributed to higher photosynthetic activity coupled with increased cell multiplication. Amanullah et al [14] also recorded higher crop growth rate under higher N rate.

A positive relationship was observed between grain yield and crop growth rate (Fig-5a), with data explaining 71 per cent variation. Similar relationship had also been found between biomass and crop growth rate (Fig-5b) with biomass variation of 69 per cent. The positive relationship between grain and biomass yield with crop growth rate may be attributed to the associated increase in dry matter accumulation with increase in leaf area and ultimately higher yield. This reflects the direct effect of subsoil compaction and N fertilization on the crop growth rate. The reduced crop growth rate under higher degree of subsoil compaction and smaller dose of N resulted in the reduced grain and biomass yield of maize.

The net assimilation rate (NAR) increased with the growing crop, maximum at 60 DAS and decreased thereafter (Table-3). An increase in NAR during the growing season is interpreted as a response of the photosynthetic apparatus to an increased demand for assimilates to afford rapid growth of the grain fraction. The higher NAR reflects higher photosynthesis or low whole plant respiration. The NAR was significantly higher in C_0 treatment than that in C_1 and C_2 at harvesting stage during the year 2013. The reduction in NAR under higher degree of subsoil compaction might have occurred due to reduction in dry matter accumulation and leaf area as a result of impedance to root growth due to higher soil strength. The impeded root growth limits nutrient and water supply to plants. The results were in conformity with the findings of Valero et al. [17]. The decrease in NAR might be attributed to the shading effect of lower leaves by the upper canopy, decline in photosynthetic efficiency with leaf age, rapid leaf senescence and also due to lack of nutrients in later stages as a result of subsoil compaction. The N application showed significant improvement in mean NAR. The mean maximum NAR (2.189 and 2.267 g plant⁻¹ d⁻¹ during 2012 and 2013 respectively) was observed under N_2 treatment at 60 DAS which decreased thereafter, because at earlier growth stage, maximum increase in dry matter and stem growth occurred (Table-3). The maize plant accumulated higher dry matter that might be responsible for more NAR under N_2 treatment. A decreasing trend in maize NAR vs its LAI over growing season was also

reported by Adelana and Milbourn [1]. A significantly higher NAR was recorded at harvest in C₀ treatment as compared to C₁ and C₂ treatments.

The subsoil compaction results in higher bulk density and penetration resistance of subsurface layer that restricted the root growth. The restricted root growth adversely affects the leaf area, dry matter accumulation and total N uptake which reduces crop growth rate and net assimilation rate. The application of higher N over the recommended dose improves the leaf area and dry matter accumulation, thereby improves the crop growth rate and net assimilation rate. The present study provides the evidence the N application could be beneficial for achieving higher yields under subsoil compacted conditions, but further studies should be done to investigate the environmental and soil health related risks involved with application of higher N.

Conclusion

The study showed that with increase in the subsoil compaction, dry matter accumulation, leaf area index, total N uptake and growth rate of the crop declined. The CGR and NAR increased till 60 DAS and declined toward maturity of crop. The CGR and NAR were higher under C₀ uncompacted subsoil condition than that in C₁ and C₂ subsoil compaction levels. The higher bulk density and penetration resistance of subsoil under C₂ treatment resulted in higher root mass density in 0-15 cm soil layer under C₂ treatment than that in C₀ and C₁ treatment, but root mass density under C₀ treatment was higher at 15-30 and 30-60 cm soil depth than that of C₁ and C₂ treatment. Nitrogen fertilizers helped in compensating the adverse effects of higher degree of subsoil compaction. The N application improved the LA and dry matter accumulation that decreased due to subsoil compaction. The CGR and NAR were also higher under higher N rates. The results presented indicate that when compared with subsoil compaction levels, N fertilization could result in favourable nutrient regime and thereby benefit maize growth, development and yield formation. The study highlights the need of deep tillage and higher N application to obtain better yield under subsoil compaction affected soils. However, soil and environmental risks associated with higher N application under such conditions are also need to be examined further.

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Table-1. Bulk density and penetration resistance of soil under various subsoil compaction and N fertilization treatments

	Bulk density (Mg m^{-3})		Penetration resistance (kPa)	
	0-15 cm	15-30 cm	10 cm	22 cm
C ₀ N ₀	1.55	1.56	1045.0	1821.6
C ₀ N ₁	1.52	1.61	961.2	1937.8
C ₀ N ₂	1.63	1.62	1019.9	1909.9
C ₁ N ₀	1.55	1.72	1046.8	2156.8
C ₁ N ₁	1.57	1.71	934.5	2011.1
C ₁ N ₂	1.52	1.74	999.8	2126.5
C ₂ N ₀	1.57	1.81	1019.9	2516.6
C ₂ N ₁	1.55	1.83	1061.7	2491.7
C ₂ N ₂	1.57	1.82	1048.3	2678.3

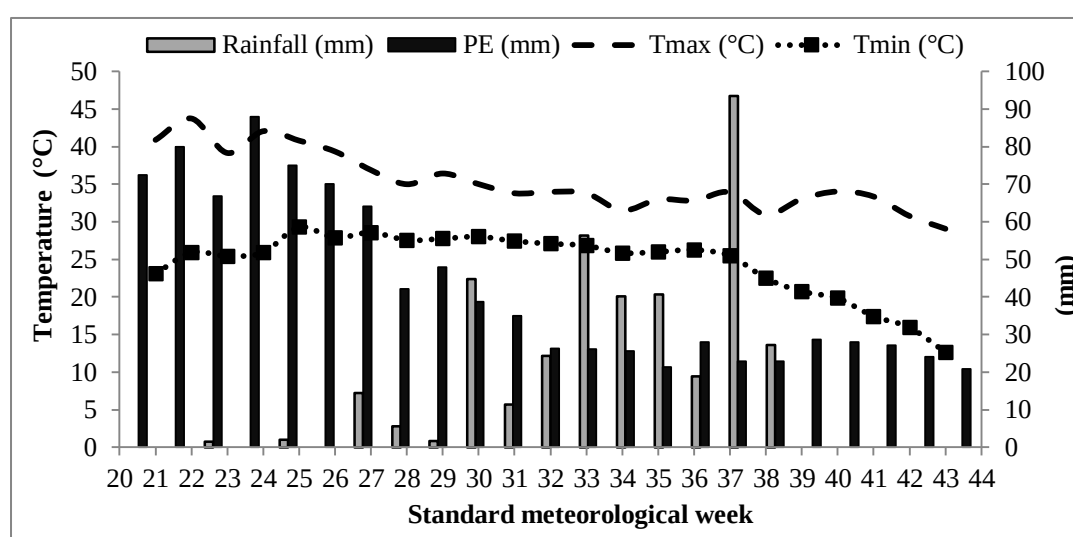


Figure-1. Weekly weather observations from 21th of June to 28th of October of the year 2012

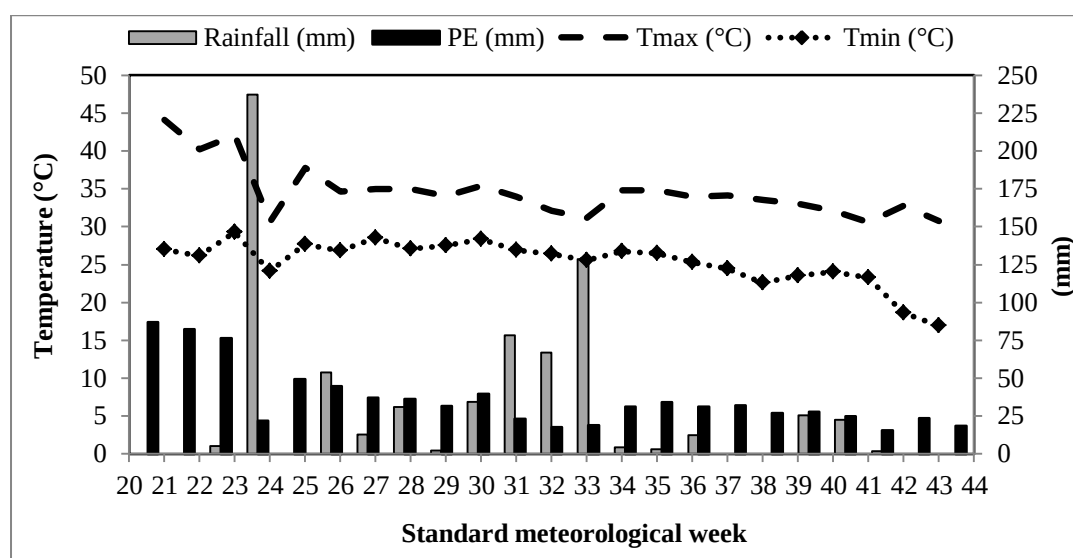


Figure-2. Weekly weather observations from 21th of June to 28th of October of the year 2013

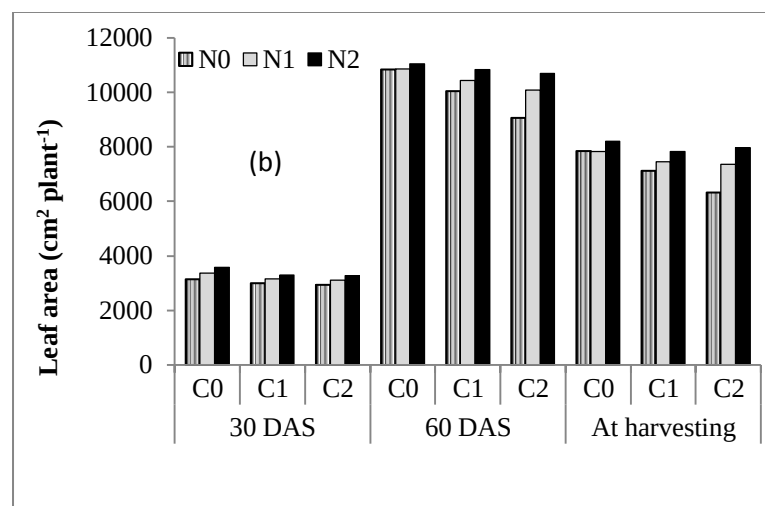
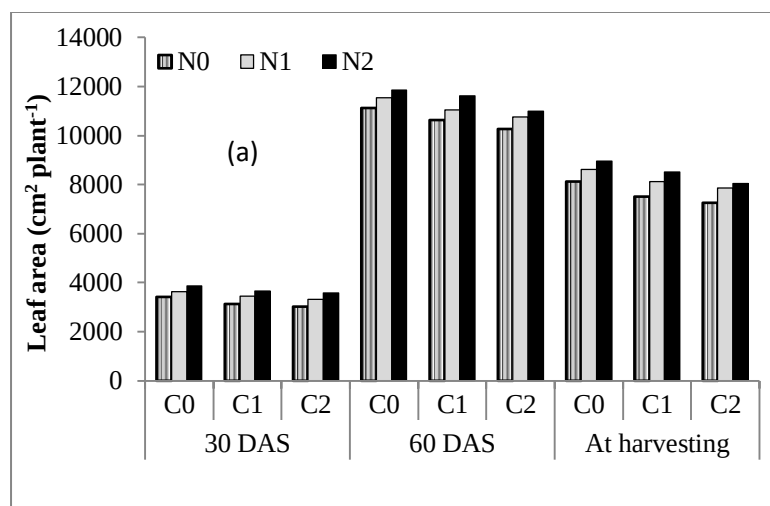


Figure-3. Periodic leaf area index of maize under subsoil compaction and nitrogen fertilization during 2012 (a) and 2013 (b)

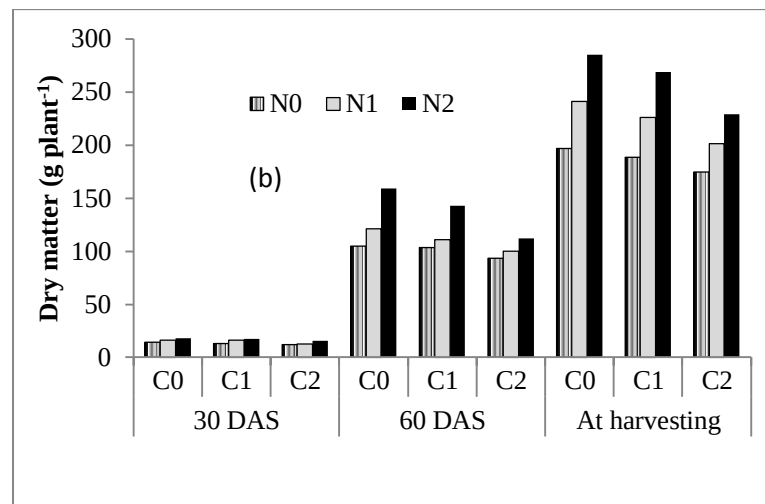
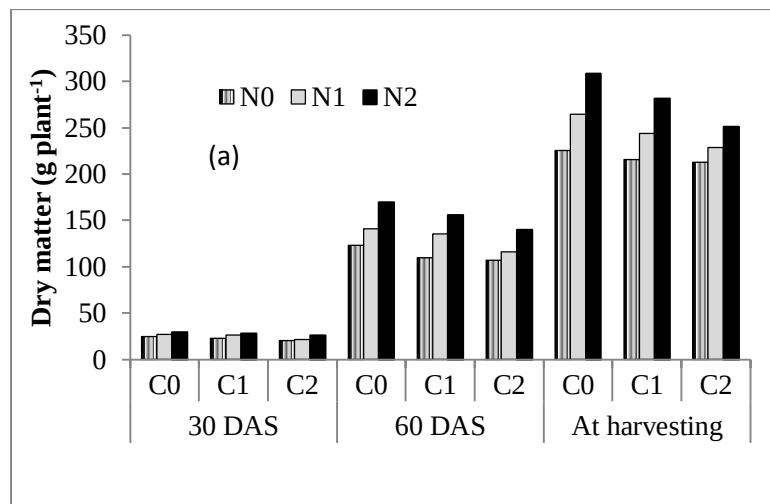


Figure-4. Periodic dry matter of maize under subsoil compaction and nitrogen fertilization during 2012 (a) and 2013 (b)

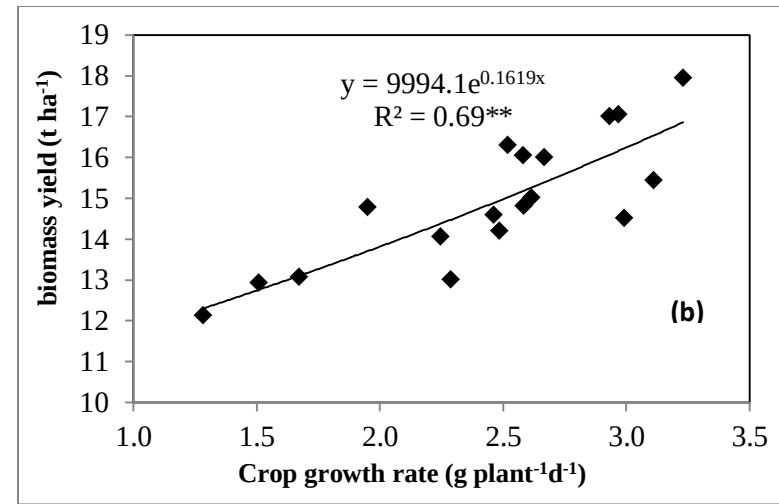
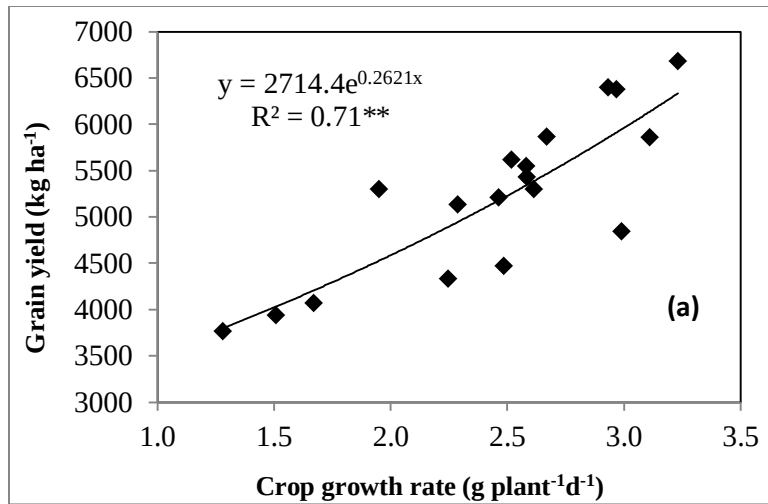


Figure-5. Relationship between crop growth rate and grain yield (a) and crop growth rate and biomass yield (b) of maize crop during the year 2012 and 2013. ** significant at 1 % level of significance

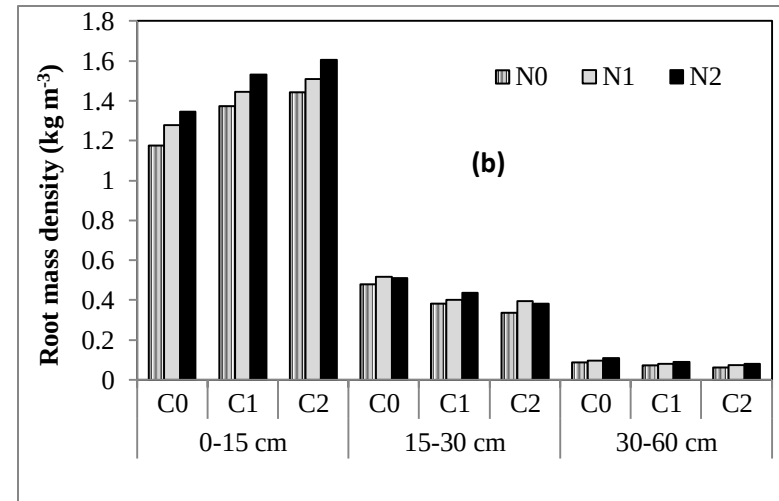
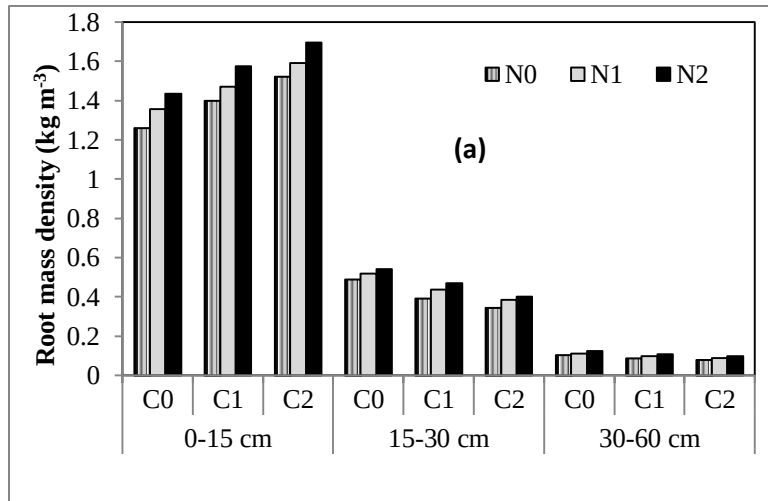


