Models for crop parameters due to normal load of tractor and number of passes

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Abstract: Multiple passage of power machinery system particularly heavy machines with high wheel loads creates sub-soil compaction which results into increasing in soil bulk density & penetration resistance and reduction in crop germination, growth as well as yield. This study was conducted to determine the wheat crop growth and yield models could be developed to predict growth as well as yield of crop considering normal load and number of passes of tractor. A 36-plot experiment consisting of 12 treatments with three replications were set up using a randomized block design in a uniform field of Division of Agricultural Engineering, IARI, New Delhi. Prediction models were developed between compaction parameters (normal loads and number of passes) and crop parameters like (a) plant height, (b) number of plants per meter, and (c) yield. Further, another relationship between crop yield and sub-soil bulk density and penetration resistance were established and their sensitivity analysis was done. The best fit model for plant height and number of plants per meter row was quadratic. However, the best fit models between yield vs soil bulk density and yield vs penetration resistance for critical layer and whole soil were exponential and quadratic, respectively. The developed model is not more sensitive for number of plants per meter row and yield vs soil bulk density. However, model was more sensitive to plant height model as well as yield vs soil penetration resistance.

Keywords: sub-soil compaction, wheel trafficking, normal load, yield and crop model

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1 Introduction

Sub-soil compaction in agricultural fields is a worldwide problem which causes soil degradation and affects crop yield. Multiple passage of power machinery system particularly heavy machines with high wheel loads results into formation of compact layer at sub-surface called hard pan (Patel and Mani, 2011), which adversely affects crop yield. Soil compaction also reduces soil porosity and oxygen movement to root surfaces (Al-Adawi and Reeder, 1996; Hillel, 1998; Da silva et al., 2003; Raper, 2005; Hamza and Anderson, 2005). In fact, the sub-soil compaction and its detrimental effect is site specific and is generally influenced by edaphic, climatic, environmental factors in addition to manmade factors including soil management practices. In India, due to increasing use of tractors and heavy machinery system particularly rotavator, laser leveler and baler the production of high power (>60 hp) tractors is increasing (Singh and Mani, 2009) which may aggravate the problem

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of hardpan formation particularly in loam and clay loam soil condition (Patel and Mani, 2011). The adverse effect of hard pan includes limited nutrient uptake, reduced infiltration and reduced exchange of air and gases which may lead to less emergence of seedling and improper development of root (Arvidsson et al., 2001; Ishaq et al., 2001). This finally results into poor yield of crops (Arvidsson et al., 2001; Radford et al., 2001; Dauda and Samari, 2002).

As sub-soil compaction also leads to other adverse effects like increased bulk density & penetration resistance, reduced root development which results into reduction in yield (Grzesiak et al., 2013; Cambi et al., 2015; Igoni and Ayotamuno, 2016; Sivarajan et al., 2018; Patel et al., 2020). If crop growth parameters and yield will be predicted by a model, it will help to understand the effect of farm machinery load and number of passes.

Modelling not only provides a better way to quantify the processes involved in the soil compaction but also helps us to predict the vulnerability of a particular soil to compaction. Modelling is useful in the organization and integration of existing knowledge and identification of gaps in knowledge. Modelling is a simulation of all the processes involved in the soil compaction but soil compaction depends on a lot of parameters and considering each parameter is difficult for heterogeneous structures of the soil. Modelling of the effects of the soil compaction on the environment and plant growth are reviewed and discussed in detail in literature (Grant, 1993; Clausnitzer and Hopmans, 1994; O'Sullivan and Simota, 1995). Several attempts have been made to model the effects of mechanical operations on the soil (Blackwell and Soane, 1981; Raper and Erbach, 1990; Dickson and Ritchie, 1993; Défossez and Richard, 2002), but most models have limited applications due to a large number of parameters as input or heterogeneous field conditions. Models can also be classified and discussed as mechanistic or empirical, depending on the treatment of underlying mechanisms, and deterministic or stochastic, depending on the treatment of variability (O'Sullivan and Simota, 1995).

