Soil cone index in relation to soil texture, moisture content, and bulk density for no-tillage and conventional tillage

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Abstract: Soil cone index (CI) is a widely used soil mechanical property to assess soil strength in tillage research. In this study, literature data relating CI to tillage practices are compiled into two datasets, one for no-tillage and the other for conventional tillage. Each dataset is analyzed to examine how CI varies with soil depth, textural parameters, bulk density, and moisture content. The results showed that for both no-tillage and conventional tillage, values of CI decrease with the increase in clay fraction, and increase with the increase in sand and silt fractions of soil. Similarly, higher bulk density and greater soil depth result in higher CI value, while higher moisture content reduces CI. Based on the literature data, regression equations were obtained to estimate CI under no-tillage and conventional tillage systems. In those regression equations, values of CI were linear functions of the other soil variables such as soil textural parameters and moisture content. Those regression equations were validated with field data collected from different sites in Manitoba, Canada. Over half of the results from the regression equations had good agreement with the field measurements, indicated by their relative errors of 20% or lower; however, greater discrepancies were noticed in some cases.

Keywords: Tillage, soil, cone index, bulk density, moisture content, soil texture, regression

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1 Introduction

Tillage for seedbed preparations and weed control changes the soil strength. Tillage operations generally loosen the soil and reduce the soil strength. A common soil mechanical property used to assess soil strength in tillage studies is soil penetration resistance. The standard instrument to measure penetration resistance is cone penetrometer (ASABE, 2006a). The soil penetration resistance measured by a cone penetrometer is also named as soil cone index (CI). CI has been used as an important indicator for soil compaction (Bédard et al., 1997; Tessier et al., 1997), crop root development (Materechera and Mloza-Banda, 1997; Chen et al., 2005), soil

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water infiltration (Busscher et al., 2006; Botta et al., 2006), draft of tillage tools (Manuwa and Ademosun, 2007) and the performance of tractors (Mari et al., 2006).

It has been observed that different tillage management systems resulted in different soil CI (Bauder et al., 1981). Soil CI is usually greater in no-tillage systems than in conventional tillage systems, especially in the top layer (Elhers et al., 1983; Roth et al., 1988; Grant and Lafond, 1993; Chen et al., 2004; Bueno et al., 2006). Soil CI also varies within the soil depth profile. Lower soil CI values are associated with a tilled layer near the soil surface, while higher CI values are associated with a compact soil layer below the tilled layer (Chen and Tessier, 1997; Doan et al., 2005). Yasin et al. (1993) found a cubic relationship between CI and depth.

Soil moisture is an important factor affecting soil CI (Yasin et al., 1993; Franzen et al., 1994). Typically drier soil has higher CI values (Tekeste et al., 2008; Francis et al., 1987). Busscher et al. (1997) found an inverse linear relationship between CI and moisture content, while Ohu et al. (1988) found an exponential relationship between CI and moisture content for loam and clay soils. Soil CI is also related to soil bulk density and soil textual parameters. Ayers and Perumpral (1982) reported a direct relationship between CI and bulk density. Hummel et al. (2004) used clay fraction of the soil as a significant variable in predictions of CI. Silt fraction was recognized as a significant modifier of CI (Jones, 1983).

Cropping system also affects soil compaction or CI. Grant and Lafond (1993) reported that inclusion of pea in crop rotation had a moderating effect on the soil CI, whereas inclusion of flax caused the increased soil CI. In measuring field CI, Doan et al. (2005) observed that pea as a previous residue resulted in less compacted or soft soil than canola or wheat. Through reviewing soil compaction in cropping systems, Hamza and Anderson (2005) indicted that one of the means for reducing soil compaction is to include plants with deep and strong taproots in crop rotations. Fallow land is also effective in reducing soil CI (Lampurlanés and Cantero-Martínez, 2003).