Figure-6. Root mass density at pre-tasseling stage of maize under subsoil compaction and nitrogen fertilization during the year 2012 (a) and 2013 (b)

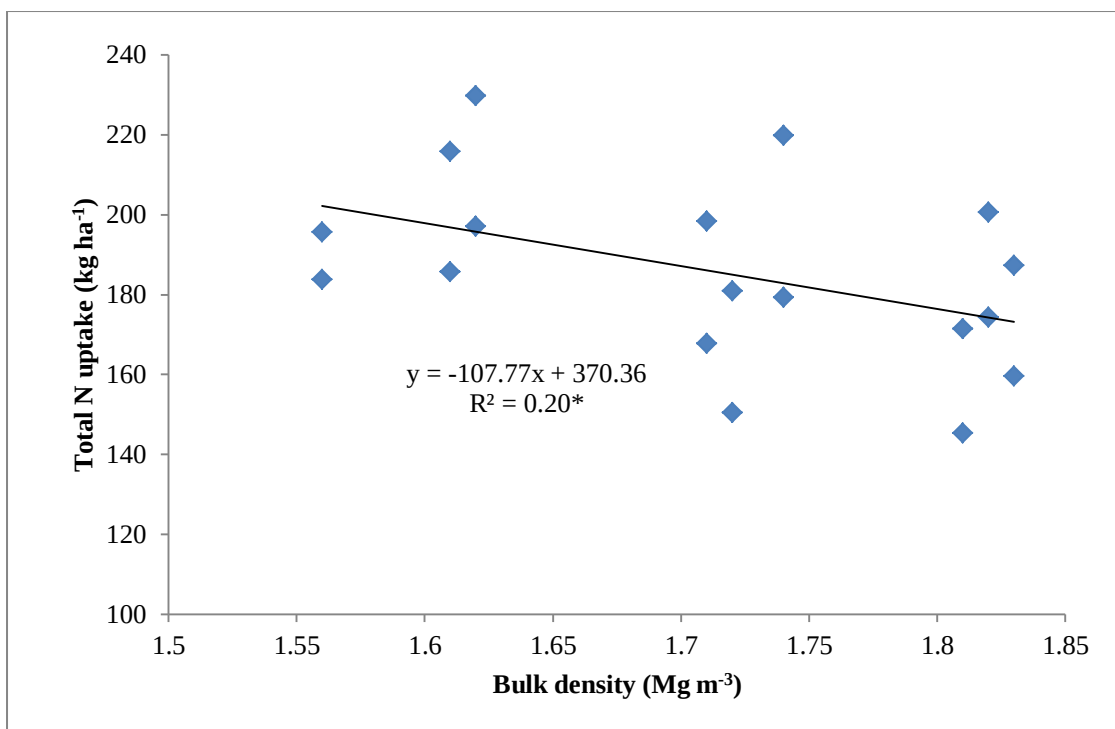


Figure-7(a) Effect of subsoil bulk density on total N uptake. * Significant at 5 % level of significance

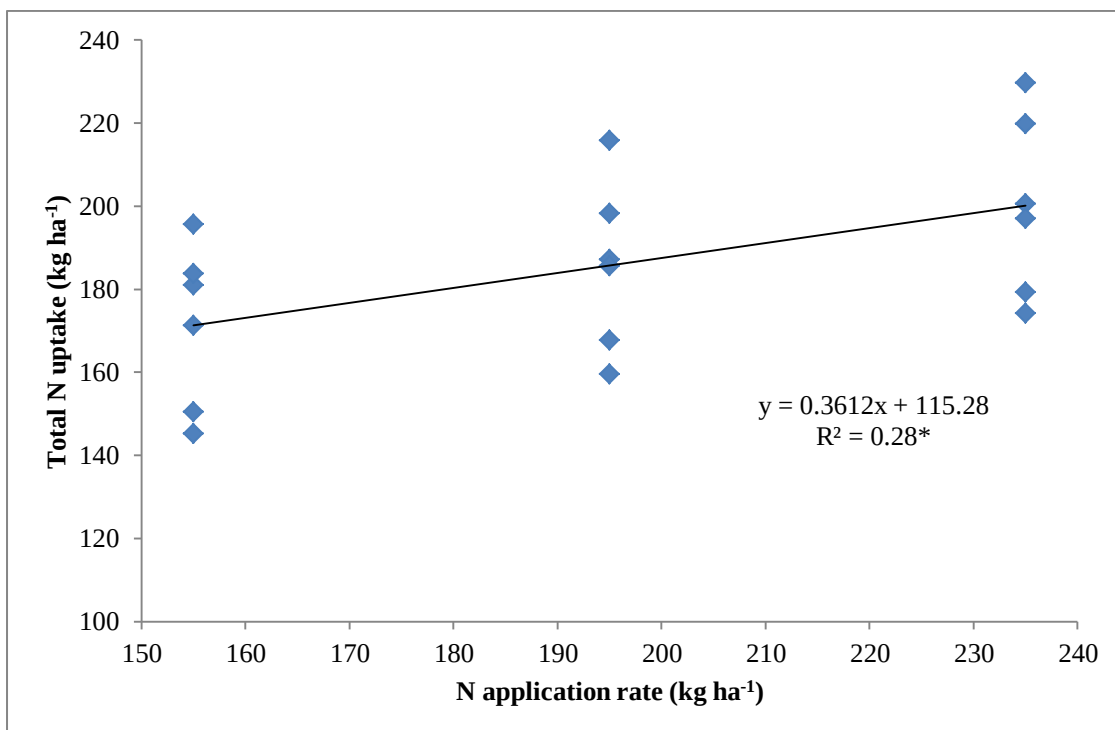


Figure-7(b) Effect of rate of N fertilization on total N uptake by maize. * Significant at 1 % level of significance

Table-2. Crop growth rate ($\text{g plant}^{-1}\text{day}^{-1}$) of the maize crop under different levels of subsoil compaction and Nitrogen fertilization

Treatments	30 DAS		60 DAS		At harvest	
	2012	2013	2012	2013	2012	2013
Subsoil compaction levels						
C ₀	0.90	0.54	3.92	3.74	2.96	2.55
C ₁	0.86	0.52	3.60	3.45	2.64	2.25
C ₂	0.75	0.45	3.28	2.94	2.49	1.81
LSD (P=0.05)	0.09	0.07	0.41	0.56	0.34	0.44
Nitrogen levels						
N ₀	0.75	0.43	3.02	2.91	2.47	1.58
N ₁	0.84	0.50	3.53	3.18	2.70	2.17
N ₂	0.92	0.57	4.25	4.04	2.91	2.86
LSD (P=0.05)	0.06	0.05	0.31	0.45	0.25	0.46
LSD C X N	ns	ns	ns	ns	ns	ns

Table-3. Net assimilation rate (NAR) ($\text{g cm}^{-2}\text{day}^{-1}$) of the maize crop under different levels of subsoil compaction and Nitrogen fertilization

Treatments	60 DAS		At harvest	
	2012	2013	2012	2013
Subsoil compaction levels				
C ₀	2.123	2.094	1.019	0.976
C ₁	1.980	2.038	1.004	0.902
C ₂	1.814	1.802	1.008	0.762
LSD (P=0.05)	0.221	ns	ns	0.135
Nitrogen levels				
N ₀	1.725	1.800	0.966	0.673
N ₁	2.003	1.867	1.006	0.871
N ₂	2.189	2.267	1.059	1.095
LSD (P=0.05)	0.155	0.25	ns	0.194
LSD C X S	ns	ns	ns	ns

Research Article: 4

Soil physical properties, root mass density and yield of maize influenced by subsoil compaction and N fertilization under sandy loam soil

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Abstract

With the advent of green revolution, the use of agricultural machinery had increased many fold for field operations during the year. The continuous use of heavy machines and puddling of rice fields results in the formation of sub-surface hard pan. This subsurface hard pan affects the plant growth, soil properties and soil-water-plant relations. The present investigation was planned to access the effect of subsoil compaction and Nitrogen fertilization on the soil physical properties, plant growth, yields and root mass density. The bulk density and penetration resistance was higher under higher degree of subsoil compaction, while total porosity, cumulative infiltration and infiltration rate were lower due to compaction. The N fertilization did not significantly affect the soil physical properties. The plant height, grain yield and biomass yield were less under higher degree of subsoil compaction over the normal. The higher dose of N fertilizer significantly improved the plant height, grain and biomass yield of maize. The root mass density was higher in 0-15 cm layer under C₂ treatment at knee high stage and pre-tasseling stage than that in C₀ treatment. However, root density was higher in C₀ treatment than that in C₁ and C₂ at 15-30, 30-60, 60-90 and 90-120 cm depths. The present study highlights the need of chiseling and breaking the hard pan to improve soil-plant-water relations and ultimately to achieve higher crop yields.

Keywords: Bulk density, Penetration resistance, Root mass density, Yield, Subsoil compaction

Introduction

Maize (*Zea mays* L.) is one of the most important cereals grown to produce grain and forage for human and animal consumption. Crop yield had significantly increased after green revolution as a result of improved varieties, fertilizers, insecticides, pesticides, assured irrigation and agricultural machinery, etc. The use of heavy farm machinery year over year for cultivation purpose lead to formation of compacted subsurface layer (Flower and Lal, 1998). Subsoil compacted layer formation also occurred due to puddling in rice-wheat cropping sequence generally followed in Indo-Gangetic plains of the Indian sub-continent. This subsoil compacted layer lead to degradation of soil health and decline crop yield (Hamza *et al.*, 2011). Soil compaction affects soil-water-plant relations, chemical and microbiological environment in subsoil which hampers root growth and crop yield (Hamza and Anderson 2005, Mosaddeghi *et al.*, 2009). The subsoil compaction reduces saturated hydraulic conductivity and infiltration, increases bulk density (Li and Zhou 1994) and penetration resistance. Mamman and Ohu, (1998) also reported that soil bulk density and penetration resistance increased with increase in the number of traffic passes while air permeability has been found to decrease with increase in traffic intensity. High soil strength layer developed as a result of heavy machinery may limit root growth and crop yield (Jamieson *et al.*, 1988;

Oussible, 1988) due to mechanical resistance offered to root growth and thus restrict the rate of oxygen supply to roots. Gaultney *et al.*, (1980) and Siemens and Peterson (1997) also reported maize yield reduction due to subsoil compaction. Under such conditions farmers apply more fertilizer to cover the risk of lower crop yields. It leads not only leads to soil and environment degradation but also increases the cost of production. Nitrogen is one of the major nutrients, applied in large quantity to crops that also improved crop yield. Maize yield responds positively to an increase in the amount of N applied until the crop achieved optimum level (Zand-Parsa and Sepaskhah, 2001). The application of higher dose of N fertilizers by the farmers in the state of Punjab for maize cultivation results much higher expense thus causing economic loss. Keeping these points in view, present investigation was carried out to access the effect of subsoil compaction and N fertilization on soil physical properties, crop yield and root mass density.

Material and methods

Location and experimental design

The experimental site is located at 30°54' N latitude and 75°48' E longitude with an altitude of 247 m (a s l), at Research Farm of Department of Soil Science, Punjab Agricultural University, Ludhiana, in the central plain region of Indian Punjab. The site has 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. The area receives 75 per cent of the average annual rainfall in July to September months. The soil is classified as alluvial, sandy loam in texture, calcareous, Typic Haplustept. The experimental site soil has P and K lied in medium category, while N and soil organic carbon content in low category. The physico-chemical properties of soils are presented in Table-1.

A split-plot design was laid out in three blocks with three subsoil compaction levels (main plot treatments) and three levels of nitrogen fertilization (subplot treatment). The subsoil compaction treatments were given 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 subsoil compaction treatments were C₀- Control (bulk density, Db= 1.55-1.65 g/cm³), C₁- Moderate compaction, (Db= 1.70-1.75 g/cm³) and C₂- High compaction (Db>1.80 g/cm³) at 15-30 cm depth. The nitrogen doses were applied as follow: N₀-125 kg N ha⁻¹, N₁-160 kg N ha⁻¹ and N₂-190 kg N ha⁻¹.

The standard Proctor test (American Society for Testing Materials, 2000) was employed to get the maximum soil bulk density that was 1.86 Mg m⁻³ at optimal water content (i.e., water content at which maximum compaction occurs) of 0.12 cm³ cm⁻³.

Cultural practices

The maize was sown on 27th June and 22th June during the years 2012 and 2013 respectively, with row to row spacing of 60 cm and plant to plant spacing of 20 cm. Phosphorus, potassium and zinc sulphate were applied @ 60, 30 and 25 kg ha⁻¹, respectively. Entire quantity of P, K and Zinc Sulphate along 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 as per “PAU package of practices for *Kharif* crops” were followed to ensure proper weed, insect and pest control.

Plant observations

Plant height was recorded at the time of harvesting. 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 (t ha⁻¹) was adjusted to 15 per cent moisture level.

Root observations

Soil core samples were taken from 0-15, 15-30, 30-60, 60-90 and 90-120 cm depth with the help of root sampling pipe having internal diameter of 7 cm. The samples were taken at knee high stage and tasselling stage by keeping the plant stump in the centre of the core in each experimental plot. The soil samples obtained were kept over one mm sieve under running water for washing and separating roots. The washed roots were picked up and then dried at 60°C in an oven to constant weight. The root density was expressed as weight of roots per unit volume of soil and calculated as follows:

$$\text{Root density (g m}^{-3}\text{ of soil)} = \frac{\text{Total root weight in particular depth (g)}}{\text{Total soil volume from which roots were collected (m}^3\text{)}}$$

Soil measurement

Replicated undisturbed soil samples were collected from the field at the depth of 0-15, 15-30, 30-45, 45-60, 60-90 cm for determination of bulk density and saturated hydraulic conductivity. Total porosity (TP) was calculated using the information on bulk density (D_b) and particle density (D_p) by equation as $TP = (1 - D_b/D_p)$. Hydraulic conductivity was measured with constant head water permeameter method (Klute and Dirksen, 1986) using Darcy's equation. *In-situ* infiltration rate was measured using double metallic ring infiltrometer method (Bouwer, 1986). Water was filled in both inner and outer rings and the fall of water level in the inner ring was recorded at different time intervals upto a cumulative time of 360 minutes from the start. Cumulative infiltration was worked out for each treatment and infiltration rate was calculated and expressed as cm hr⁻¹. The moisture content was determined gravimetrically by drying soil samples in the oven at 105 °C till the constant weight was achieved and the difference in wet and dry weights of samples was expressed as soil moisture content on dry weight basis of soil. Penetration resistance offered by soil was measured using cone penetrometer and expressed in KPa.

Statistical procedure

The standard statistical analysis procedure given by Gomez and Gomez (1984) was used for analysis of variance (ANOVA) for split plot design. The least significant difference (LSD) technique was employed for mean comparisons when F-tests were found significant at P values =0.05.

Results and discussion

Effect of subsoil compaction and N fertilization on soil physical properties

The D_b of surface 0-15 cm soil layer was not significantly different among various treatments during the year the 2012 and 2013. However, the D_b for 15-30 cm subsoil layer was significantly higher under C_2 treatment than that in C_0 and C_1 treatment during the year 2012 and 2013 (Table 2). The higher D_b under C_2 treatment was due to subsoil compaction treatment. The D_b of 30-45 cm subsoil layer followed almost similar trend as that of 15-30 cm subsoil layer, except the D_b under this layer was less than that in layer above. Our results are in conformity with Mamman and Ohu, (1998) who reported that dry soil bulk density and penetration resistance increased with increase in the number of traffic passes.

The penetration resistance (PR) of soil increased with depth (Table 3). The PR of C_2 treatment at 15-30 cm subsoil layer was significantly higher than that in C_0 and C_1 treatment, which reached the critical limit (ICPA, 1987) that negatively affected the root growth. The PR values at 30-45 cm soil depth were statistically different among themselves, were higher under C_2 treatment than that in C_0 and C_1 treatment. The PR values were higher at 15-30 cm soil depth were higher than that in 0-15 cm surface layer. Kozicz (1996) observed two times more PR in subsoil layer than that in plough layer. Mamman and Ohu, (1998), Becher, (1998) and Munkholm et al., (2002) also reported higher soil strength under compacted zones due to cultivation.

The porosity was higher under lower D_b than that in higher D_b soil. The total porosity followed the similar trend as that of bulk density at all the soil depths, since it was calculated for D_b values (Table 4). Total porosity was higher under C_0 treatment than that in C_1 and C_2 treatment at all depths during the year 2012 and 2013. The porosity values were significantly higher under C_0 treatment than that in C_1 and C_2 treatment at 15-30 cm and 30-45 cm soil depth.

The interactive effect of subsoil compaction and N fertilization were non significant for bulk density, penetration resistance and total porosity.

The saturated hydraulic conductivity showed non-significant of subsoil compaction and N fertilization at 5-10 cm depth after the harvesting of maize of year 2013 (Table 5). However, subsoil compaction had significantly reduced the saturated hydraulic conductivity of the 17-22 cm soil depth. The saturated hydraulic conductivity was 2.8 and 1.6 times less

under C_2 and C_1 treatment respectively than that in C_0 treatment. The subsoil compaction had resulted in the reduction of macropores, those are primarily responsible for the saturated hydraulic conductivity.

The increase in the soil moisture retention was observed at 0.3 bar at 15-30 and 30-60 cm soil layer under C_2 and C_1 treatment compared to C_0 treatment after the harvesting of maize during the year 2013 (Table 6). At 15 bar suction pressure soil moisture retention was also higher at 15-30 and 30-60 cm layer under C_2 treatment followed by C_1 treatment than that in C_0 treatment. The increase in soil moisture retention at 0.3 and 15 bar pressure might be attributed to reduced porosity and increase in microporosity of soil as a result of soil compaction.

The cumulative infiltration decreases with the increase in the bulk density of subsoil. After 360 minutes of initiation of infiltration, cumulative infiltration was 25.1, 17.6 and 12.5 cm in C_0 , C_1 and C_2 treatment, respectively during the year 2012, while it was 27.5, 19.9 and 14.9 cm in C_0 , C_1 and C_2 treatment respectively during the year 2013 (Figs 1 & 2). The infiltration rate also decreased with the further increase in the subsoil compaction level. After 360 minutes, infiltration rate was 4.18, 2.93 and 2.08 cm hr⁻¹ through C_0 , C_1 and C_2 treatment respectively during the year 2012 and 4.58, 3.31 and 2.48 cm hr⁻¹ in C_0 , C_1 and C_2 treatment respectively during the year 2013. The decrease in infiltration rate and cumulative infiltration under C_2 treatment than that in C_0 treatment might be attributed due to decreased total porosity due higher bulk density of subsoil layer under C_2 treatment. Dikinya, (1994) also observed lower infiltration rate in compacted sandy loam soil. Reicosky *et al.*, (1981) attributed the decrease in infiltration due to compaction, increased number of contacts between individual soil particles which lead to increase in tortuosity of water flow, and thereby lower infiltration.