The aim of the study was to determine the wheat crop growth parameters and yield models due to normal load, number of passes, bulk density and penetration resistance of sub-soil.

2 Materials and methods

A 36-plot experiment consisting of 12 treatments with three replications were set up using a randomized block design in a uniform field of Division of Agricultural Engineering, IARI, New Delhi during the period of 2007-08. The study area is situated at 28.38 ^{0}N, 77.2 ^{0}E and is at an altitude of 228.7 m above sea level. The climate of the study area is semi-arid and subtropical with hot summers and cool winters. The mean monthly maximum and minimum temperatures during the year ranges from 3.9^{0}C to 45.0^{0}C and 6.0^{0}C to 8.0^{0}C, respectively.

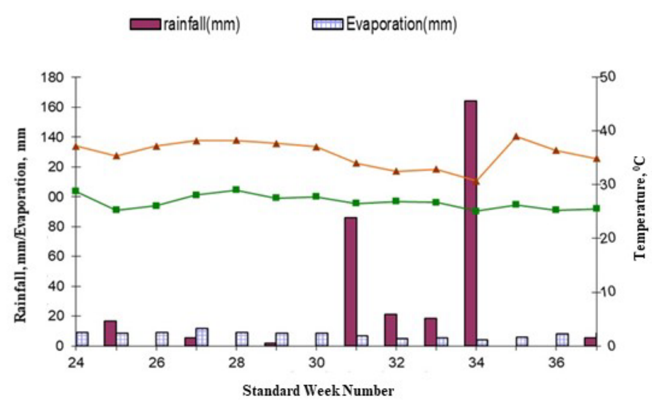

Figure 1 Weekly meteorological data during wheat growth (24th -37th week)

There is an occasional occurrence of frost in December and January. The annual normal rainfall is 708.6 mm of which on an average 597 mm (84%) is received from June to September. The meteorological data during wheat crop growth is given in Figure 1. The soil of the experimental field has been classified as alluvial soil group and is of sandy loam texture. The major characteristics of this soil are given in Table 1.

Total 12 treatment combinations made up of three traction device load, 400 kg, 560 kg and 600 kg (the weights of the standard 2-wheel drive tractors used in the treatments were 1756 kg) and numbers of tractor passes of 1, 6, 11 and 16. The plots of dimension 10 × 5.0 m were separated by alleys of 10 × 1.00 m. These 12 treatment combinations were used in three replicates of a randomized block design. The soil bulk density, penetration resistance and moisture content of the soil samples were collected. The soil samples at randomly selected locations were taken at intervals of 5 cm up to a total soil depth of 30 cm. Soil samples were collected using a core sampler to determine the bulk density and water content of the soil. The penetration resistance was measured using dynamic cone penetrometer consisting of nylon rope of 2.5 m attached to a weight of 0.5 kg mounted over the pulley which facilitated smooth lift of the weight. The movement of weight was guided in a cylinder. The cylinder of the penetrometer, housing was placed in the sleeve of the tripod stand to permit unidirectional motion. The diameter and height of the cylinder was kept as 10 cm and 75 cm, respectively with the effective cylinder height of 50 cm. The cylinder was attached with 2.1 cm diameter cone rod and tip angle of cone was kept as 30 degree. The penetrometer was set level vertically at the predetermined location by positioning the tripod legs. After ensuring freefall of the weight, 10 numbers of strokes were given so as to flush the cone base with the soil surface. The number of strokes was recorded for a cumulative penetration up to 50 cm of depth. This approach generated an average resistance (J cm^{-1}) across the depth the cone travel. At a fixed forward speed tractor was run at a particular load and number of passes. The whole plots were covered with tire paths of the assigned load and number of passes. In the same manner other treatments i.e. number of passage and corresponding loads in all plots were completed. After completing the soil compaction, the top soil layer i.e. 10 cm was tilled in each treatment and level for sowing of wheat crop. The bulk density and penetration resistance were maximum at 20 cm soil depth. In this paper the maximum bulk density and maximum penetration resistance are called critical layer bulk density and critical layer penetration resistance.

The sowing of wheat crop was done with tractor drawn seed-cum-ferti drill. The variety of wheat crop was PBW 343. The number of rows in seed drill were 11. Standard agronomical practices were followed for the application of fertilizers (NPK-120, 60 and 40 kg ha^{-1}) and herbicides. The crop parameters such as germination count, tiller count, plant height, and grain yield were measured. The germination count was recorded after 18 days of sowing. Number of plants per meter row and number of tillers per plant was measured after 90 days of sowing. The grain yield was measured after harvesting the crop.

Table 1 Particle size distribution (sandy loam to loam)

Depth, cm	Coarse sand, %	Fine sand, %	Coarse silt, %	Fine silt, %	Clay, %
0-21	1	49	25	12	13
21-52	1	54	24	9	12
52-93	1	54	21	10	14

A SPSS package was used for multiple regression analysis to predict the bulk density in terms of input variables. Out of linear, exponential and power curves the best fit was selected on respective values of correlation coefficient. Models were developed according to data obtained from field.

3 Results and discussions

3.1 Models for plant height

Average values of plant height (*H*) in each plot at 20, 40, 60, 80, 100 and 120 days were compared and the regression model was developed. The different models like linear, exponential, logarithm and polynomial were tested. The multiple regression was also checked and it was found that coefficient of determination was less than $n×L$ (combined effect) model. The developed best fit regression model is

$$H= C_o+C_1(n×L)+C_2(n×L)^2 \quad (1)$$

Where, H= height, cm; n=number of passes; L= load, kg and C_0, C_1 and C_2 are regression coefficients. The value of C_0, C_1 and C_2 for 20, 40, 60, 80, 100 and 120 days along with the regression coefficients and probability levels are listed in Table 2. Using the data, overall models plant height in terms of the traffic variables (product of number of passes, n, and load, L in kg) and the days after seeding were established. The model was not significant for initial 20, 40, 60 and 80 days after sowing of crop. It might be due to uniform soil conditions. However, it was significant after 80 days of sowing because increase in bulk density and penetration resistance of critical layer resulted in the higher concentration of roots in the upper part of the subsoil layer and in reduced rooting in the deeper layers. Same trend was reported by Patel et al. (2020).

Table 2 Regression coefficients for plant height in Equation 1 for 20, 40, 60, 80, 100 and 120 days after seeding

Days	Plant height (cm)				
	C_0	C_1	C_2	R^2	*p*-value
20	18.810	-2.789	-9.561×10^{-8}	0.522	0.136
40	30.153	0.000	-1.179×10^{-8}	0.264	0.251
60	43.168	0.000	6.263×10^{-9}	0.269	0.245
80	63.387	0.000	-1.508×10^{-8}	0.382	0.115
100	80.876	0.000	-1.359×10^{-8}	0.620	0.013
120	84.088	0.000	8.092×10^{-8}	0.600	0.016

3.2 Models for number of plant per meter row

Average values of plant per meter (N) in each plot at the time of harvesting was compared and the regression model was developed which includes interaction of number of passes and normal load. Initially, the number of plant per meter row was almost same but after 40 DAS (days after sowing) it was varied due to better growth and condition which resulted into more tiller per plants. The best fit regression model is

$$N = A_0 + A_1 \times n + A_2 \times L + A_3 \times n \times L \quad (2)$$

Where, N= plant per meter row, n=number of passes, L= load, kg and A_0, A_1, $A_2$and A_3 are regression coefficients. Using the data, overall model for plant per meter in terms of the amount of sub-soil compaction was established. Similar model was developed by Raghavan et al. (1979). The value of regression coefficients is given below:

$A_0 = 146.1133$, $A_1 = -0.7633$, $A_2 = -0.023$, $A_3 = 0.0005$, $R^2 = 0.973$ and $R^2_{adj} = 0.962$

The *p*-values of A_0, A_1, A_2, A_3 and model are0.0488, 0.0086, 0.4668 and 0, respectively. The model is significant for all the variables except interaction. It showed that number of plant per meter row did not depends on interaction of number of passes and normal load ($n \times L$). Hence model is $N = A_0 + A_1 \times n + A_2 \times L + A_3 \times n \times L$.