Effect of subsoil compaction and N fertilization on plant growth, grain and biomass yield

The plant height decreased significantly with the increase in the soil strength of subsoil layer (Table 7). Maximum plant height (267.4 and 258.75 cm) was recorded at C_0 treatment against minimum (248.33 and 223.5 cm) under C_2 during the year 2012 and 2013 respectively. The C_2 treatment resulted in reduced plant height by 7.1 and 13.6 per cent than that in C_0 treatment at the time of harvesting during the year 2012 and 2013, respectively. The reduced plant height in C_2 treatment might have occurred due to restricted root growth under higher subsoil strength. The N fertilization significantly affected the plant height. The maximum plant height at harvesting stage (265.31 and 252.84 cm) was recorded in N_2 plots against minimum (251.56 and 234.2 cm) under N_0 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 due to more N application

might be attributed to more vegetative development that resulted in increased mutual shading and internodal extension. Hussaini *et al.*, 2001 also found significantly higher dry matter per plant, plant height, leaf area index and growth rate with application of higher N dose.

Subsoil compaction and N fertilization had significantly affected the grain yield of maize during the years 2012 and 2013 (Table 7). The maximum grain yield was recorded under C₀ treatment than that in C₁ and C₂ treatments. The C₂ treatment resulted in yield reduction of 15.5 and 24.3 per cent than that in C₀ treatment during the years 2012 and 2013, respectively. Gaultney *et al.*, (1980) also reported 45-50 per cent yield reduction in maize due to subsoil compaction. Siemens and Peterson (1997) reported an average yield reduction of 13 per cent due to compaction resulting from vehicular traffic. The maize yield reductions under higher degree of subsoil compaction occurred due to the restricted root growth. Allmaras *et al.*, (1988) also recorded lower yield due to root growth restrictions under higher subsoil compaction. Also crop took less number of days to mature under C₂ treatment could be responsible for reduced crop yields. Muchow (1990) also observed grain yield reduction due to shorter grain filling period might have occurred due to early maturity of crop. The N application had significantly improved the maize grain yield. The N₂ treatment resulted in 14.8 and 16.1 per cent increase in grain yield than that in N₀ during the year 2012 and 2013, respectively. An increase in grain yield may be attributed to higher plant growth in response to higher level of N fertilization over the recommended dose of N. The study supports the findings of Inamullah *et al.*, (2011) who reported an increase in grain yield with higher dose of N application.

The biomass yield was significantly higher under C₀ than that in C₁ and C₂ during both the years (Table 7). The higher biomass yield under C₀ treatment may be attributed to higher plant height and dry matter accumulation. 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 more prevalence of diseases. The N₂ treatment resulted in 17.0 and 10.8 per cent higher biomass yield than that in N₀ treatment during the year 2012 and 2013, respectively. Application of higher dose of N had resulted in increased vegetative growth which had improved the biomass yield. Inamullah *et al.*, (2011) also reported improvement in biomass yield with higher dose of N application.

The interaction effect of subsoil compaction and N fertilization were non-significant for plant height, grain yield and biomass yield during the year 2012 and 2013 (Table 7).

Effect of subsoil compaction and N fertilization on root growth At knee high stage

The root mass density at 0-15 cm was highest under C₂ treatment during the year 2012 and 2013 (Table 8). Root mass density at 0-15 cm depth was significantly higher under C₂

treatment followed by C_1 and C_2 treatments. The root mass density decreased with depth during both years. There was reverse trend that was recorded at 15-30 and 30-45 cm depth where root mass density was higher under C_0 treatment than that in C_1 and C_2 treatments. The bulk density and penetration resistance of 15-30 cm soil layer was higher under C_2 treatment, might be the reason of higher root mass density in 0-15 cm layer under C_2 treatment. However, bulk density and penetration resistance of 15-30 cm soil layer was lower under C_0 treatment that had resulted in higher root mass density in 15-30 and 30-45 cm soil layer in this treatment. Laboski *et al.*, (1998) in a field experiment found that a compacted soil layer confined roots almost entirely to the top 60 cm of soil because it had high soil strength and bulk density. Application of higher dose of N had significantly improved the root mass density at all depths than that in lower N dose. The higher penetration resistance might had restricted root penetration to deeper soil layer while N fertilization had increased the root mass density in the all layers due to proper supply of N for plant growth. The interaction effect of subsoil compaction and N fertilization were non-significant for root mass density at knee high stage of maize.

At pre-tasseling stage

The information on root mass density as affected by various subsoil compaction and N fertilization treatments recorded at tasseling stage of crop are presented in Table 9 & 10. Most of the root mass was confined to 0-15 cm of soil profile (65-75 per cent of total) followed by 15-30 cm (16-24 per cent of total) and very low root mass was in 30-60 cm soil depth (4-6 per cent of total), insignificant amount (2.0-3.5 per cent of total) in 60-90 cm soil depth and insignificant amount (0.9-1.8 percent of total) was recorded in 90-120 cm soil profile. The highest root mass density of 1603.3 and 1568.6 g m⁻³ was observed at 0-15 cm layer under C_2 treatment during the year 2012 and 2013. In 0-15 cm soil layer root density was significantly higher under C_2 treatment than that in C_0 and C_1 treatment during the year 2012 and 2013. Rosolem and Takahashi (1998) also reported that sub-surface compaction led to an increase in root growth in the superficial soil layer with a corresponding quadratic decrease in root growth in the compacted layer. However, a reverse trend in root mass density was observed for deeper layers, where a significantly higher root mass density under C_0 treatment was observed than that in C_1 and C_2 treatment. Higher root growth restriction under C_2 treatment due to its higher bulk density and penetration resistance had confined higher root mass in 0-15 cm soil layer, while in deeper soil depths C_0 treatment had higher root mass density due to lower penetration resistance of subsoil layer. The results are in conformity with Grzesiak (2009) who reported that root growth of maize was heavily restricted by the soil compaction as it offered higher penetration resistance and bulk density. Several studies (Sidhu 1980, Sur et al., 1980, Sur and Sidhu 1982) also reported that the presence of subsoil compacted layer affect the root amount and their distribution pattern in the soils.

The N fertilization significantly affected the root mass density. The root mass density was higher under N_2 treatment than that in N_0 and N_1 treatment due to higher plant growth as a result of proper nutrition of maize crop. The interaction effect of subsoil compaction and N fertilization were non-significant for root mass density at pre-tasseling stage of maize.

Conclusions

The present investigation was carried out to access the effect of subsoil compaction and Nitrogen fertilization on the soil physical properties, plant growth, yield and root mass density under sandy loam soil in the central alluvial plain of Indian Punjab. The results show that bulk density and penetration resistance were significantly higher under higher degree of subsoil compaction. However, there was decrease in total porosity, cumulative infiltration and infiltration rate due to compacted subsoil layer. The N fertilization showed non-significant affect on the soil physical properties. The plant height, grain yield and biomass yield were less under C_2 treatment than that in C_0 treatment. The higher dose of N fertilizer significantly improved the plant height, grain and biomass yield of maize. The root mass density was higher in 0-15 cm layer under C_2 treatment at knee high stage and pre-tasseling stage than that in C_0 treatment. However, a reverse trend was observed at 15-30, 30-60, 60-90 and 90-120 cm soil depth, where root mass density was higher in C_0 treatment than that in C_1 and C_2 . The paper suggests the need of employing deep tillage to improve the rooting depth of plants to achieve higher yields.

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

Parameter	Value
Sand (%)	64.8
Silt (%)	18.9
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. Effect of subsoil compaction and N fertilization on Bulk density (Mg m^{-3}). Different letters in each column of experimental factors show significant differences at < 0.05 probability level.

	2012			2013		
	0-15	15-30	30-45	0-15	15-30	30-45
C_0	1.53a	1.60c	1.52c	1.49a	1.60c	1.54b
C_1	1.52a	1.73b	1.64b	1.55a	1.73b	1.62a
C_2	1.53a	1.82a	1.72a	1.52a	1.81a	1.69a
<i>p-value C</i>	0.76	<0.0001	<0.0001	0.29	0.0001	0.004
N_0	1.53a	1.70a	1.59b	1.50a	1.69a	1.59a
N_1	1.52a	1.72a	1.63ab	1.52a	1.71a	1.62a
N_2	1.54a	1.73a	1.64a	1.53a	1.72a	1.63a
<i>p-value N</i>	0.66	0.14	0.068	0.60	0.61	0.44
<i>p-value C x N</i>	0.18	0.43	0.53	0.48	0.40	0.64

Table-3. Effect of subsoil compaction and N fertilization on Penetration resistance (KPa). Different letters in each column of experimental factors show significant differences at < 0.05 probability level.

Soil depth	2012			2013		
	10 cm	22 cm	45 cm	10 cm	22 cm	45 cm
C ₀	1026.50ab	1889.84c	1588.66b	1044.49ab	1981.10c	1605.32b
C ₁	992.63b	2098.19b	1640.70b	1011.80b	2201.12b	1657.03b
C ₂	1048.89a	2562.23a	1852.86a	1060.36a	2650.38a	1888.09a
<i>p-value C</i>	0.037	<0.001	0.005	0.072	<0.001	0.002
N ₀	1020.61a	2165.06a	1683.12a	1030.89a	2229.55a	1715.01a
N ₁	1025.81a	2146.93a	1678.32a	1036.09a	2251.80a	1690.54a
N ₂	1021.61a	2238.28a	1720.78a	1049.67a	2351.26a	1744.90a
<i>p-value N</i>	0.95	0.21	0.66	0.61	0.42	0.70
<i>p-value C x N</i>	0.45	0.23	0.30	0.81	0.59	0.44

Table-4. Effect of subsoil compaction and N fertilization on total porosity (v/v). Different letters in each column of experimental factors show significant differences at < 0.05 probability level.

Treatments/ Soil depth	2012			2013		
	0-15 cm	15-30 cm	30-45 cm	0-15 cm	15-30 cm	30-45 cm
C ₀	0.416a	0.379a	0.398a	0.428a	0.396a	0.419a
C ₁	0.423a	0.341b	0.367b	0.406a	0.347b	0.391b
C ₂	0.417a	0.308c	0.337c	0.417a	0.317c	0.365b
<i>p-value C</i>	0.76	<0.001	<0.001	0.19	0.0002	0.004
N ₀	0.419a	0.355a	0.371a	0.425a	0.360a	0.402a
N ₁	0.423a	0.333b	0.367a	0.416a	0.352a	0.388a
N ₂	0.414a	0.341ab	0.365a	0.411a	0.348a	0.386a
<i>p-value N</i>	0.66	0.07	0.69	0.50	0.65	0.44
<i>p-value C x N</i>	0.18	0.20	0.76	0.32	0.47	0.64

Table-5. Effect of subsoil compaction and N fertilization on saturated hydraulic conductivity of soil after the harvesting of maize during the year 2013. Different letters in each column of experimental factors show significant differences at < 0.05 probability level.

Treatment	5-10 cm	17-22 cm
C ₀	6.750a	2.876a
C ₁	6.627a	1.562b
C ₂	6.526a	0.992c
<i>p-value C</i>	0.65	<0.0001
N ₀	6.761a	1.749a
N ₁	6.643a	1.804a
N ₂	6.500a	1.878a
<i>p-value N</i>	0.56	0.71
<i>p-value C x N</i>	0.07	0.56

Table-6. Effect of subsoil compaction on soil moisture retention of soil after the harvesting of maize during the year 2013.

Soil depth	Soil moisture retention at 0.3 bar			Moisture content at 15 bar		
	C ₀	C ₁	C ₂	C ₀	C ₁	C ₂
0-15	13.30	13.40	13.45	5.60	5.60	5.70
15-30	13.80	14.10	15.20	5.80	6.10	6.63
30-60	14.70	14.84	15.30	5.90	6.30	6.54
60-90	14.90	14.70	15.20	6.30	6.30	6.40
90-120	15.40	15.30	15.30	6.60	6.70	6.65
120-150	15.50	15.60	15.60	6.70	6.70	6.60
150-180	15.50	15.62	15.60	6.70	6.60	6.70

Table-7. Effect of subsoil compaction and N fertilization on plant height, grain and biomass yield of maize. Different letters in each column of experimental factors show significant differences at < 0.05 probability level.

Treatments	Plant height (cm)		Grain yield (t ha ⁻¹)		Biomass yield (t ha ⁻¹)	
	2012	2012	2012	2012	2012	2012
C ₀	267.39a	258.75a	6.307a	5.494a	16.99a	15.00a
C ₁	256.33b	244.83b	5.738b	4.391b	15.96ab	13.83b
C ₂	248.32b	223.50c	5.326b	4.158b	14.69b	13.13b
<i>p-value C</i>	0.003	<0.0001	0.0026	0.0003	0.016	0.0004
N ₀	251.56b	234.20b	5.400a	4.346b	14.53b	13.28b
N ₁	255.18b	240.04b	5.763ab	4.646ab	16.12a	13.98b
N ₂	265.31a	252.84a	6.208a	5.049a	17.00a	14.72a
<i>p-value N</i>	0.023	0.002	0.01	0.038	0.009	0.0034
<i>p-value C x N</i>	0.053	0.40	0.65	0.99	0.96	0.44

Table-8. Effect of subsoil compaction and N fertilization on root mass density (g m⁻³) at knee high stage of Maize. Different letters in each column of experimental factors show significant differences at < 0.05 probability level.

Soil depth	2012			2013		
	0-15 cm	15-30 cm	30-45 cm	0-15 cm	15-30 cm	30-45 cm
C ₀	424.90b	98.13a	15.59a	374.17b	95.82a	13.98a
C ₁	475.54a	83.36b	11.21b	430.20a	81.31b	9.68b
C ₂	480.17a	75.90c	9.56b	441.97a	75.45b	8.47b
<i>p-value C</i>	0.028	<0.001	<0.001	<0.001	0.001	0.0004
N ₀	427.48b	80.49b	11.02b	388.69b	78.67b	9.65a
N ₁	468.56ab	84.24b	11.65b	410.66b	83.41ab	10.77a
N ₂	484.57a	92.67a	13.69a	446.99a	90.49a	11.71a
<i>p-value N</i>	0.034	0.0005	0.019	<0.001	0.045	0.16
<i>p-value C x N</i>	0.76	0.078	0.41	0.90	0.96	0.15

Table-9. Effect of subsoil compaction and N fertilization on root mass density (g m^{-3}) at pre-tasseling stage of maize different soil depth during the year 2012. Different letters in each column of experimental factors show significant differences at < 0.05 probability level.

Soil depth	0-15 cm	15-30 cm	30-60 cm	60-90 cm	90-120 cm
C ₀	1350.9c	476.2a	112.9a	61.8a	38.2a
C ₁	1482.0b	429.8b	96.9b	54.7b	32.9b
C ₂	1603.3a	379.5c	88.3c	48.5c	20.3c
<i>p-value C</i>	<0.001	<0.001	<0.001	<0.001	<0.001
N ₀	1394.1c	400.3b	90.2c	49.3b	26.9b
N ₁	1473.5b	434.8ab	98.0b	53.1b	31.0a
N ₂	1568.6a	450.4a	110.0a	62.7a	33.6a
<i>p-value N</i>	<0.001	0.27	<0.001	<0.001	0.01
<i>p-value C x N</i>	0.98	0.93	0.80	0.28	0.69

Table-10. Effect of subsoil compaction and N fertilization on root mass density (g m^{-3}) at pre-tasseling stage of maize at different soil depth during the year 2013. Different letters in each column of experimental factors show significant differences at < 0.05 probability level.