3.3 Model for predicting yield due to different traction load and number of passes

Average values of wheat yield in each plot were compared and a two types of multiple regression equations were developed by considering the number of passes and different load on tractor. In one model n and L are factors. However, in other model (combined effect) was developed by considering the amount of soil compaction (product of number of passes, n, and load, L in kg). The second model was tried to study because Patel and Mani (2011) found that combined effect (n * L) has more pronounced effect to sub-soil compaction. A similar model was reported by Raghavan et al. (1979). The regression models are

$$Y = B_0 + B_1 \times n + B_2 \times L \quad (3)$$

$$Y = D_o + D_1 \times (n \times L) + D_2 \times (n \times L)^2 \quad (4)$$

Where, Y= yield, kg, n= number of passes, L= load, kg, B_0, B_1 and B_2 and D_0, D_1 and D_2 are the regression coefficients and probability levels are listed in Table 3 and Table 4.

3.4 Model for predicting yield versus critical layer bulk density and average bulk density

Average values of wheat yield in each plot at critical layer bulk density i.e. sub-surface bulk density (*CBD*) and average bulk density (across the depth) (*ABD*) were compared. The critical layer bulk density was observed at soil depth of 0.20 m in each treatment combination while average bulk density was taken across 0.50 m soil depth. A statistical regression models between critical layer bulk density and yield and average bulk density and yield were developed. A best fit statistical model was selected. An exponential model was observed best for both cases. Similar model was reported by Patel et al. (2020). The regression models are

$$Y_1= E_0e^{E_1 CBD} \quad (5)$$

$$Y_1= F_0e^{F_1 ABD} \quad (6)$$

Where, Y_1= yield, kg ha^{-1}, CBD and ABD are critical layer bulk density, mg m^{-3} and average bulk density, mg m^{-3}, E_0 and E_1 and F_0 and F_1 are the regression coefficients and probability levels are listed in Table 5.

Table 3 Parameters of regression models of Equation 3

Model	Unstandardized coefficients		Standardized Coefficients	t	*p*-value	R^2	Std. error of the estimate
	B	Std. Error	Beta				
Constant	6519.726	193.364	-	33.717	<0.001	0.971	64.611
n	-49.532	3.336	-.848	-14.846	<0.001		
L	-3.335	.381	-.501	-8.760	<0.001		

Table 4 Parameters of regression models of Equation 4

Model	Unstandardized coefficients		Standardized Coefficients	t	*p*-value	R^2	Std. error of the estimate
	D	Std. Error	Beta				
Constant	4898.590	110.573	-	44.302	<0.001	0.820	160.043
$n\times L$	-0.124	0.060	-1.082	-2.071	0.068		
$(n\times L)^2$	2.345×10^{-6}	0.000	0.185	0.354	0.731		

Table 5 Parameters of regression models of Equations 5-6

Model	Unstandardized Coefficients		Standardized Coefficients	t	*p*-value	R^2	Std. error of the estimate
	B	Std. Error	Beta				
			Average bulk density (BD) at 50 cm depth of soil				
BD	-2.061	.224	-.946	-9.212	<0.001	0.895	0.026
Constant	102471.695	34978.661	-	2.930	0.015		
			Maximum bulk density (BD) at 20 cm depth of soil				
BD	-1.510	0.166	-0.945	-9.123	<0.001	0.893	0.027
Constant	50199.826	13377.388	-	3.753	0.004		

3.5 Model for predicting yield versus critical layer cone penetration energy per meter and average cone penetration energy per meter

Average values of wheat yield in each plot at critical cone penetration energy per meter (*CCPE*) and average cone penetration energy per meter (*ACPE*) were compared and the results are shown in Figure 1. The critical cone penetration energy per meter was observed at soil depth of 0.20 m in each treatment combination while average cone penetration energy per meter was taken across 0.50 m soil depth. A statistical regression models between critical cone penetration energy per meter and yield and average cone penetration energy per meter and yield were developed. A best fit statistical model was selected. A quadratic model was observed best for both cases. The regression models are

$$Y= A_{00}+A_{11}CCPE+A_{22} (CCPE)^2 \quad (7)$$

$$Y= B_{00}+B_{11}ACPE+B_{22} (ACPE)^2 \quad (8)$$

Where, Y=yield in kg, CCPE, and ACPE penetration energy per meter = J m^{-1}, A_{00}, A_{11} and A_{22} and B_{00}, B_{11} and B_{22} is the regression coefficients and probability levels are listed in Table 6.

From the Table 6 it is clear that both the models are significant and their coefficient of determination are 0.910 and 0.957. However, in second model *CCPE*^{2} was not significant. It might be root penetrated due to low intensity of compaction level by different treatments. The moisture content was almost same in all the treatment. Plant germination was not significant because up to 20 cm soil depth the soil was tilled to know the subsoil effect. Similar model was reported by Raghavan et al. (1979).

3.6 Sensitivity analyses

3.6.1 Number of plant per meter row

A sensitivity analysis was carried out for the parameters influencing the number of plant per meter row estimation, viz., number of pass and normal load. While performing the sensitivity analysis, all the parameters were varied in a definite ratio (i.e. increasing or decreasing the parameters by 5% to its estimated values). This variation was randomly chosen and any other variation could have been opted. It was observed that at increasing of 5% in nL (number of pass*normal load) the variation in plant per meter row was 0.69% (maximum) and -2.10% (minimum) whereas at some point the same was decreased and increased (Figure 2). Again it was observed that at decreasing of 5% in nL (number of pass*normal load) the per cent variation in plant per meter row was 0.49% (maximum) and -2.15% (minimum). Hence, the same variation in the parameter i.e. number of pass and normal load the variation in is not more sensitive to number of plant per meter row. Similar model was reported by Raghavan et al. (1979).

Table 6 Parameters of regression models of Equations 7 - 8

Model	Unstandardized Coefficients		Standardized Coefficients	t	*p*-value	R^2	Std. error of the estimate
	B	Std. Error	Beta				
Average cone penetration energy (ACPE) at 50 cm soil depth							
ACPE	-744.122	265.837	-7.194	-2.799	0.021		
$ACPE^2$	7.567	3.098	6.277	2.442	0.037	0.910	113.106
Constant	22283.196	5678.436	-	3.924	0.003		
Critical cone penetration energy (CCPE) at 20 cm soil depth							
CCPE	-271.230	210.819	-2.005	-1.287	0.230		
$CCPE^2$	2.458	3.725	1.028	0.660	0.526	0.957	77.705
Constant	10146.828	2967.178	-	3.420	0.008		