	0-15 cm	15-30 cm	30-60 cm	60-90 cm	90-120 cm
Subsoil compaction levels					
C ₀	1267.0c	444.8a	97.7a	47.0a	29.4a
C ₁	1450.8b	397.7b	81.7b	43.0b	24.7b
C ₂	1519.6a	370.1b	72.0c	38.7c	16.9c
<i>p-value C</i>	<0.001	0.004	<0.001	<0.001	<0.001
Nitrogen fertilization levels					
N ₀	1331.5c	376.1b	74.6c	39.4c	20.3b
N ₁	1410.6b	413.0ab	83.8b	41.7b	24.4a
N ₂	1495.3a	423.5a	93.1a	47.7a	26.3a
<i>p-value N</i>	<0.001	0.049	<0.001	<0.001	0.018
<i>p-value C x N</i>	0.97	0.95	0.87	0.088	0.76

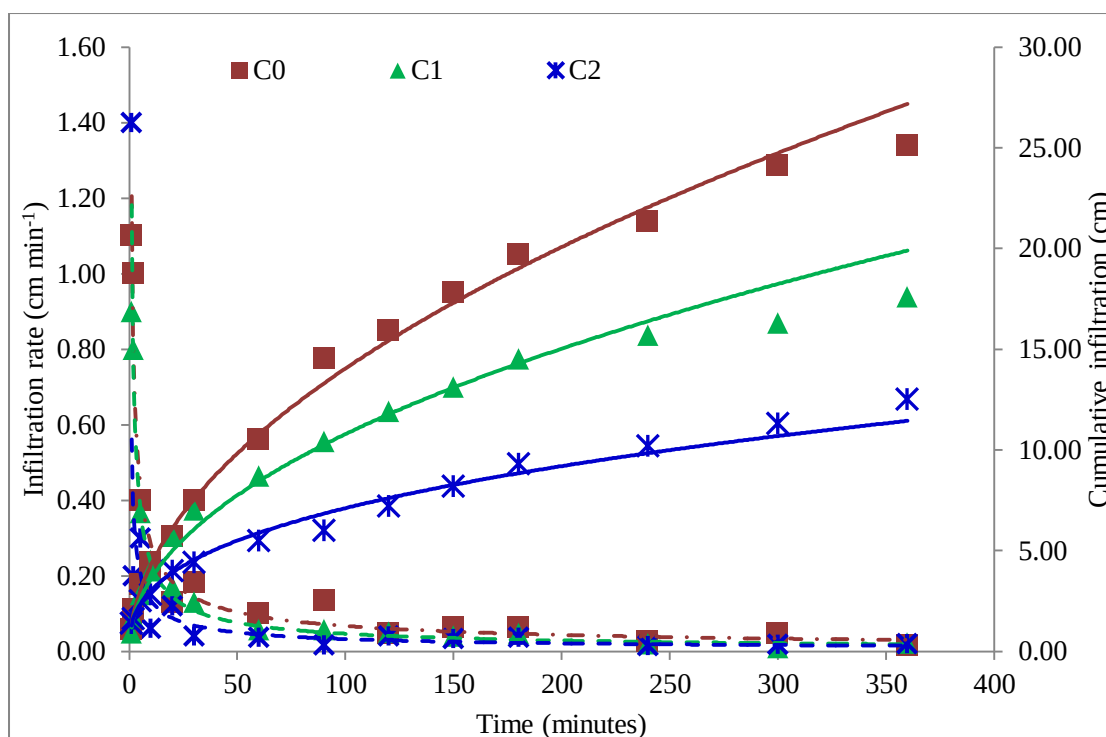


Fig-1 Cumulative infiltration (solid line) and infiltration rate (dotted line) as affected by subsoil compaction treatments during the year of 2012

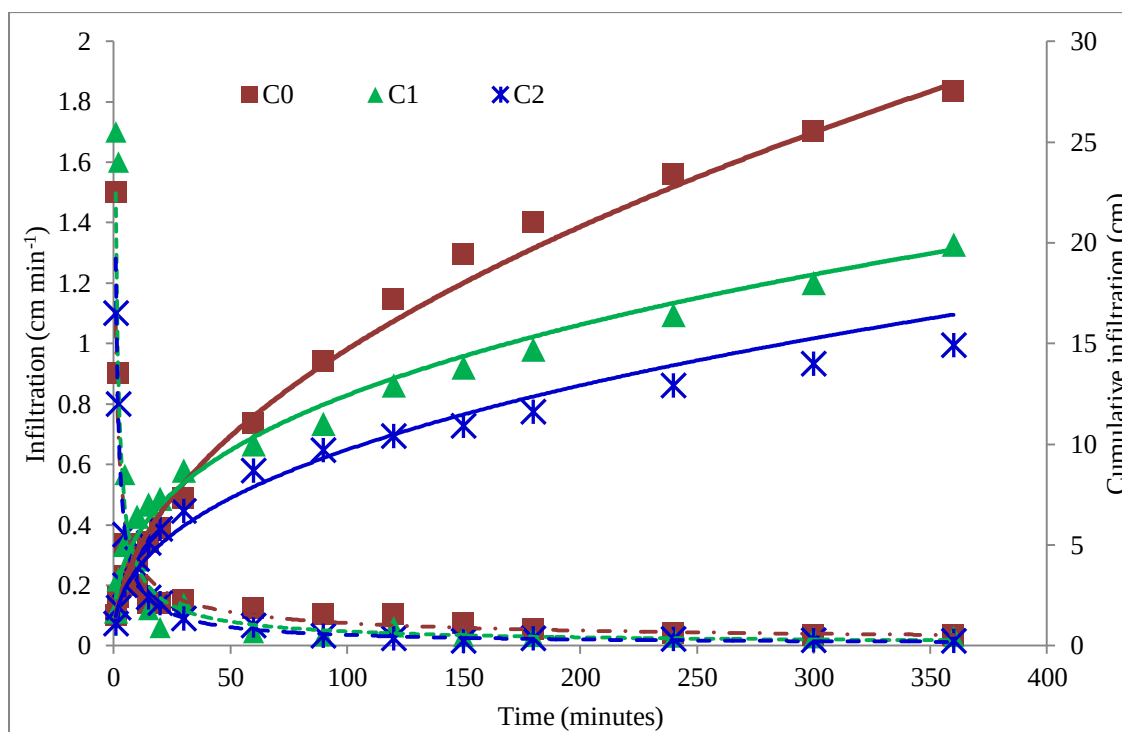


Fig-2 Cumulative infiltration (solid line) and infiltration rate (dotted lines) as affected by subsoil compaction treatments during the year of 2013

Research Article: 5

Water use and water productivity of maize as influenced by subsoil compaction and nitrogen fertilization under semi-arid irrigated conditions

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Abstract

Agriculture utilizes 72 and 85 per cent water resources in developed and developing countries, respectively. The major cropping sequence followed in state of Indian Punjab is rice-wheat cropping sequence (RWCS) that utilizes major portion of ground water resources, leading to fast decline in ground water table and requires more energy for pumping ground water. The falling water table problem is further aggravated when subsoil compacted layer formed due to use of heavy machinery. The present investigation was carried out at research farm of department of soil science, Punjab agricultural University, Ludhiana, India, with an objective to access the effect of subsoil compaction and nitrogen fertilization on the yield, water use and water productivity of maize under alluvial sandy loam soil. The results revealed that the yield reduction occur to the extent of 15.5 to 23.5 per cent due to subsoil compaction; however nitrogen fertilization improved the yield by 14.8 to 16.1 per cent. Crop water use was less under higher subsoil strength condition owing to lower vegetative growth of maize, while nitrogen increase the water use. Water productivity was significantly higher under uncompacted subsoil condition than that in highly compacted subsoils. The present investigation draws attention toward the need of deep tillage to improve soil water storage and yield of crop.

Keywords: Subsoil compaction, nitrogen, yield, consumptive water use, water productivity

Introduction

Agriculture is biggest consumer of water resources; it utilizes 72 and 85 per cent water resources in developed and developing countries, respectively. The major cropping sequence followed in state of Indian Punjab is rice-wheat cropping sequence (RWCS). It utilizes major portion of ground water resources, leading to fast decline in ground water table (Hira *et al.*, 2004) and requires more energy for pumping ground water. The main reason for fast declining water table includes: indiscriminate and unchecked over exploitation of groundwater (with about 1.2 million tubewell), decline in number of rainy days since past few years, declining rainfall trend, increasing population, industrialization and urbanization. Shrinking water resources alarm the need of reducing area under RWCS to low water requiring crops, as the future agricultural production will be constrained by water limitation. Under present context, maize could be best alternative to reduce area under rice. The falling water table problem is further aggravated when subsoil compacted layer formed due to use of heavy machinery (flower and Lal, 1998). The compact layer also formed as a result of puddling that destroys soil aggregates, reduces water transmitting pores and hydraulic conductivity of soil (Prihar *et al.*, 1976), which also reduces ground water recharge (Sur *et al.*, 1980) by affecting water transmission characteristics such as saturated hydraulic conductivity

and infiltration, etc. The compacted layer is also known to reduce shoot growth and yield (Gaultney *et al.*, 1980; Siemens & Peterson, 1997) by restricting root growth, water and nutrient transformation and uptake. Thus farmers apply more fertilizer to obtain higher grain yields and also to cover the risk associated with soil and weather conditions. The over application of fertilizer not only increases cost of production but also degrade soil and environmental health. Thus, the present investigation was carried out to access the effect of subsoil compaction and nitrogen fertilization maize yield, water use and water productivity.

Materials and methods

Site and experimental design

The experimental site is located at research farm, Department of Soil Science, Punjab Agricultural University, Ludhiana, in the central plain region of Indian Punjab. The site has 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 months. The area receives about 75 per cent of the average annual rainfall in July to September months. The soil is classified as alluvial, sandy loam in texture, calcareous, typic Haplustept. The physico-chemical properties of soils are reported in Table-1.

A split-plot design was employed with three blocks, three subsoil compaction levels (main plot treatments) and three levels of nitrogen fertilizers (subplot treatment). The subsoil compaction treatments were imposed by removing 15-cm surface 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 C₀- Control (bulk density, $D_b = 1.55\text{--}1.65 \text{ g/cm}^3$), C₁- Moderate compaction, ($D_b = 1.70\text{--}1.75 \text{ g/cm}^3$) and C₂- High compaction ($D_b > 1.80 \text{ g/cm}^3$) at 15-30 cm depth. The nitrogen levels applied were -155 kg N ha⁻¹, N₁-195 kg N ha⁻¹ and N₂-235 kg N ha⁻¹.

Cultural practices

The sowing of maize was done on June 27 during 2012 and June 22 during 2013 with row to row spacing of 60 cm and plant to plant spacing of 20 cm. Phosphorus, potassium and zinc sulphate were applied @ 60, 30 and 25 kg ha⁻¹, respectively. Entire quantity of P, K and Zinc Sulphate along 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 as per “PAU package of practices for *kharif* crops” were followed to ensure proper weed, insect and pest control.

Plant measurements

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 (t ha⁻¹) was adjusted to 15 per cent moisture content on fresh weight basis.

Soil moisture and consumptive water use measurements

Soil samples from 0-15, 15-30, 30-60, 60-90, 90-120 and 120-150 cm were collected at the time of sowing and harvesting for determining gravimetric soil moisture content. The moisture content was determined gravimetrically by drying soil samples in the oven at 105 °C till the constant weight was achieved and the difference in wet and dry weights of samples was expressed on dry weight basis.

Seasonal consumptive use (cm) was calculated by using equation (Majumdar, 2012) given below:

$$CU \text{ (cm)} = ER + IR_n + \sum_{i=1}^n \frac{M_{si} - M_{hi}}{100} A_{si} \times D_i$$

Where, ER is effective rainfall (cm) (ER was considered as 70 % of the net seasonal rainfall), IR_n is net irrigation water applied (cm), M_{si} is soil water at the time of sowing of crop, M_{hi} is soil water at the time of harvesting of the crop. A_{si} is bulk density of the soil and D_i is the depth of the i-th layer of the soil (cm) and n is the number of soil layers in the root zone D. Data for daily rainfall (cm), pan evaporation, minimum and maximum temperature was collected from Agrometeorological Observatory, School of Climate Change and Agricultural Meteorology, Punjab Agricultural University, Ludhiana, situated near the experimental site. Depth of irrigation was measured using measuring scale installed in the field, as a plot took about 5-7 minutes for irrigation and therefore, the percolation was considered negligible. Water productivity was computed as the ratio of grain yield to consumptive water use.

Statistical analysis

Statistical significance for detection of differences between various means was carried out using the general linear model procedure (PROC GLM) of the Statistical Analysis System (SAS 9.1, from SAS Institute Inc. CA) as per the standard procedure for split plot design given by Gomez and Gomez (1984). Differences between treatment means were determined using Duncan's Multiple Range Test (DMRT).

Results and discussion

Climatic conditions during crop growth

Meteorological conditions varied considerably during the period of study, as shown in figures 1 & 2. Minimum temperature remained higher than that the normal minimum temperature during both the years of the study and maximum temperature during the year 2012 was more than the normal maximum temperature. However, maximum temperature during the year 2013 was skewed around normal maximum temperature. 9 out of 23 week of total study period during the year 2013, maximum temperature remain lower than the normal maximum temperature. Pan evaporation during the year 2012 was higher than normal pan evaporation till the vegetative period of the crop, later it was lower than the normal pan evaporation, while

pan evaporation remained about normal during 2013 except few instances when it was lower than that of normal. Rainfall received was lower than the average normal rainfall during the year 2012 and 2013.

Grain yield

Subsoil compaction and N fertilization significantly affected the grain yield of maize during the years 2012 and 2013 (Table-2). Highest grain yield was recorded under C_0 treatment than that in C_1 and C_2 treatments. The C_2 treatment resulted in yield reduction of 15.5 and 24.3 per cent than that in C_0 treatment during the year 2012 and 2013, respectively. Gaultney *et al.*, (1980) also reported 45-50 per cent yield reduction in maize due to subsoil compaction. Siemens and Peterson (1997) reported an average yield reduction of 13 per cent due to compaction resulting from vehicular traffic. The maize yield reductions under higher degree of subsoil compaction occurred due to root growth restrictions. Allmaras *et al.*, (1988) also recorded lower yields due to root growth restrictions under higher subsoil compaction. The grain yield reduced as the bulk density of subsoil increased, the decrease was 15-25 per cent under different treatments. The crop took less number of days to mature under C_2 treatment might have resulted in reduced crop yields. Muchow (1990) also observed grain yield reduction due to shorter grain filling period due to early maturity of crop. The N application had significantly improved the maize grain yield. The N_2 treatment resulted in 14.8 and 16.1 per cent increase in grain yield than that in N_0 during the year 2012 and 2013, respectively. An increase in grain yield may be attributed to higher plant growth in response to higher level of N fertilization over the recommended doses of N. The study supports the findings of Inamullah *et al.*, (2011) who reported an increase in grain yield with higher dose of N application. However, no significant interaction was observed for yield due to subsoil compaction and nitrogen fertilization.

Soil water depletion and water use

The net irrigation water applied to crop was 51.5 and 45.0 cm during the year 2012 and 2013, respectively, while effective rainfall received was 26.7 and 33.3 cm during the crop season of the year 2012 and 2013 respectively. The soil water storage occurred in root zone during the year 2012, while water depletion took place, during 2013. In the year 2012, mean water storage was more under C_2 treatment than that in C_0 and C_1 . This might have been resulted from more vegetative growth and evapo-transpiration loss under C_0 and C_1 than that in C_2 . However there was more water storage in C_1 treatment than that in C_0 and C_2 during the year 2012. The lesser water storage might be attributing to more water use by crop during vegetative, reproductive stages and more ET losses. Nitrogen fertilization had shown negative effect on water storage. Each additional dose of nitrogen had lead to more vegetative growth i.e. leaf area and plant height (data presented in appendix), which ultimately lead to more ET losses. A positive and relationship between consumptive water use and maize yield had been

observed i. e grain yield increased as consumptive water use increased (Fig. 3). The increase in consumptive water use also resulted in increased grain yield that might be attributed to the more water available for mobilization and uptake of nutrient in soils and translocation of photosynthates in the plants.

A negative relationship had been observed between bulk density and consumptive water use (Fig 4). The higher level of subsoil compaction had reduced the consumptive use, which might be resulted from lesser vegetative growth under higher subsoil bulk density levels.

Water productivity

Water productivity was significantly affected by subsoil compaction and nitrogen fertilization (Table 2). Water productivity was 17.5 and 31.6 per cent higher under C_0 treatment than that in C_2 treatment during the year 2012 and 2013, respectively. Although water productivity in C_1 treatment was more than that in C_2 , but this difference was statistically non-significant during the study years 2012 and 2013. The reduced water productivity under higher level of subsoil compaction might be responsible for lower crop yield and water use. Water productivity was higher under N_2 treatment than that in N_0 treatment, however water productivity was at par in N_1 and N_2 treatments during the year 2012 and 2013. Cai *et al.*, (2002) reported that fertilization maximize the use of stored water in the root zone and lead to higher yields. Fan *et al.*, (2004) reported that nitrogen fertilization increased grain yields and WUE in China by 50–60 per cent. Nangia *et al.*, (2008) also showed that the water productivity of maize can be enhanced with the addition of nitrogen fertilizer. The interactive effect of subsoil compaction and nitrogen fertilization was non-significant for water productivity.

Conclusion

The present investigation showed that water productivity is influenced by subsoil compaction and nitrogen fertilization. The results revealed that subsoil compaction reduces grain yield of maize and also reduces water storage by reducing infiltration. Nitrogen fertilization improved the grain yield even under compacted subsurface soil, by providing proper fertilization leading to higher grain yield. The consumptive water use was higher under the plots receiving higher dose of nitrogen. The water productivity was more under non-compacted subsurface conditions than that in compacted subsoil condition, due to higher grain yield and water use. Nitrogen fertilization improved water productivity leading to more grains per unit water used. The study confirmed that compacted subsurface layer not only reduces grain yield but also reduces ground water recharge. Thus, the deep tillage or chiseling should be done to break the compacted subsurface layer to improve yield and groundwater recharge to arrest the falling water table.

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Table: 1. Physico-chemical properties of experimental site

Parameter	Value
Sand (%)	64.8
Silt (%)	18.9
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. Grain yield and water use efficiency as influenced by subsoil compaction and nitrogen fertilization. Different letters in each column show significant differences between treatments at < 0.05 probability level.

	Yield (t ha ⁻¹)		Water productivity (t ha ⁻¹ cm ⁻¹)	
	2012	2013	2012	2013
C ₀	6.307a	5.494a	0.0798a	0.0716a
C ₁	5.738b	4.391b	0.0729b	0.0584b
C ₂	5.326b	4.158b	0.0679b	0.0544b
<i>p-value C</i>	0.0026	0.0003	0.0038	0.0004
N ₀	5.40b	4.346a	0.0689b	0.0572b
N ₁	5.76ab	4.646ab	0.0732ab	0.0612ab
N ₂	6.20a	5.049a	0.0786a	0.0660a
<i>p-value N</i>	0.01	0.038	0.015	0.049
<i>p-value C X N</i>	0.65	0.99	0.70	0.98

Table: 3. Soil moisture storage, rainfall, irrigation and consumptive use of water during the year 2012 and 2013

	2012				2013			
	Soil water storage (cm)	Effective rainfall (mm)	Irrigation (mm)	Consumptive use (cm)	Soil water storage (cm)	Effective rainfall (mm)	Irrigation (mm)	Consumptive use (cm)
C ₀ N ₀	0.334	26.75	51.5	78.585	-1.85	33.32	45.0	76.46
C ₀ N ₁	0.751			79.0015	-1.88			76.43
C ₀ N ₂	1.123			79.3735	-0.95			77.37
C ₁ N ₀	0.003			78.2533	-3.51			75.80
C ₁ N ₁	0.156			78.4063	-3.06			75.25
C ₁ N ₂	0.856			79.1068	-2.95			75.36
C ₂ N ₀	-0.103			78.1465	-1.90			76.41
C ₂ N ₁	0.211			78.4614	-1.77			76.54
C ₂ N ₂	0.169			78.4191	-1.25			77.07

-ve sign in soil water storage change shows moisture depletion, +ve depict increase in soil moisture storage.