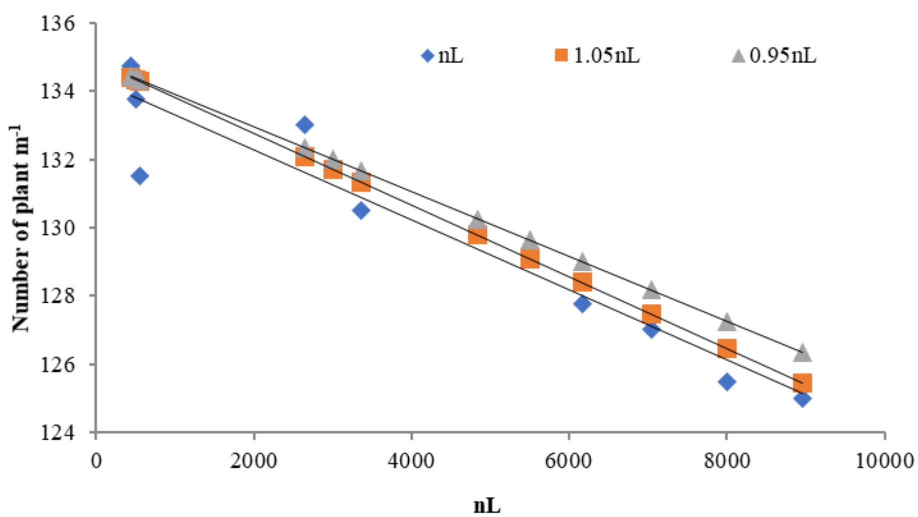

Figure 2 Sensitivity of plant per meter with nL

3.6.2 Plant height

It was observed that the increasing or decreasing of 5% in nL the maximum per cent variation in plant height was initial 20 DAS (Table 7). It is observed that for the same variation in nL, the variation in height is less sensitive to increasing the parameters. The height was reduced because increased in bulk density and penetration resistance of sub-soil which affect the root growth of wheat crop. However, after 80 DAS height was significant because after 80 DAS bulk density and penetration resistance of soil affect the root growth of wheat crop by different treatment. Similar, results were reported by Ishaq et.al. (2001), Nawaz et al. (2013), and Patel et al. (2020).

3.6.3 Grain yield

(1) Normal load and number of pass

It was observed that the increasing or decreasing of 5% in nL (Interaction of normal load and number of passes) the yield variation was decreasing and increasing pattern.

The model was consistence because variation is very low (Figure 3). From the figure it is clear that for the same variation in nL, the variation in wheat yield is not more sensitive to increasing as well decreasing the parameters.

The variation is very low because it is interaction model of normal load and number of passes. Similar result was reported by Sivarajan et al. (2018), Patel et al. (2020), and Bartzen et al. (2019).

Table 7 Sensitivity of plant height to translation

	20 DAS	40 DAS	60 DAS	80 DAS	100 DAS	120 DAS
			5% increase in nL			
Max. variation	43.34	5.78	5.95	4.21	2.52	2.35
	(1, 5.6 kN)	(1, 5.6 kN)	(1, 5.6 kN)	(1, 5.6 kN)	(1, 5.6 kN)	(1, 5.6 kN)
Min. variation	-2.14	-7.17	-9.49	-10.61	-11.64	-19.59
	(1, 5.6 kN)	(6, 5.6 kN)	(16, 5.6 kN)	(16, 5.6 kN)	(16, 5.6 kN)	(16, 5.6 kN)
			5% decrease in nL			
Max. variation	34.58	5.78	5.95	4.21	2.52	2.35
	(16, 560 kN)	(1, 4.4 kN)	(1, 4.4 kN)	(1, 4.4 kN)	(1, 4.4 kN)	(1, 4.4 kN)
Min. variation	-2.19	-6.80	-9.24	-11.04	-11.94	-17.89
	(1, 5.6 kN)	(1, 5.6 kN)	(1, 5.6 kN)	(1, 5.6 kN)	(1, 5.6 kN)	(1, 5.6 kN)