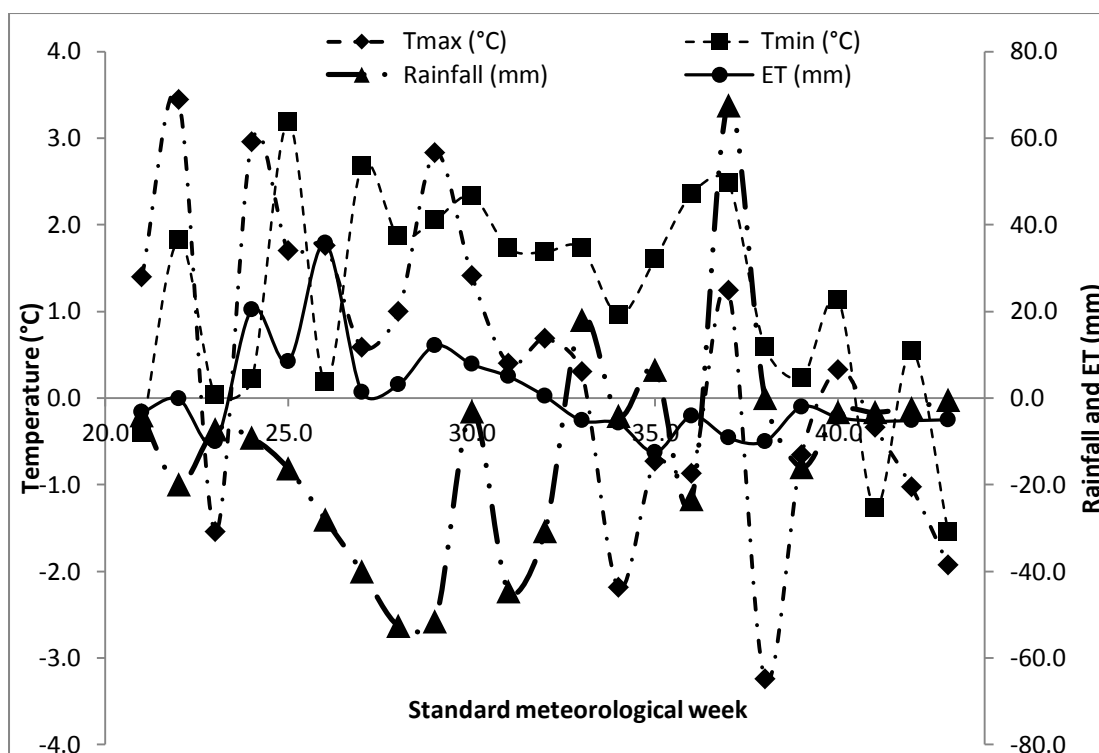


Figure: 1 Rainfall, pan evaporation, minimum and maximum temperature deviation from normal data during 2012.

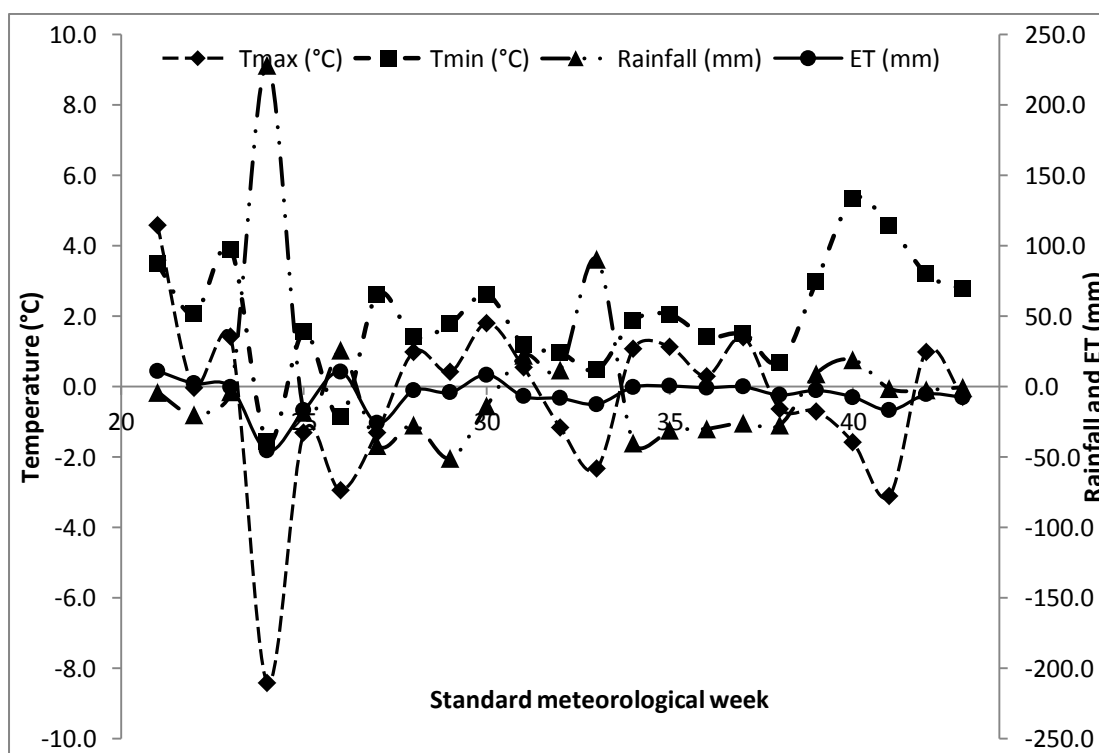


Figure: 2 Rainfall, pan evaporation, minimum and maximum temperature deviation from normal data during the year 2013

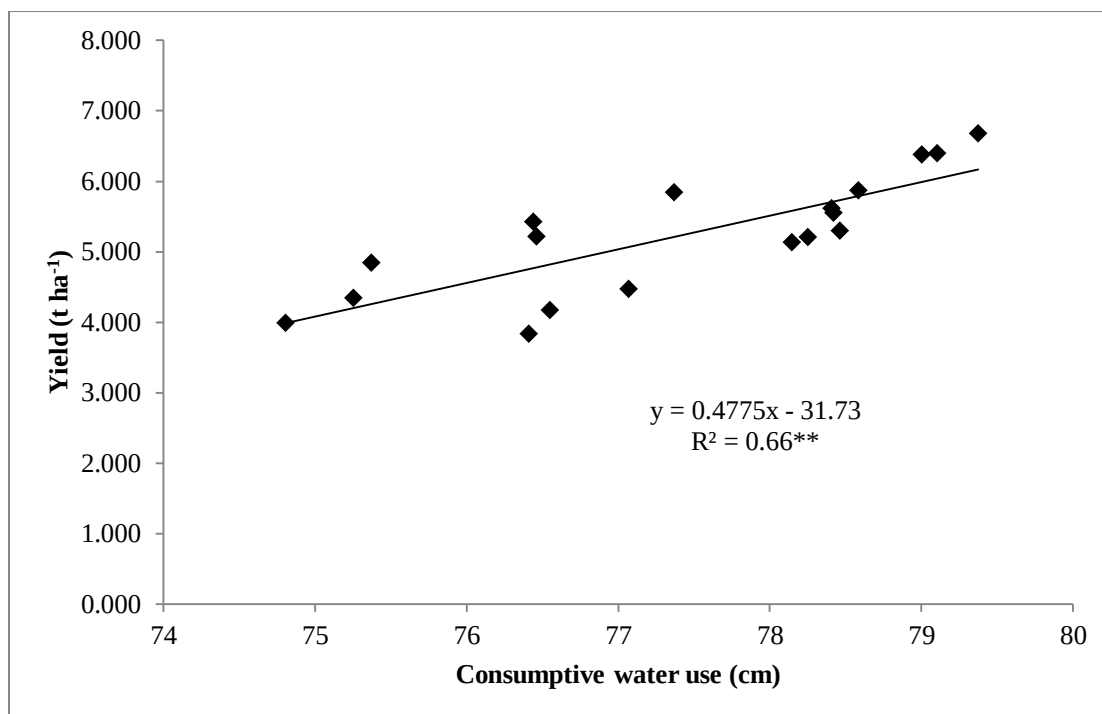


Figure: 3 Relationship between consumptive water use and yield of maize under subsoil compaction and nitrogen fertilization. ** significant at 1 % level of significance.

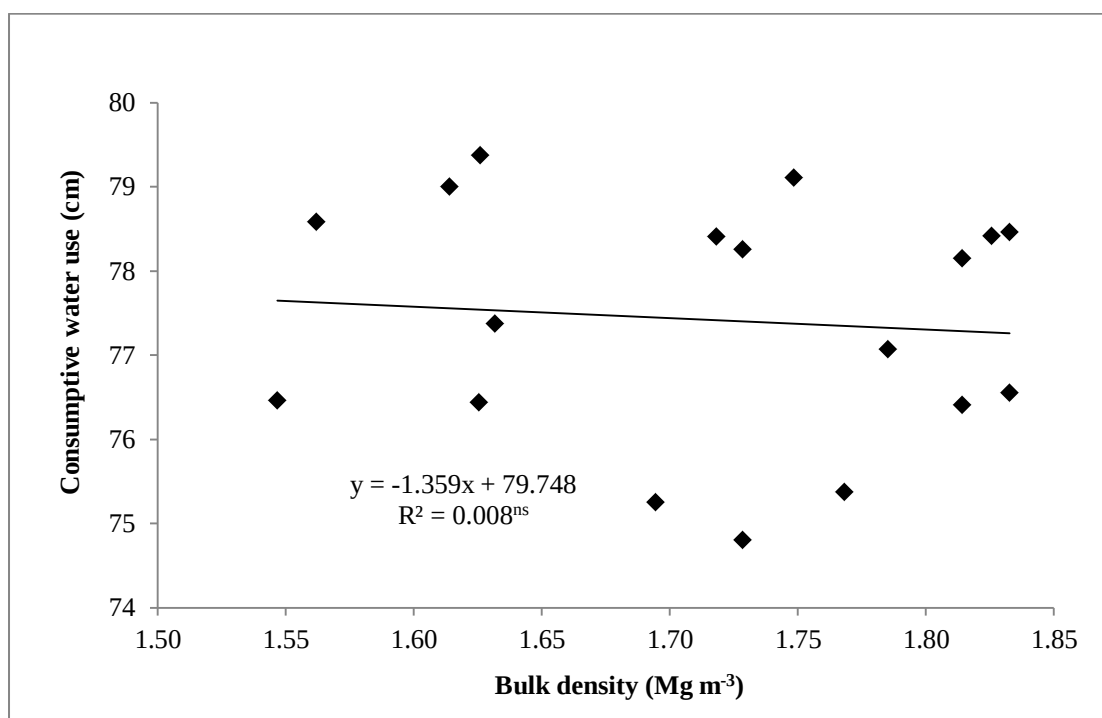


Figure: 4 Relationship between subsoil bulk density and consumptive water use of maize.

Research Article: 6

Soil and plant response to subsoil compaction and slope steepness under semi-arid irrigated condition

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Abstract

The present investigation was carried out with the objective to access the effect of subsoil compaction and slope steepness on soil physical properties, plant growth, yields and yield attributes of maize. The results revealed that the subsoil compaction significantly affected the bulk density, total porosity, infiltration rate and cumulative infiltration. However slope steepness did not show significant effect on all these physical properties. The plant height, yield and cob length was significantly higher under lower level of subsoil compaction than that in higher degree of subsoil compaction, while cob barrenness and crop lodging was more under higher degree of subsoil compaction. The slope steepness significantly improved both the grain yield and biomass yield of maize by reducing the crop lodging as a result of high intensity rainstorms those occurred during summer moonson season. The study will encourage the fine tuning of existing technology to improve the crop yield under compacted subsoil conditions especially under rice-wheat cropping sequence.

Keywords: Slope steepness, Penetration resistance, Porosity, Infiltration rate, Maize yield and Yield attributes.

Introduction

The introduction of green revolution in the mid 1960's has helped in improving the income of farmers, that was possible only with the introduction of improved crop varieties, fertilizers, pesticides, assured irrigation and agricultural machinery. This has promised a better technology that is cost effective and time saving. The continuous use of agricultural machines such as tractor, harvester, etc for routine agricultural practices over the same piece of land resulted in the formation of hard pan below the surface of soil (Flower and Lal, 1998). This 'thick compacted layer' builds up in the root zone also as a consequence of poor tillage practices, primarily as a result of the farmer failing to vary the depth of ploughing over several years (Tursic *et al* 2008). The extent of the soil compaction problem is a function of soil type and water content, vehicle weight, speed, ground contact pressure and number of passes, and their interactions with cropping frequency and farming practices (Larson *et al* 1994, Chamen *et al* 2003). Soil degradation due to puddling also leads to development of subsurface compact layer. Compaction of soil affects nearly all soil properties and soil-plant-water relations, which in turn affect the growth and productivity of plants. Compacted soils are characterized by high strength, high bulk density, and low saturated hydraulic conductivity and air filled porosity (Soane and van Ouwerkerk 1994). Soil characteristics such as bulk density and mechanical impedance can be affected by tillage practices, and may

alter root growth and distribution (Russell, 1981). Soil with high strength impedes the growth, distribution, and function of roots. The magnitude of restriction to roots is closely related to the soil water content, because of the resulting increases in soil resistance due to decreasing soil moisture content (Gupta and Allmaras 1987, Raper 2005). With these restrictions, root systems develop superficially and, as a consequence, the roots exploit a smaller volume of soil and hence intercept a limited amount of water and nutrients. Reduced oxygen content in compacted surface soils, resulted from reduced porosity and soil structure degradation, can in turn affect the transport, transformation (e.g., mineralization) and uptake of nutrients (Kemper *et al* 1971) and also restrict soil gas diffusion and water availability (Hansen *et al* 1993).

In the semi-arid tropical environment, as in Indian Punjab, erratic distribution of rainfall in time and space, and maize is mainly dependent on rainfall for its water requirements during summer. Maize growth is affected by rainfall characteristics especially during summer monsoon months. It has been observed under field conditions that most of high intensity rainstorms arise in rainy season which cause damage to crop. Crop lodging took place due to combined effect of rainfall, wind storm and also coupled with shallow root system of maize under subsurface compacted soils. It is proposed that if a slope is provides in maize field, lodging can be reduced and excess rainwater can be drained off quickly from the field. In this field study, a broad approach was employed to evaluate the integrated effects of subsurface compaction and slope steepness on crop growth, yield, yield attributes and physical properties of soil.

Material and methods

Location and experimental design

The experimental site is located at 30°54' N latitude and 75°48' E longitude with an altitude of 247 m above the MSL (mean sea level), at research farm, Department of Soil Science, Punjab Agricultural University, Ludhiana, in the central plain region of Punjab. The site has 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. The site receives 75 per cent of the average annual rainfall in the July to September months. The soil was classified as alluvial, sandy loam in texture, calcareous, Typic Haplustept. The experimental site soil has P and K lied in medium category, while, N and soil organic carbon content were in low category. The physico-chemical properties of soils are reported in Table 1.

A split-plot design was laid out in three blocks with three subsoil compaction levels (main plot treatments) and three levels of slope steepness (subplot treatment). The subsoil compaction treatments were given 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 C₀- Control (bulk density, Db= 1.55-1.65 Mg cm⁻³), C₁- Moderate compaction, (Db= 1.70-1.75 Mg cm⁻³) and C₂- High compaction (Db>1.80 Mg cm⁻³) at 15-30 cm depth. The slope steepness treatments imposed manually were: S₀- flat leveled field, S₁- 0.5% slope and S₂-1.0% slope. The standard Proctor test (American Society for Testing Materials, 2000) was employed to establish the maximum soil bulk density that is 1.86 Mg m⁻³, at optimal soil water content (i.e., water content at which maximum compaction occurs) of 0.12 cm³ cm⁻³.

Cultural practices

The maize crop was sown (June 27 during 2012 and June 22 during 2013) with row to row spacing of 60 cm and plant to plant spacing of 20 cm. Phosphorus, potassium and zinc sulphate were applied @ 60, 30 and 25 kg ha⁻¹, respectively. Entire quantity of P, K and Zinc Sulphate along 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 as per “PAU Package of Practices for *kharif* crops” were followed to ensure proper weed, insect and pest control.

Plant observations

The plant height (cm) was recorded as average from randomly selected five plants 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) and cob bareness (%) and plant lodging (%) were recorded at the time of threshing. Unfilled portion of cobs selected for length was measured with scale and noted as 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 (t ha⁻¹) to the total biomass yield (t ha⁻¹).

Soil measurement

Replicated undisturbed soil samples were collected from the field at the depth of 0-15, 15-30, 30-45, 45-60, 60-90 cm and determinations were made for bulk density and saturated hydraulic conductivity. Total porosity was calculated using the information on bulk density (D_b) and particle density (D_p) by employing equation as TP= (1-D_b/D_p). Hydraulic conductivity was measured with constant head permeameter method (Klute and Dirksen, 1986) using Darcy's equation. *In-situ* infiltration rate was measured using double metallic ring infiltrometers (Bouwer, 1986). Water was filled in both inner and outer rings and the fall of water level in the inner ring was recorded at different time intervals upto a cumulative time of 360 minutes from the start. Cumulative infiltration was worked out for each treatment and infiltration rate was calculated and expressed in cm hr⁻¹. Soil samples from various depths

were collected at the time of sowing and harvesting of crop to determine for gravimetric soil moisture content. The moisture content was determined gravimetrically by drying soil samples in the oven at 105 °C till the constant weight was achieved and the difference in wet and dry weights of soil samples was divided by dry weight and expressed as soil moisture content on dry weight basis. Penetration resistance was measured using cone penetrometer and was expressed in KPa.

Statistical procedure

The analysis of variance (ANOVA) technique was employed using PROC GLM (SAS software 9.1, SAS institute Ltd., USA) as per the standard procedure given by Gomez and Gomez (1984) for split plot design. All mean comparisons were made using Duncan's Multiple Range Test at $p=0.05$.

RESULTS AND DISCUSSION

Effect of subsoil compaction and slope steepness on soil physical properties

The mean values of bulk density (D_b) ranged from 1.49 to 1.61 Mg m^{-3} in 0-15 cm, 1.56 to 1.84 Mg m^{-3} in 15-30 cm, 1.51 to 1.74 Mg m^{-3} in 30-45 cm soil depth during the year the 2012 and 2013 (Table 2). The D_b of surface 0-15 cm soil layer was not significantly different among various treatments during the year the 2012 and 2013. However, the D_b for 15-30 cm subsoil layer was significantly higher under C_2 treatment than that in C_0 and C_1 treatment during the year 2012 and 2013. The higher D_b under C_2 treatment was attributed to treatment effect. However, slope steepness did not significantly affect the D_b during the period of study. The D_b of 30-45 cm subsoil layer followed almost similar trend as that of 15-30 cm subsoil layer, except the D_b under this layer was less than that in layer above.

The Penetration resistance (PR) of surface soil was less and it increased with depth (Table 2). The PR of C_2 treatment at 15-30 cm subsoil layer was significantly higher than that in C_0 and C_1 treatment, which reached to critical limit (ICPA, 1987) that affected the root growth negatively. The PR values averaged over 2 years at 30-45 cm soil depth were statistically different among themselves. The PR was higher under C_2 treatment than that in C_0 and C_1 treatment. The PR values were higher at 15-30 cm soil depth were higher than that in 0-15 cm surface layer. Kozicz (1996) also reported twice greater PR in subsoil layer than that in plough layer. Becher (1998) and Munkholm *et al* (2002) also observed higher soil strength under compacted zones due to intensive cultivation.

The porosity was higher under lower D_b than that in higher D_b soil. The total porosity followed the similar trend as bulk density behaves at all the soil depths (Table-3). Porosity was higher under C_0 treatment than that in C_1 and C_2 treatment at all depths during the year 2012 and 2013. The porosity values were significantly higher under C_0 treatment than that in C_1 and C_2 treatments at 15-30 cm and 30-45 cm soil depth.

The cumulative infiltration decreased with the increase in the subsoil bulk density (Fig 1 & 2). After lapse of 360 minutes of initiation of infiltration, cumulative infiltration was 25.1, 17.6 and 12.5 cm in C₀, C₁ and C₂ treatment, respectively during the year 2012, while it was 25.5, 18.8 and 11.3 cm in C₀, C₁ and C₂ treatment respectively during the year 2013 (Fig 1 & 2). The infiltration rate also decreased with increase in the subsoil compaction level. After 360 minutes, infiltration rate was 4.18, 2.93 and 2.08 cm hr⁻¹ through C₀, C₁ and C₂ treatment respectively during the year 2012 and 4.25, 3.13 and 1.88 cm hr⁻¹ through C₀, C₁ and C₂ treatment respectively during the year 2013. There was 2.01 times and 2.26 times decrease in infiltration rate under C₂ than that in C₀ treatment during the year 2012 and 2013, respectively. The decrease in infiltration rate and cumulative infiltration might be attributed to decrease in total porosity under higher level of subsoil compaction and entrapment of air in the soil profile that resisted infiltration.

Effect of subsoil compaction and slope steepness on plant height

A significant effect of soil compaction was observed on plant height of maize (Table 4). Plant height decreased significantly with the increase in strength of subsoil layer at 30, 60 DAS (days after sowing) and at harvesting stage. Maximum plant height (260.7 and 245.8 cm) was recorded at harvesting in plots with no subsoil compaction against minimum (239.9 and 214.3 cm) with higher subsoil compaction during the year 2012 and 2013 respectively. The C₂ treatment resulted in reduced plant height by 13.3 and 7.5 per cent at 30 DAS, 8.4 and 4.4 per cent at 60 DAS and 7.9 and 12.6 per cent at harvesting than that in C₀ treatment during the year 2012 and 2013 respectively. The reduced plant height in response to subsoil compaction may be ascribed to restricted root growth under higher subsoil strength. Slope steepness did not significantly affected the plant height at 30, 60 DAS and at harvesting stage.

Effect of subsoil compaction and slope steepness on yield

Subsoil compaction significantly affected the grain yield of maize during the years 2012 and 2013 (Table 5). The grain yield was higher under C₀ treatment than that in C₁ and C₂ treatments. Higher subsoil compaction level C₁ and C₂ resulted in yield reduction of 15.8 and 19.8 per cent, respectively than that in C₀ treatment during the year 2012. The yield reduction of 5.6 and 17.2 per cent was recorded in C₁ and C₂ treatment respectively than that in C₀ treatment during the year 2013, although this difference was statistically non-significant. The yield reduction of maize due to subsoil compaction have also been reported by Gaultney *et al* (1980) and Canarache *et al* (1984). Siemens and Peterson (1997) reported an average yield reduction of 13 per cent due to sub-soil compaction resulting from vehicular traffic. The maize yield reductions under higher degree of subsoil compaction might be attributed to restricted root growth, limited oxygen and nutrient supply (Allmaras *et al* 1988). Schuler and Lowery (1986) reported corn yield decreased up to 40%, partially due to subsoil compaction on silty clay soil.

Slope steepness treatment S_2 improved maize yield by 10.2 per cent than that in S_0 treatment, during year 2012. While, non-significant affect of slope steepness was observed in the year 2013. The improvement in yield might have occurred due to lesser water stagnation in the field after rainstorm and lesser plant lodging (Table 6) under higher slope steepness than that on flat land surface.

Biomass yield of maize was significantly higher under C_0 than that in C_1 and C_2 . 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 might be attributed to taller plants. Unger and Kaspar (1994) also 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. Slope steepness had significantly improved the biomass yield of maize. Biomass yield was significantly higher under higher slope steepness than that in flat land surface treatment. The better crop stand resulted in better crop growth and lesser lodging could be responsible for this yield improvement.

Harvest index of maize was not significantly affected by the subsoil compaction and slope steepness during both the years (Table 5). However, slope steepness had shown significant and negative effect on the harvest index of maize.

Effect of subsoil compaction and slope steepness on yield attributes of maize

The cob length was 14.1 and 9.4 per cent higher under C_0 treatment than that in C_2 treatment during the year 2012 and 2013 respectively (Table 6). However, slope steepness showed non-significant affect on the cob length of maize during both the years.

Subsoil compaction and slope steepness significantly affected cob barrenness. The barrenness was 13.97 and 33.6 per cent higher under C_2 treatment than that in C_0 treatment during the year 2012 and 2013, respectively (Table-6). Cob barrenness was 16.24 and 50.6 per cent higher under C_2 treatment over C_1 treatment during the year 2012 and 2013, respectively. The higher barrenness under C_2 treatment might be attributed to poor dry matter accumulation and translocation of photosynthates. The cob barrenness was lower by 14.4 per cent in S_2 than that in S_0 during the year 2013. The reduced cob barrenness was attributed to the higher vegetative growth, dry matter accumulation and its role in reproductive functioning of plant.

Conclusion

The increased usage of heavy machinery for field cultivation resulted in the formation of compacted layer just below the plough layer. This layer found to reduce the water infiltration rate as a result water stagnation occur over the surface posing a risk of crop lodging and aeration stress due to increase in risk of soil erosion during monsoon season, that receive rainstorms with high intensity. Thus the present study was initiated to access the effect of

subsoil compaction and slope steepness on the growth, yield and yield attributes of maize and on the physical properties of the soil. The compacted subsoil layer exhibited higher soil strength that resulted in higher bulk density, higher penetration resistance, lower total porosity and lower cumulative infiltration and infiltration rate. Thus the compacted subsoil layer negatively affected the soil-plant-water relations than that in uncompacted subsurface soil. A significant grain and biomass yield reduction was observed in response to the higher level of subsoil compaction. The steeper slope helped in the safe drainage of excess runoff water during monsoon season. It further helped in reducing the crop lodging even under higher subsoil compaction. The present study will help in fine tuning the existing technology for enhancing crop production under adverse environmental conditions.

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

Parameter	Value
Sand (%)	64.8
Silt (%)	18.9
Clay (%)	16.3
Bulk density, (Mg m^{-3})	
0-15 cm depth	1.49
15-30 cm depth	1.67
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. Bulk density and Penetration resistance as affected by subsoil compaction (average of 2 years).

Treatment	<u>Bulk Density (Mg m^{-3})</u>			<u>Penetration resistance (KPa)</u>		
	Soil depth			Soil depth		
	0-15 cm	15-30 cm	30-45 cm	10 cm	22 cm	45 cm
C ₀	1.57a	1.601c	1.523c	1008.7a	1889.8c	1588.6b
C ₁	1.55a	1.732b	1.648b	993.7a	2098.1b	1640.7b
C ₂	1.56a	1.824a	1.727a	1043.3a	2562.2a	1852.8a
<i>P-value</i> subsoil compaction	0.76	<0.0001	<0.0001	0.15	<0.0001	0.0005
S ₀	1.56a	1.70a	1.591b	1037.3a	2165.0a	1683.1a
S ₁	1.55a	1.72a	1.63ab	985.8a	2146.9a	1678.3a
S ₂	1.57a	1.73a	1.64a	1022.7a	2238.2a	1720.7a
<i>P-value</i> Slope steepness	0.66	0.14	0.06	0.13	0.21	0.66
<i>P-value</i> C X S	0.18	0.43	0.53	0.17	0.23	0.30

Different letters in each column of experimental factors show significant differences at 0.05 probability level.

Table-3. Total porosity (v/v) as affected by subsoil compaction (average of 2 years).

Treatments	Soil Depth		
	0-15 cm	15-30 cm	30-45 cm
C ₀	0.410a	0.379a	0.398a
C ₁	0.407a	0.341b	0.368b
C ₂	0.409a	0.308c	0.337c
<i>P-value</i> subsoil compaction	0.15	<0.0001	<0.0001
S ₀	0.413a	0.356a	0.370a
S ₁	0.410a	0.332ab	0.366a
S ₂	0.403a	0.341a	0.365a
<i>P-value</i> Slope steepness	0.13	0.07	0.69
<i>P-value</i> C X S	0.17	0.20	0.73

Different letters in each column of experimental factors show significant differences at 0.05 probability level.

Table-4. Plant height (cm) of maize under different subsoil compaction and slope steepness treatments.

Treatments	30 DAS		60 DAS		At harvesting	
	2012	2013	2012	2013	2012	2013
C ₀	65.73a	54.89a	223.44a	218.56a	260.73a	245.81a
C ₁	61.09b	50.56a	210.00ab	217.67a	253.00a	230.36b
C ₂	56.99b	50.78a	203.78b	208.78a	239.99b	214.32c
<i>P-value</i> subsoil compaction	0.003	0.20	0.04	0.27	0.004	<0.0001
S ₀	59.73a	51.22a	205.44a	207.89b	253.23a	225.04a
S ₁	61.38a	54.67a	217.00a	214.22ab	250.18a	233.03a
S ₂	62.71a	50.33a	214.78a	222.89a	250.31a	232.42a
<i>P-value</i> slope	0.36	0.24	0.26	0.09	0.79	0.16
<i>P-value</i> C X S	0.97	0.20	0.56	0.23	0.11	0.64

Different letters in each column of experimental factors show significant differences at 0.05 probability level.

Table-5. Grain yield, biomass yield and Harvest Index of maize under different subsoil compaction and slope steepness treatments.

Treatments	Grain yield (t/ha)		Biomass yield (t/ha)		Harvest Index	
	2012	2013	2012	2013	2012	2013
Subsoil compaction levels						
C ₀	5.98a	4.86a	18.71a	15.30a	0.30a	0.32a
C ₁	5.03b	4.59ab	16.00b	13.13b	0.31a	0.35a
C ₂	4.79b	4.02b	14.65b	12.82b	0.34a	0.31a
LSD (P=0.05)	0.0003	0.06	0.001	0.001	0.35	0.19
Slope steepness levels						
S ₀	5.08b	4.52a	15.39b	12.32b	0.32a	0.37a
S ₁	5.12b	4.26a	15.87b	13.42b	0.33a	0.31b
S ₂	5.60a	4.69a	18.09a	15.11a	0.30a	0.30b
LSD (P=0.05)	0.056	0.43	0.01	0.0003	0.11	0.038
LSD C X S	0.14	0.65	0.37	0.62	0.47	0.78

Different letters in each column of experimental factors show significant differences at 0.05 probability level.

Table-6. Growth and yield attributing characters of maize under different subsoil compaction and slope steepness treatments. Different letters in each column of experimental factors show significant differences at 0.05 probability level.

Treatments	Cob length (cm)		Cob barrenness (%)		Lodging (%)	
	2012	2013	2012	2013	2012	2013
Subsoil compaction levels						
C ₀	17.01a	18.07a	11.39a	9.46b	7.24c	9.10c
C ₁	15.77ab	17.06ab	12.51a	10.95ab	8.90b	10.76b
C ₂	14.61b	16.36b	13.24a	14.25a	10.4a	13.39a
LSD (P=0.05)	0.004	0.03	0.29	0.042	<0.0001	<0.0001
Slope steepness levels						
S ₀	15.90a	17.45a	11.49a	12.19a	10.22a	12.70a
S ₁	15.73a	17.24a	13.21a	11.82a	9.19b	11.62a
S ₂	15.77a	16.80a	12.44a	10.65a	7.55c	9.01b
LSD (P=0.05)	0.95	0.52	0.34	0.64	<0.0001	0.0003
LSD C X S	0.96	0.20	0.76	0.057	0.065	0.167

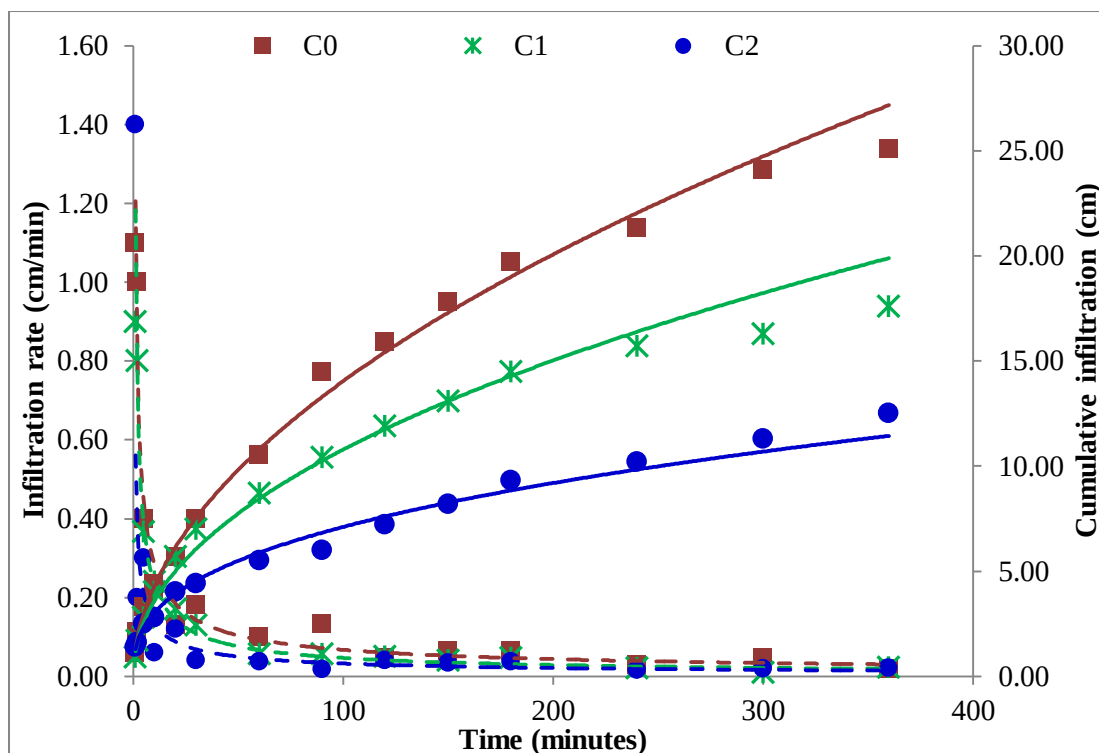


Fig: 1. Cumulative infiltration (straight line) and infiltration rate (dotted) as influenced by subsoil compaction during the year 2012.

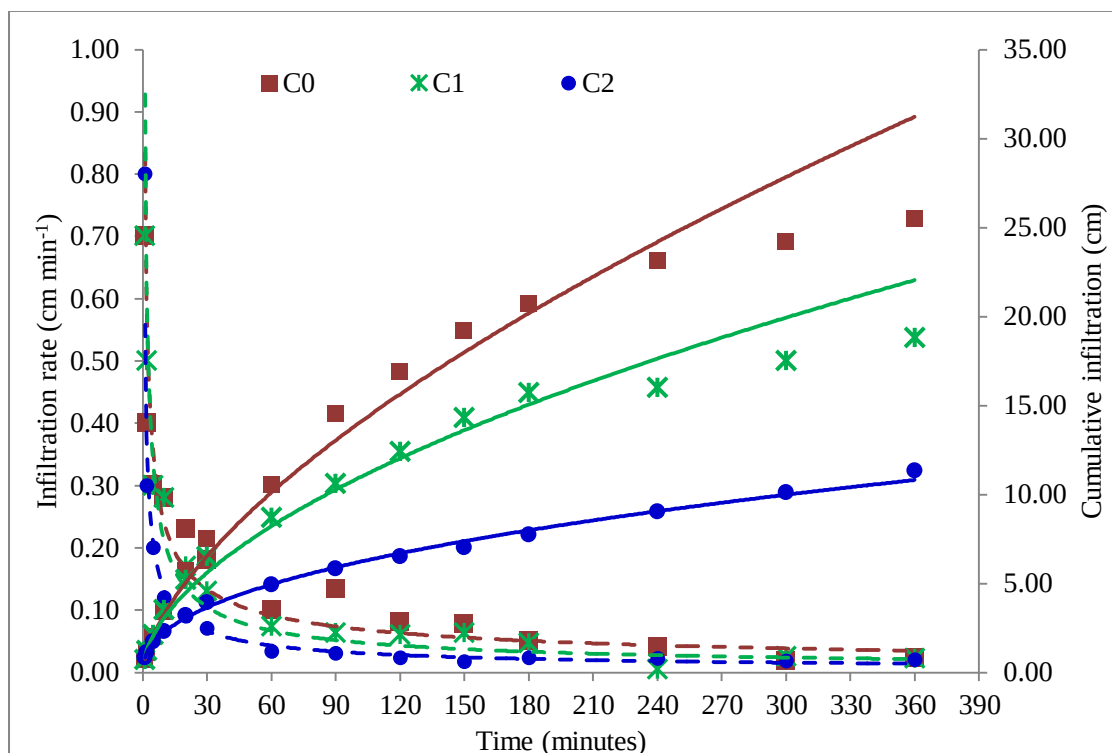


Fig: 2. Cumulative infiltration (straight line) and infiltration rate (dotted) as influenced by subsoil compaction during the year 2013.

CHAPTER IV

GENERAL DISCUSSION

4.1 Experiment-I

4.1.1 Climatic condition during crop growth

Minimum temperature remained higher over the normal minimum temperature during both the years of study and maximum temperature during the year 2012. This was more than the normal maximum temperature. However, maximum temperature during the year 2013 was well distributed around normal maximum temperature. In about 9 out of 23 weeks of total study period during the year 2013, maximum temperature remain lower over the normal maximum temperature. The pan evaporation during the year 2012 was higher than normal pan evaporation till the vegetative period of the crop. However, it was lower than the normal pan evaporation. While pan evaporation remained distributed around normal during 2013 except few instances when it was lower than normal. The rainfall received was lower than the average normal rainfall during the year 2012 and 2013.

4.1.2 Subsoil compaction and germination of maize

The higher level of subsoil compaction (C_2) significantly advanced the days taken to emergence during the year 2013. Maize crop took almost 10 days for complete germination in plot with no subsoil compaction, while germination advances by about 3 days with increased level of subsoil compaction over no subsoil compaction treatment during the year 2013. Higher soil moisture at the time of sowing during the year 2013, might be responsible for early emergence during year 2013, because rainfall occurred few days prior to the sowing of crop that helped in breaking the seed dormancy. However, Sheikh (1976) found a linear decrease in per cent seed germination with increase in bulk density.