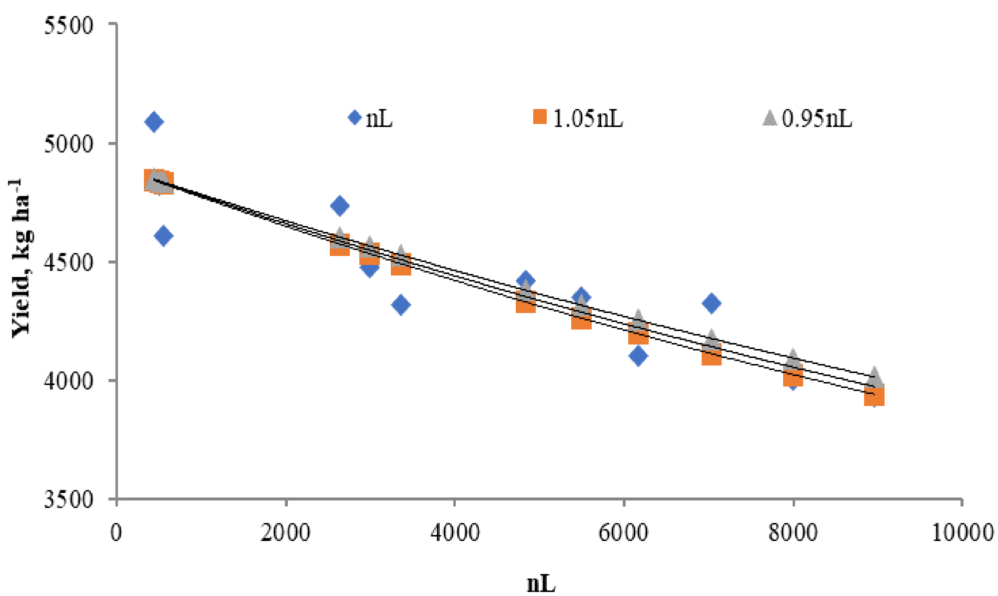

Figure 3 Sensitivity of wheat yield with of nL

(2) Critical bulk density

The effect of variation in 5% in critical bulk density is shown in Figure 4. It is clear that for the same per cent variation in the parameter i.e. critical bulk density, the per cent variation in yield is more sensitive to decreasing the parameters. The yield was reduced because root was spread into surface zone due to high bulk density sub-surface layer. Other reason might be due to no use of sub-surface moisture content of soil because penetration of root was decreases due to increase in critical bulk density. Similar results were obtained by Igoni and Ayotamuno (2016), Sivarajan et al. (2018), and Patel et al. (2020).

(3) Critical cone penetration resistance

From the Figure 4, it is clear that the increasing or decreasing of 5% in critical cone penetration resistance the yield was decreasing and increasing. The yield increased with decrease of critical cone penetration resistance whereas, the same was decreased with increase of critical cone penetration resistance (Figure 5). From the figure it is clear that the yield is more sensitive to increasing as well as decreasing the critical cone penetration resistance. Same results were reported by Bartzen et al. (2019) and Patel et al. (2020). The crop yield was reduced due to increase in critical cone penetration resistance of soil. The yield was reduced because the penetration of root was decreased results into spreading of root between surface and sub-surface of soil.