4.1.3 Effect of subsoil compaction and N fertilization on phenology of maize

The crop took 48-52 days during the year 2012 and 55-60 days during 2013 to the appearance of tassel. The subsoil compaction delayed the tasseling by 4 days during 2012 and about 5 days during 2013. It delayed the silking by about 4 days during 2012 and 2013 than that in no subsoil compaction treatment. The delaying of tasseling and silking may be attributed to the higher level of subsoil compaction which restricted the growth and expansion of roots. It thereby adversely affected the plant growth, development and yield (Tubeileh *et al* 2003). The N being the most limiting nutrient to crop production significantly delayed the days to tasseling and silking stage. An increase in the dose of N from 125 kg N ha⁻¹ to 190 kg N ha⁻¹ significantly advances the tasseling and silking during both the years. The increase in N dose resulted in advancement in the occurrence of tasseling by 3 days during 2012 and about 4 days during 2013 than that in N₀ treatment. An increase in N dose advanced the occurrence of silking by about 3 days during 2012 and 2013. The results of study confirmed

the findings of Dawadi and Sah (2012) who reported that increasing N levels decreased the number of days to reach tasseling and silking. Aboyami and Adedoyin (2004) also found that the application of higher dose of N significantly reduced time to tasseling and silk emergence. Gajri *et al* (1994) also reported that phenological parameters of maize were significantly affected by the amount of N fertilization and deep tillage.

The subsoil compaction advanced the dough stage by about 6 days and 4 days during the years 2012 and 2013, respectively, than that in no subsoil compaction treatment. The N application delayed dough stage by about 4 days and 3 days during the year 2012 and 2013, respectively. The delay in the dough stage with higher dose of N fertilizer is attributed to the higher vegetative growth under higher level of N application over the lower N application.

The subsoil compaction advanced the physiological maturity by about 7 days and 6 days during the years 2012 and 2013, respectively over no subsoil compaction treatment. The advancement in physiological maturity under higher level of subsoil compaction is attributed to lesser plant growth resulting from restricted root growth and shortened period of flowering and grain filling. The N application delayed physiological maturity by 3 days during 2012 and 5 days during 2013. The delay in the physiological maturity with higher dose of N application is attributed to the higher vegetative growth than that with lower N dose. Ali *et al* (2012) found that increasing dose of N application in maize delayed physiological maturity, because higher N level delayed leaf senescence, sustained photosynthesis longer, extend duration of vegetative growth and increase the succulence of plants.

4.1.4 Effect of soil compaction and N fertilization on plant height, periodic dry matter accumulation and leaf area index

The increase in the bulk density of subsoil layer from 1.6 to 1.8 Mg m⁻³ result 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 during the year 2012 and 2013 respectively. The reduced plant height in response to subsoil compaction may be attributed to restricted root growth under higher subsoil strength. The N fertilization significantly affected the plant height at 30, 60 DAS and at harvesting stage. The maximum plant height at harvesting stage (265.31 and 252.84 cm) was recorded in N₀ plots against minimum (251.56 and 234.2 cm) under N₂ 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 due to more N application may be attributed to more vegetative growth that resulted in increased mutual shading and internodal extension (Rasheed *et al* 2004).

Dry matter production (DMA) serves as a reliable measure of the relative influence of different treatments on plant growth and ultimately on the crop yield. The well-timed accumulation of dry matter by crop is followed up by adequate transfer of assimilates to the

sink resulting in higher yield. The DMA by crop reveals that dry matter decreased with increase in the bulk density of subsoil layer. The crop sown under C_0 treatment had 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 DMA 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 Gee-Clough *et al* (1990) who found reduction in dry matter yield by 16 per cent under higher degree of compaction than that in uncompacted soil. N fertilization had significantly increased dry matter accumulation at 30, 60 DAS and at harvesting stage. The DMA 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 DMA 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 years 2012 and 2013 respectively. The enhanced DMA 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, which was due to the cumulative effect of higher plant height and higher leaf area index under higher N application over the lower N application (Bangarwa *et al* 1988).

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. LAI was highest under C_0 treatment, which was significantly higher than that of C_2 at 30 DAS, 60 DAS and at harvesting during the year 2012 and 2013. 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 at 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. 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) have reported more leaf elongation and less leaf

senescence with higher nitrogen application. Prasad *et al* (1990) also reported increased LAI with application of higher dose of N.

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

4.1.5 Effect of soil compaction and N fertilization on yield attributes

Cob length is considered an important indicator of total number of grains and considered as desirable yield component of maize. The cob length was significantly higher under C₀ treatment (17.08 cm and 17.74 cm) than that in C₂ treatment during the year 2012 and 2013 respectively. However, cob length was statistically at par under C₀ and C₁ subsoil compaction treatment. Higher dose of N fertilizer significantly improves the cob length. The N₂ treatment resulted in 11.3 and 10.8 per cent increase in cob length than that in N₀ treatment during the year 2012 and 2013 respectively.

Cob barrenness was significantly affected by subsoil compaction and N fertilization. The barrenness was highest (14.63 and 13.62 per cent) under C₂ treatment during the years 2012 and 2013, respectively. Cob barrenness was 33 and 39 per cent higher under C₂ treatment over C₁ treatment during the year 2012 and 2013, respectively. The higher barrenness under C₂ treatment may be attributed to poor dry matter accumulation and translocation of photosynthates. In general, cob barrenness decreased with increase in nitrogen dose. Cob barrenness in N₂ was significantly higher than that in N₀ and N₁ during the year 2013. The cob barrenness was lower by 25.6 and 41.6 per cent during the years 2012 and 2013, respectively under N₂ than that in N₀. The reduced cob barrenness might be attributed to the higher vegetative growth and dry matter accumulation and its role in reproductive system of plant. Similarly, Shivay and Singh (2000) and Kumar (2008) also reported reduced barrenness with increased N application in maize crop.

Test weight (1000-grain weight) was not affected statistically by the subsoil compaction and N fertilization during the year 2012 and 2013. However, 1000-grain weight was numerically higher in C₀ treatment than that in C₁ and C₂ treatment.

4.1.6 Effect of soil compaction and N fertilization on grain yield, biomass yield and harvest index

Highest grain yield was achieved under C₀ treatment than that in C₁ and C₂ treatments. Higher levels of subsoil compaction resulted in yield reduction of 15 to 25 per cent. Gaultney *et al* (1980) also reported 45-50 per cent yield reductions in maize due to subsoil compaction. Siemens and Peterson (1997) reported an average yield reduction of 13 per cent due to compaction resulting from vehicular traffic. The maize yield reductions under higher degree of subsoil compaction occurred due to root growth restrictions. Allmaras *et al* (1988) reported lower yield due to root growth restrictions under higher subsoil compaction.

Crop took less number of days to mature under higher degree of subsoil compaction that might be responsible for reduced crop yields. Muchow (1990) also observed grain yield reduction due to shorter grain filling period due to early maturity of crop. N application significantly affected the grain yield. 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 findings of Inamullah *et al* (2011) who reported an increase in grain yield with higher dose of N application.

Biomass yield was significantly higher under C_0 than that in C_1 and C_2 . 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. 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 resulted in increased vegetative growth (plant height and dry matter accumulation) which improved the biomass yield. Inamullah *et al* (2011) also reported improvement in biomass yield with higher of N application.

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.

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

Crop growth rate (CGR) increased progressively with time, reaching peak during 60 DAS and thereafter declined till maturity of the crop. Reduction in growth rate with plant age was probably due to cessation of vegetative growth, loss of leaves, and senescence. The CGR was significantly higher in C_0 treatment than that in C_1 and C_2 treatment. With increasing N dose, crop growth rate (CGR) was increased. The significantly highest CGR was observed in N_2 treatment at all the growth stages. The minimum CGR was obtained in lower levels of nitrogen fertilizer (N_0). Increase in CGR rate with N was mainly due to higher vegetative growth and larger LAI. This behavior is in conformity with the findings of Valero *et al* (2005). Also, increase in CGR at 60 DAS might have resulted due to transformation of plant into reproductive phase or by increase in dry matter production as influenced by different N treatments, which could be attributed to higher photosynthetic activity coupled with increased cell multiplication.

The net assimilation rate (NAR) increased with the growing crop, maximum at 60 DAS and decreased thereafter. An increase in NAR during the growing season is interpreted as a response of the photosynthetic apparatus to an increased demand for assimilates to afford rapid growth of the grain fraction. The decrease in NAR might be attributed to the shading effect of lower leaves by the upper canopy, decline in photosynthetic efficiency with leaf age and also due to lack of nutrients in later stages. Leaf area near harvesting also declined due to leaf senescence. The NAR was significantly higher in C₀ treatment than that in C₁ and C₂ at harvesting stage during the year 2013. The reduction in NAR under higher degree of subsoil compaction might have occurred due to reduced dry matter accumulation and leaf area as a result of impedance to root growth due to higher soil strength. The impeded root growth limits nutrient and water supply to plants. The results confirmed the findings of Valero *et al* (2005).

The N application showed significant effect on mean NAR and mean maximum NAR (2.189 and 2.267 g plant⁻¹ d⁻¹ during 2012 and 2013 respectively) that was achieved under N₂ treatment at 60 DAS which decreased thereafter, because at earlier growth stage, maximum increase in stem growth occurred. The maize plant accumulated higher dry matter that might be responsible for more NAR under N₂ treatment. A decreasing trend in maize NAR vs its LAI over growing season has also been reported by Adelana and Milbourn (1976).

4.1.7 Effect of subsoil compaction and N fertilization on soil physical properties

The D_b of surface 0-15 cm soil layer was not significantly different among various treatments during the year the 2012 and 2013. However, the D_b for 15-30 cm subsoil layer was significantly higher under C₂ treatment than that in C₀ and C₁ treatment during the year 2012 and 2013. The higher D_b under C₂ treatment occurred due to subsoil compaction treatments. The D_b of 30-45 cm subsoil layer followed almost similar trend as that in 15-30 cm subsoil layer, except the D_b under this layer was less than that in layer above. Our results are in conformity with Mamman and Ohu, (1998) who reported that dry soil bulk density and penetration resistance increased with increase in the number of traffic passes.

The penetration resistance (PR) of soil increased with depth. The PR of C₂ treatment at 15-30 cm subsoil layer was significantly higher than that in C₀ and C₁ treatment, which reached the critical limit (ICPA, 1987) that, affected the root growth negatively. The PR values at 30-45 cm soil depth were statistically different among themselves, were higher under C₂ treatment than that in C₀ and C₁ treatment. The PR values were higher at 15-30 cm soil depth than that in 0-15 cm surface layer. Kozicz (1996) observed 2 times more PR in subsoil layer than that in plough layer. Mamman and Ohu, (1998), Becher (1998) and Munkholm *et al* (2002) also reported higher soil strength under compacted zones due to cultivation.

The porosity was higher under lower D_b than that in higher D_b soil. The total porosity followed the similar trend as that of bulk density at all the soil depths. Total porosity was higher under C_0 treatment than that in C_1 and C_2 treatment at all depths during the year 2012 and 2013. The porosity values were significantly higher under C_0 treatment than that in C_1 and C_2 treatment at 15-30 cm and 30-45 cm soil depth.

The interactive effect of subsoil compaction and N fertilization were non-significant for bulk density, penetration resistance and total porosity.

After 360 minutes of initiation of infiltration, cumulative infiltration was 25.1, 17.6 and 12.5 cm in C_0 , C_1 and C_2 treatment, respectively during the year 2012, while it was 27.5, 19.9 and 14.9 cm in C_0 , C_1 and C_2 treatment respectively during the year 2013. The infiltration rate was 4.18, 2.93 and 2.08 cm hr⁻¹ through C_0 , C_1 and C_2 treatment respectively during the year 2012 and 4.58, 3.31 and 2.48 cm hr⁻¹ in C_0 , C_1 and C_2 treatment respectively during the year 2013. The decrease in infiltration rate and cumulative infiltration under C_2 treatment than that in C_0 treatment might be attributed from decreased total porosity due to higher bulk density of subsoil layer under C_2 treatment. Dikinya (1994) also observed lower infiltration rate in compacted sandy loam soil. Reicosky *et al* (1981) attributed this decrease in infiltration due to compaction as it increased the number of contacts between individual soil particles which lead to increase in tortuosity of water flow, and therefore lowers the infiltration.

The subsoil compaction significantly reduced the saturated hydraulic conductivity of the 17-22 cm soil depth. The saturated hydraulic conductivity was 2.8 and 1.6 times less under C_2 and C_1 treatment respectively than that in C_0 treatment. The subsoil compaction reduced the macropores, those are primarily responsible for the saturated hydraulic conductivity.

The increase in the soil moisture retention at 0.3 bar at 15-30 and 30- 60 cm soil layer under C_2 and C_1 treatment over C_0 treatment after the harvesting of maize crop during the year 2013. At 15 bar suction pressure, soil moisture retention was also higher at 15-30 and 30-60 cm layer under C_2 treatment followed by C_1 treatment than that in C_0 treatment. The increase in soil moisture retention at 0.3 and 15 bar pressure might be attributed to reduced porosity and increase in microporosity of soil as a result of soil compaction.

4.1.8 Effect of subsoil compaction and N fertilization on root growth

4.1.8.1 At knee high stage

The root mass density at 0-15 cm depth was significantly higher under C_2 treatment followed by C_1 and C_0 treatments. The root mass density decreased with increase in depth during both years. The reverse trend was recorded at 15-30 and 30-45 cm depth where root mass density was higher under C_0 treatment than that in C_1 and C_2 treatments. The bulk density and penetration resistance of 15-30 cm soil layer was higher under C_2 treatment than

might be responsible for higher root mass density in 0-15 cm layer under C_2 treatment. However, bulk density and penetration resistance of 15-30 cm soil layer was lower under C_0 treatment that resulted in higher root mass density in 15-30 and 30-45 cm soil layer. Laboski *et al* (1998) in a field experiment found that a compacted soil layer confined roots almost entirely to the top 60 cm of soil because it had high soil strength and bulk density. Application of higher dose of N had improved the root mass density at all depths than that in lower N dose. The higher penetration resistance might had restricted root penetration to deeper soil layers while N fertilization had increased the root mass density in the all layers due to proper supply of N for optimum plant growth. The interaction effect of subsoil compaction and N fertilization were non-significant for root mass density at knee high stage of maize.

4.1.8.2 At pre-tasseling stage

The highest root mass density of 1603.3 and 1568.6 g m⁻³ was observed at 0-15 cm layer under C_2 treatment during the year 2012 and 2013. In 0-15 cm soil layer, root density was significantly higher under C_2 treatment than that in C_0 and C_1 treatment during the year 2012 and 2013. Rosolem and Takahashi (1998) also reported that sub-surface compaction led to an increase in root growth in the superficial soil layer with a corresponding quadratic decrease in the compacted layer. However, a reverse trend in root mass density was observed for deeper layers, where a significantly higher root mass density under C_0 treatment was observed than that in C_1 and C_2 treatment. More root growth restriction under C_2 treatment due to its higher bulk density and penetration resistance confined to more root mass in 0-15 cm soil layer. While in deeper soil depths, C_0 treatment showed higher root mass density due to lower penetration resistance of subsoil layer. Grzesiak (2009) also reported that root growth of maize was heavily restricted by the soil compaction due to its higher penetration resistance and bulk density. Sidhu (1980), Sur *et al* (1980) and Sur and Sidhu (1982) also reported that the presence of subsoil compacted layer affected the root amount and their distribution pattern in the soils especially in paddy-wheat crop rotation.

The root mass density was higher under N_2 treatment than that in N_0 and N_1 treatment due to higher plant growth as a result of proper nutrition of maize crop. The interaction effect of subsoil compaction and N fertilization were non-significant for root mass density at pre-tasseling stage of maize.

4.1.9 Water studies

4.1.9.1 Soil water depletion and water use

The net irrigation water applied to crop was 51.5 and 45.0 cm during the year 2012 and 2013, respectively, while effective rainfall received was 26.7 and 33.3 cm during the crop season of the year 2012 and 2013 respectively. The soil moisture storage was recorded in root zone during the year 2012, while soil moisture depletion was observed, during 2013. In the

year 2012, mean water storage was more under C_2 treatment than that in C_0 and C_1 . This might have resulted from more vegetative growth and evapo-transpiration loss under C_0 and C_1 than that in C_2 . However, there was more water storage in C_1 treatment than that in C_0 and C_2 during the year 2012. The lesser water storage might be attributed to more water use by crop during vegetative, reproductive stages and more ET losses. Nitrogen fertilization showed negative effect on water storage. Each additional dose of nitrogen lead to more vegetative growth i.e. leaf area and plant height, which ultimately lead to more ET losses.

4.1.9.2 Water productivity

Water productivity was 17.5 and 31.6 per cent higher under C_0 treatment than that in C_2 treatment during the year 2012 and 2013, respectively. Although water productivity in C_1 treatment was more than that in C_2 , but this difference was statistically non-significant during the study years 2012 and 2013. The reduced water productivity under higher level of subsoil compaction might be responsible for lower crop yield and water use. Water productivity was higher under N_2 treatment than that in N_0 treatment. However, water productivity was at par in N_1 and N_2 treatments during the year 2012 and 2013. Cai *et al* (2002) reported that fertilization maximizes the use of stored water in the root zone and lead to higher crop yields. Fan *et al* (2004) reported that nitrogen fertilization increased grain yields and WUE in China by 50–60 per cent. Nangia *et al* (2008) also showed that the water productivity of maize can be enhanced with the addition of nitrogen fertilizer. The interactive effect of subsoil compaction and nitrogen fertilization was non-significant on water productivity.

4.2 Experiment-II

4.2.1 Effect of subsoil compaction and slope steepness on soil physical properties

The D_b of surface 0-15 cm soil layer was not significantly different among various treatments during the year the 2012 and 2013. However, the D_b for 15-30 cm subsoil layer was significantly higher under C_2 treatment than that in C_0 and C_1 treatment during the year 2012 and 2013. The higher D_b under C_2 treatment was attributed to treatment effect. However, slope steepness did not significantly affect the D_b during the period of study. The D_b of 30-45 cm subsoil layer followed almost similar trend as that of 15-30 cm subsoil layer, except the D_b under this layer was less than that in layer above.

The penetration resistance (PR) of surface soil was less and it increased with depth. The PR of C_2 treatment at 15-30 cm subsoil layer was significantly higher than that in C_0 and C_1 treatment, which reached critical limit (ICPA 1987), that negatively, affected the root growth. The PR values averaged over 2 years at 30-45 cm soil depth were statistically different among themselves. The PR was higher under C_2 treatment than that in C_0 and C_1 treatment. The PR values were higher at 15-30 cm soil depth were higher than that in 0-15 cm surface layer. Kozicz (1996) also reported twice greater PR in subsoil layer than that in

plough layer. Becher (1998) and Munkholm *et al* (2002) also observed higher soil strength under compacted zones due to cultivation.

The porosity was higher under lower D_b than that in higher D_b soil. The total porosity followed the similar trend of bulk density at all the soil depths, since it was calculated for D_b values. Porosity was higher under C_0 treatment than that in C_1 and C_2 treatment at all depths during the year 2012 and 2013. The porosity values were significantly higher under C_0 treatment than that in C_1 and C_2 treatments at 15-30 cm and 30-45 cm soil depth.

The cumulative infiltration decreased with the increase in the subsoil bulk density. After 360 minutes of initiation of infiltration, cumulative infiltration was 25.10, 17.60 and 12.50 cm in C_0 , C_1 and C_2 treatment, respectively during the year 2012, while it was 25.50, 18.80 and 11.30 cm in C_0 , C_1 and C_2 treatment respectively during the year 2013. The infiltration rate also decreased with increase in the subsoil compaction level. After 360 minutes, infiltration rate was 4.2, 2.9 and 2.1 cm hr⁻¹ C_0 , C_1 and C_2 treatment respectively during the year 2012 and 4.2, 3.1 and 1.9 cm hr⁻¹ C_0 , C_1 and C_2 treatment respectively during the year 2013. There was 2.01 times and 2.26 times decrease in infiltration rate under C_2 than that in C_0 treatment during the year 2012 and 2013, respectively. The decrease in infiltration rate and cumulative infiltration resulted from decreased total porosity under higher level of subsoil compaction and entrapment of air.

4.2.2 Effect of subsoil compaction and slope steepness on plant height

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. Maximum plant height (260.7 and 245.8 cm) was recorded at harvesting in plots with no subsoil compaction against minimum (239.9 and 214.3 cm) with higher subsoil compaction during the year 2012 and 2013 respectively. The C_2 treatment resulted in reduced plant height by 13.3 and 7.5 per cent at 30 DAS, 8.4 and 4.4 per cent at 60 DAS and 7.9 and 12.6 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 might be attributed to restricted root growth under higher subsoil strength. Slope steepness did not affect the plant height significantly at 30, 60 DAS and at harvesting stage.

4.2.3 Effect of subsoil compaction and slope steepness on yield

The grain yield was higher under C_0 treatment than that in C_1 and C_2 treatments. The C_1 and C_2 treatments resulted in yield reduction of 15.8 and 19.8 per cent, respectively than that in C_0 treatment during the year 2012. The yield reduction of 5.6 and 17.2 per cent was recorded in C_1 and C_2 treatment respectively than that in C_0 treatment during the year 2013, although this difference was statistically non-significant. The yield reduction of maize due to subsoil compaction was reported by Gaultney *et al* (1980) and Canarache *et al* (1984). Siemens and Peterson (1997) also reported an average yield reduction of 13 per cent due to

compaction resulting from vehicular traffic. The maize yield reductions under higher degree of subsoil compaction might be attributed to restricted root growth, limited oxygen and nutrient supply (Allmaras *et al* 1988). Schuler and Lowery (1986) reported corn yield decreased up to 40 per cent, partially due to subsoil compaction on silty clay soil.

Slope steepness treatment S_2 improved maize yield by 10.2 per cent than that in S_0 treatment, during year 2012. However, non-significant affect of slope steepness was observed in the year 2013. The improvement in yield might be due to lesser water stagnation and proper aeration in the field after rainfall and lesser plant lodging under higher slope steepness than that on flat land surface.

Biomass yield of maize was significantly higher under C_0 than that in C_1 and C_2 . 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 might be attributed to taller plants. Unger and Kaspar (1994) also 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. Slope steepness significantly improved the biomass yield of maize. Biomass yield was significantly higher under higher slope steepness than that on flat surface treatment. The better crop growth and lesser lodging could be the responsible for the better crop yield.

Harvest index of maize was not significantly affected by the subsoil compaction and slope steepness during both the years. However, slope steepness showed significant negative effect on the harvest index of maize.

4.2.4 Effect of subsoil compaction and slope steepness on yield attributes of maize

The cob length was 14.1 and 9.4 per cent higher under C_0 treatment than that in C_2 treatment during the year 2012 and 2013 respectively. However, slope steepness showed non-significant affect on the cob length of maize during both the years.

The barrenness was 13.9 and 33.6 per cent higher under C_2 treatment than that in C_0 treatment during the year 2012 and 2013, respectively. Cob barrenness was 16.2 and 50.6 per cent higher under C_2 treatment over C_1 treatment during the year 2012 and 2013, respectively. The higher barrenness under C_2 treatment might be attributed to poor dry matter accumulation and translocation of photosynthates. The cob barrenness was lower by 14.4 per cent in S_2 than that in S_0 during the year 2013. The reduced cob barrenness was attributed to the higher vegetative growth, dry matter accumulation and its role in reproductive functioning of plant.

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CHAPTER V

SUMMARY

The continuous use of farm machinery and adoption of rice-wheat cropping sequence resulted in the formation of compacted subsoil layer at the depth of 10-40 cm. The subsoil compacted layer affects nearly all soil properties and functions, which in turn affect the growth and productivity of plants. The information on the relationships among the degree of compaction, soil physical properties, N fertilizer rates, slope steepness and annual row crop performance are limited. Thus, the present investigation entitled “Soil and maize response to compaction, slope steepness and nitrogen fertilization in coarse textured soil” was conducted in the *kharif* season during the year 2012 and 2013 at the research farm, department of Soil Science, Punjab Agricultural University, Ludhiana. Subsurface compacted layer of desired bulk density was created by removing the surface layer of 0-15 cm depth and then compacted with tractor mounted stone roller. After achieving the desired bulk density the surface soil was put in place. The nitrogen treatments N_0 -155 kg N ha⁻¹, N_1 -195 kg N ha⁻¹ and N_2 -235 kg N ha⁻¹ were evaluated for their effect on soil physical properties, plant growth and yield under different subsoil compaction levels. Also, best dose of N fertilization for maize cultivation was calculated under subsurface compaction affected soils.

The bulk density (D_b) 15-30 cm subsoil layer was significantly higher under C_2 treatment than that in C_0 and C_1 treatment during the year 2012 and 2013. The D_b of 30-45 cm subsoil layer followed almost similar trend as that of 15-30 cm subsoil layer, except the D_b under this layer was less than that in layer above. The penetration resistance (PR) of C_2 treatment at 15-30 cm subsoil layer was significantly higher than that in C_0 and C_1 treatment. The PR values at 30-45 cm soil depth were higher under C_2 treatment than that in C_0 and C_1 treatment. The PR values were higher at 15-30 cm soil depth than that in 0-15 cm surface layer. Total porosity was higher under C_0 treatment than that in C_1 and C_2 treatment at all depths during the year 2012 and 2013. The porosity values were significantly higher under C_0 treatment than that in C_1 and C_2 treatment at 15-30 cm and 30-45 cm soil depth.

The saturated hydraulic conductivity was 2.8 and 1.6 times less under C_2 and C_1 treatment respectively than that in C_0 treatment at 17-22 cm soil depth. The increase in the soil moisture retention occurred at 0.3 bar at 15-30 and 30-60 cm soil layer under C_2 and C_1 treatment compared to C_0 treatment. At 15 bar pressure, soil moisture retention was also higher at 15-30 and 30-60 cm layer under C_2 treatment followed by C_1 treatment than that in C_0 treatment.

The cumulative infiltration decreased with the increase in the bulk density of subsoil. After 360 minutes, infiltration rate was 4.2, 2.9 and 2.1 cm h⁻¹ through C_0 , C_1 and C_2 treatment

respectively during the year 2012 and 4.6, 3.3 and 2.5 cm h⁻¹ in C₀, C₁ and C₂ treatment respectively during the year 2013.

Maize crop took about 10 days to complete germination in plot with no subsoil compaction, while germination advances by about 3 days with increased level of subsoil compaction over no subsoil compaction treatment during the year 2013. The subsoil compaction delays the tasseling by 4 days during 2012 and about 5 days during 2013. An increase in the dose of N from 155 kg N ha⁻¹ to 235 kg N ha⁻¹ significantly advanced the tasseling and silking during both the years. The subsoil compaction advanced the dough stage by about 6 days and 4 days during the year 2012 and 2013, whereas N application delayed dough stage by about 4 days and 3 days during the year 2012 and 2013, respectively. The subsoil compaction advanced the physiological maturity by about 7 days and 6 days during the year 2012 and 2013, respectively. However, N application delayed physiological maturity by 3 days during 2012 and 5 days during 2013.

The increase in the bulk density of subsoil layer from 1.6 to 1.8 Mg m⁻³ resulted in reduced plant height by 15.7 and 10.8 per cent at harvesting stage during the year 2012 and 2013 respectively. Increased plant height in response to higher N application was observed during the year 2012 and 2013. The increase in bulk density of subsoil from C₀ treatment to C₁, decreased dry matter accumulation (DMA) by 7.1 and 6.2 per cent, while increase in bulk density of subsoil from C₀ treatment to C₂ treatment resulted in 13.2 and 18.1 per cent decrease at the time of harvesting during the year 2012 and 2013 respectively. Increase in N dose from N₀ to N₁ increased DMA by 12.8 and 19.4 per cent, while increase in N dose from N₀ to N₂ resulted in 28.7 and 48.5 per cent increase at the time of harvesting during the year 2012 and 2013 respectively. The LAI increased upto 60 DAS and thereafter declined due to senescence. LAI was highest under C₀ subsoil compaction and N₂ nitrogen treatment. Crop growth rate (CGR) was significantly higher in C₀ treatment than that in C₁ and C₂ treatment. Crop growth rate (CGR) increased with increase in nitrogen dose that was significantly higher in N₂ treatment at all the growth stages.

The highest grain yield was achieved under C₀ treatment than that in C₁ and C₂ treatments. Higher levels of subsoil compaction resulted in yield reduction by 15 to 25 per cent, whereas, the increase in N dose from N₀ to N₂ resulted in 14.8 and 16.1 per cent increase in grain yield during the year 2012 and 2013, respectively.

The N₁ fertilizer application rate is recommended for application even under higher degree of subsoil compaction due to higher maize yield. However, maize yield under N₂ treatment was statistically at par with N₁ dose of N.

Biomass yield was significantly higher under C₀ than that in C₁ and C₂ but it was statistically at par among C₁ and C₂ during the year 2012 and 2013. The N₂ treatment improved the biomass yield by 17 and 10.8 per cent over N₀ treatment.

The root mass density at 0-15 cm was highest under C_2 treatment during the year 2012 and 2013. The root mass density decreased with depth during both years. There was reverse trend was recorded at 15-30 and 30-45 cm depth where root mass density was higher under C_0 treatment than that in C_1 and C_2 treatments. Application of higher dose of N had significantly improved the root mass density at all depths.

At pre-tasseling stage, highest root mass density of 1603.3 and 1568.6 g m⁻³ was observed at 0-15 cm layer under C_2 treatment during the year 2012 and 2013. In 0-15 cm soil layer, root density was significantly higher under C_2 treatment than that in C_0 and C_1 treatment during the year 2012 and 2013. However at deeper depths, higher root mass density was observed under C_0 treatment than that in C_1 and C_2 treatment. The root mass density was higher under N_2 treatment than that in N_0 and N_1 treatment due to higher plant growth as a result of proper nutrition of maize crop.

The C_2 treatment reduced heat use efficiency (HUE) by 15.2 and 20.9 percent than that in C_0 treatment during the year 2012 and 2013, respectively. The N_2 treatment improved the HUE by 15.2 and 14.3 percent than that in N_0 treatment during the year 2012 and 2013, respectively.

In the year 2012, mean soil water storage was more under C_2 treatment than that in C_0 and C_1 . Nitrogen fertilization had shown negative effect on water storage. Each additional dose of nitrogen had lead to more vegetative growth i.e. leaf area and plant height, which ultimately lead to more ET losses.

Water productivity was 17.5 and 31.6 per cent higher under C_0 treatment than that in C_2 treatment during the year 2012 and 2013, respectively. Water productivity was higher under N_2 treatment than that in N_0 treatment; however water productivity was at par in N_1 and N_2 treatments during the year 2012 and 2013. The interactive effect of subsoil compaction and nitrogen fertilization was non-significant for water productivity.

The slope steepness treatments S_0 - leveled field, S_1 - 0.5% slope steepness and S_2 - 1.0% slope steepness under subsoil compacted condition were tested for their effect on yield of maize. The D_b of surface 0-15 cm soil layer was not significantly different among various treatments during the year the 2012 and 2013. However the D_b for 15-30 cm subsoil layer was significantly higher under C_2 treatment than that in C_0 and C_1 treatment during the year 2012 and 2013. Slope steepness did not significantly affect the D_b . The D_b of 30-45 cm subsoil layer followed almost similar trend as that of 15-30 cm subsoil layer, except the D_b under this layer was less than that in layer above. The Penetration resistance (PR) PR of C_2 treatment at 15-30 cm subsoil layer was significantly higher than that in C_0 and C_1 treatment. The PR was higher under C_2 treatment than that in C_0 and C_1 treatment. The PR values were higher at 15-30 cm soil depth than that in 0-15 cm surface layer. The total porosity followed the similar trend of bulk density at all the soil depths. Porosity was higher under C_0 treatment than that in

C₁ and C₂ treatment at all depths during the years 2012 and 2013. The porosity values were significantly higher under C₀ treatment than that in C₁ and C₂ treatments at 15-30 cm and 30-45 cm soil depth.

The cumulative infiltration decreased with the increase in the subsoil bulk density. There was 2.01 times and 2.26 times decrease in infiltration rate under C₂ than that in C₀ treatment during the year 2012 and 2013, respectively.

Plant height decreased significantly with the increase in the strength of subsoil layer at 30, 60 DAS (days after sowing) and at harvesting stage. Slope steepness did not significantly affected the plant height at 30, 60 DAS and at harvesting stage.

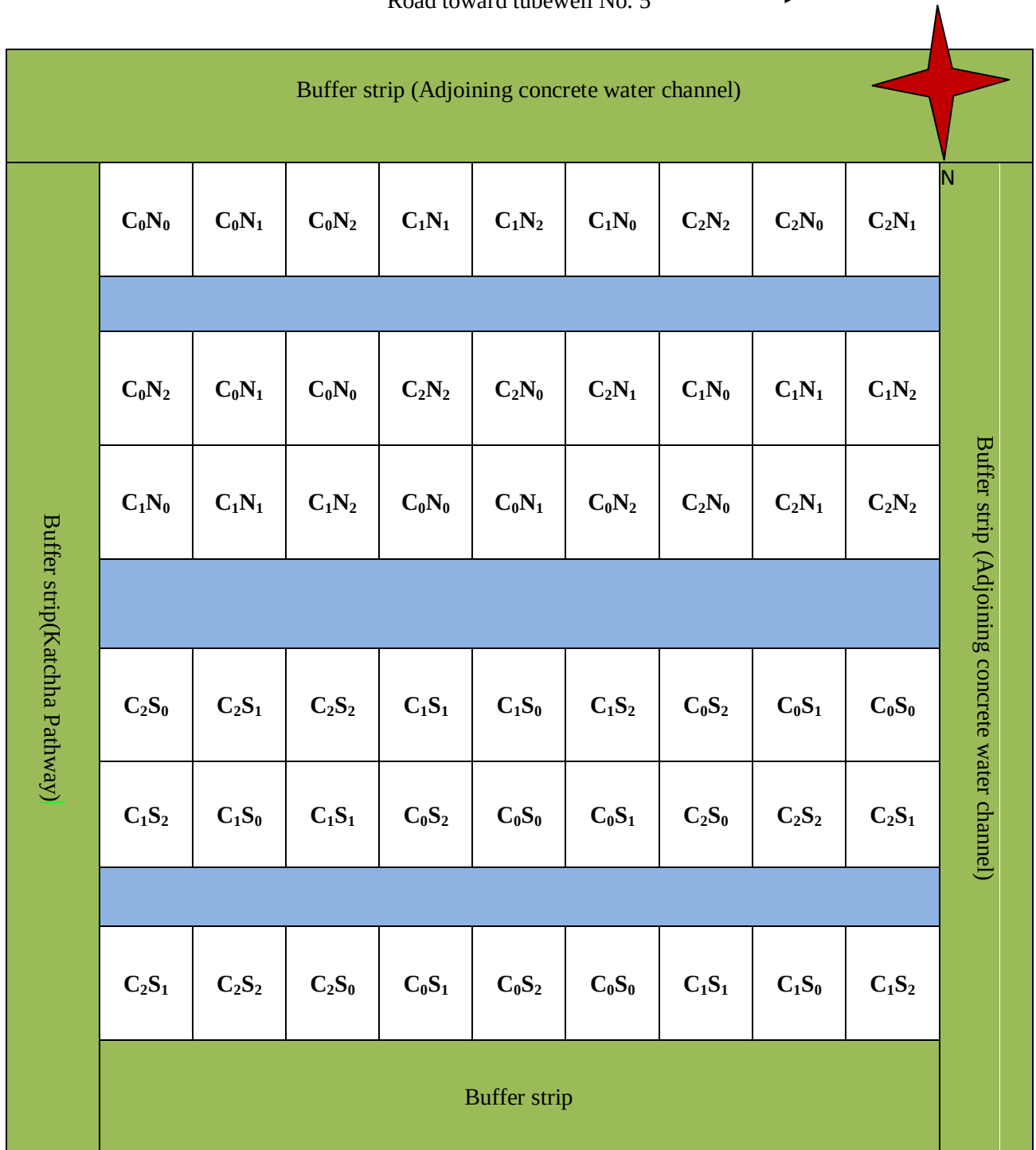
Slope steepness treatment S₂ had improved maize yield by 5.6 to 19.8 per cent than that in S₀ treatment. Biomass yield of maize was significantly higher under C₀ than that in C₁ and C₂ treatments. The biomass yield from treatments C₁ and C₂ were statistically at par among themselves during the year 2012 and 2013. Biomass yield was significantly higher under higher slope steepness than that in without slope. Subsoil compaction and slope steepness significantly affected cob barrenness. The barrenness was 13.97 and 33.6 per cent higher under C₂ treatment than that in C₀ treatment during the year 2012 and 2013, respectively. Cob barrenness was 16.24 and 50.6 per cent higher under C₂ treatment over C₁ treatment during the year 2012 and 2013, respectively. The cob barrenness was lower by 14.4 per cent in S₂ than that in S₀ during the year 2013.

Conclusively, subsoil compaction affected soil physical properties, plant growth and yield, while N fertilization positively affected plant growth and yield of maize. The 25 per cent higher N could be applied over the recommended N to obtain higher maize yield under subsoil compaction affected soil. The study pointed out that there is need to adopt an integrated approach involving soil, land and agronomic practices those could lead to a simultaneous increase in yield, N use efficiency, N uptake, greater dry matter (DM) production and balanced partitioning of N and DM during grain filling. Thus, it suggests exploring innovative soil, land and agronomic management strategies those could be fine-tuned to enhance yield and nitrogen use efficiency by balancing dry matter and N accumulation between the vegetative and reproductive stages of plant growth.

APPENDIX

Layout plan

Road toward tubewell No. 5 →



Plot size= 6.4 m × 4.2 m

Water channel= 1 m wide

VITA

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