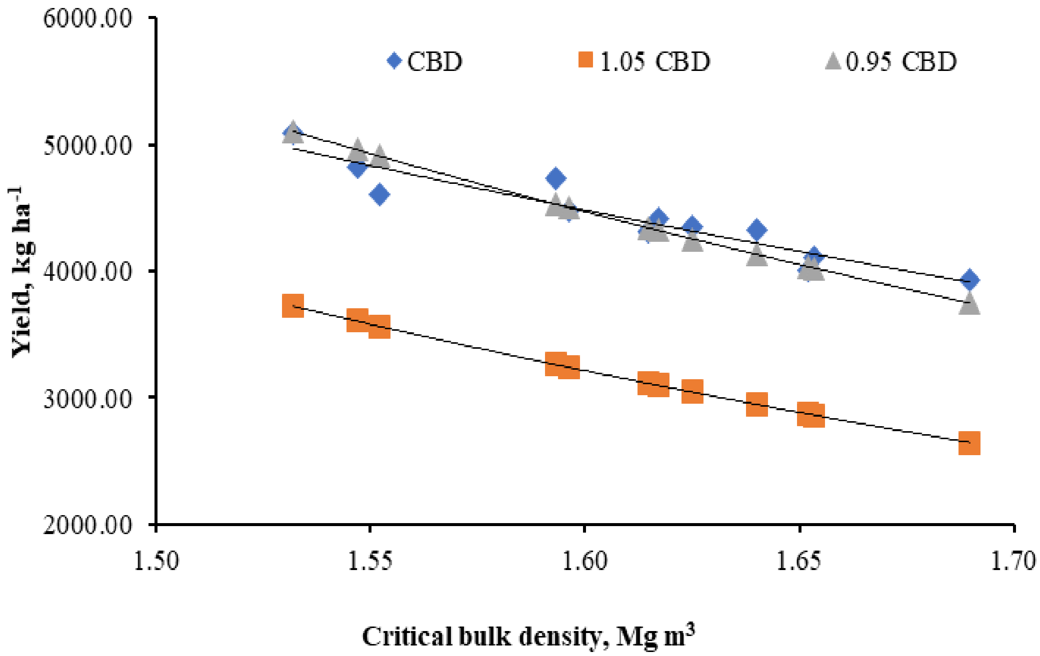

Figure 4 Sensitivity of wheat yield with translation of CBD

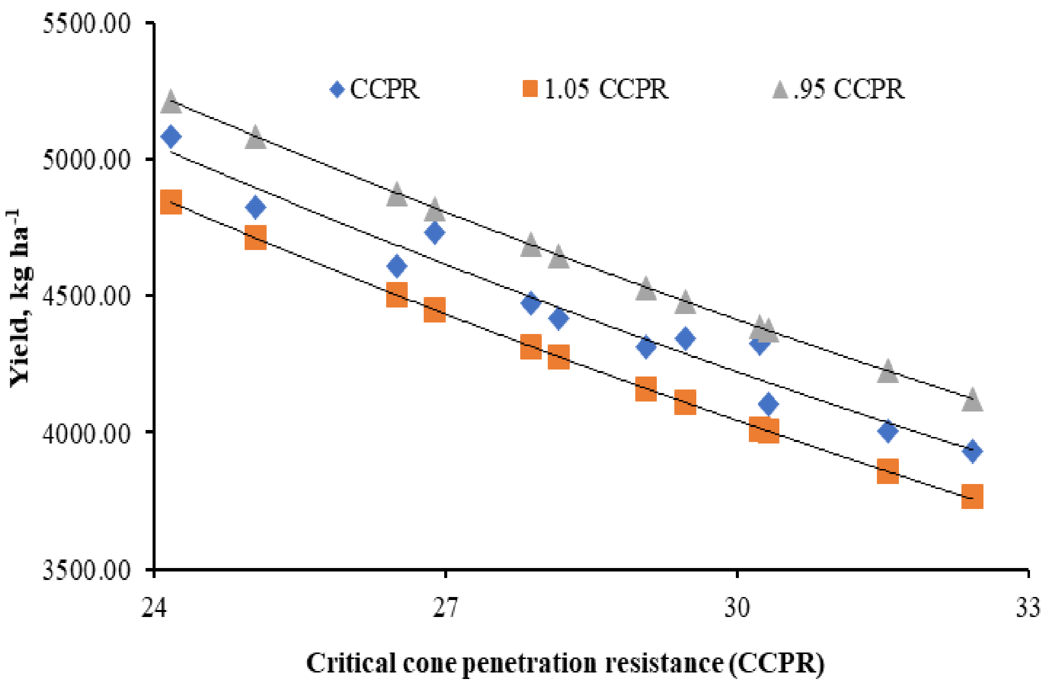

Figure 5 Sensitivity of wheat yield with translation of CCPR

4 Conclusions

Within the limits of the experimental conditions, it can be concluded that:

(1) Repeated traffic and normal load create sub-soil compaction layer which reduces the wheat crop growth and yield. A maximum 17.01% decrease in yield was observed at 6.40 kN normal load from 1 pass to 16 passes.

(2) Highest number of passes have more effect on sub-soil compaction and wheat crop yield than highest normal

load.

(3) Exponential model is best model to present wheat crop yield vs bulk density of soil.

(4) The linear model is best fit model to predict wheat crop yield due to penetration resistance of soil.

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