In summary, soil CI is related to soil physical properties such as soil textual parameters (e.g., sand, silt. and clay content), moisture content, bulk density, and cropping system, along with tillage practices (Taylor and Gardner, 1963; Camp and Lund, 1968; Perumpral, 1987). Most research in the past focused on the relationships between soil bulk density and soil textural parameters (Chen et al., 1998; Reichert et al., 2009). Existing studies on relationships between soil CI and other parameters focused only on CI versus soil moisture content. Also most existing research separated the effect of tillage on CI from the effect of soil physical properties on CI.

Large numbers of CI data from different tillage practices are available in the literature. Synthesis of those literature data to examine CI in relation to each of the soil physical properties will provide important insight into the soil strength change with soil physical properties and tillage types, which will ultimately lead to the design of improved tillage equipment and tillage practices. The objectives of this study were to (1) investigate soil CI in relation to individual soil physical properties under no-tillage and conventional tillage systems based on the published data, (2) develop regression equations to relate CI to soil properties under these two tillage systems, and (3) validate the regression equations using field data collected in this study.

2 Material and methods

2.1 Compilation of the literature data

2.1.1 Limitations associated with data collection

Literature on soil CI related to tillage studies since 1980 was reviewed to compile a database of soil cone index. Those studies were conducted under different tillage systems and soil conditions. As a result it was difficult to group CI values for all types of tillage systems and all conditions due to lack of sufficient data. Therefore, the database covered only two contrasting tillage systems: no-tillage and conventional tillage.

From literature, soil physical properties such as soil texture, moisture content, and bulk density were selected since they influence the CI most. The data sources which provided the required information for the database are listed in Table 1. The collected data subjected to the following major limitations: i) most of the CI studies in this database were conducted in USA and Canada; ii) studies were carried out under different soil, crop and weather conditions; iii) data were taken at different times following tillage operations. All these limitations may have effects on the accuracy of CI data. The purpose of this study was not to predict the CI with other soil properties, but to examine the trends of CI variations with individual soil properties under two contrasting tillage systems.

Table 1 Description of literature data sources for the database

Author	Location	Soil texture	Tillage type[1]
Bauder et al., 1981	MN, USA	Nicollet clay loam	CT (plow, chisel), NT
Brye et al., 2004	AR, USA	Stuttgart silt loam	CT (disk harrow, chisel, cultivator)
Busscher et al., 1995	SC, USA	Norfolk loamy sand	NT
Busscher et al., 1997	SC, USA	Norfolk loamy sand	CT (disk harrow)
Busscher et al., 2000	SC, USA	Goldsboro loamy sand	CT (disk harrow)
Busscher and Bauer, 2002	SC, USA	Norfolk loamy sand	CT (disc harrow, shank para till)
Carter, 1987	PEI, Canada	Sandy loam	CT (plow), NT
Chaplin et al., 1986	MN, USA	Hubbard loamy sand	CT (plow, chisel), NT,
Chen et al., 2004	MB, Canada	Red River clay	NT, CT (cultivator)
Ehlers et al., 1983	Germany	Grey brown podzolic (Silt)	CT (plow, harrow)
Grant and Lafond, 1993	SK, Canada	Clay	CT (chisel), NT
Hammel, 1989	ID, USA	Silt loam	CT (plow, chisel), NT
Hill, 1990	MD, USA	Bertie silt loam	CT (plow, disk harrow), NT
Karayel and Ozmerzi, 2002	Turkey	Silty loam	CT (chisel, disk harrow)
Larney and Kladivko, 1989	IN, USA	Chalmers silty clay loam	CT (plow, disk harrow), NT
Lopez-Fando et al., 2007	Spain	Loamy sand	CT (plow), NT
López et al., 1996	Spain	Silty clay loam	CT (plow, disk harrow), NT
Materechera and Mloza-Banda, 1997	Malawi	Sandy clay loam	CT (Disk harrow), NT
McFarland et al., 1990	TX, USA	Weswood silt loam	CT (disk harrow), NT
Mielke et al., 1984	NE, USA	Alliance silt loam	CT (plow)
Moreno et al., 1997	Spain	Sandy clay loam	CT (plow, chisel)
Osunbitan et al.,2005	Nigeria	Oxic Tropudalf	NT, CT (disc plow)
Pierce et al., 1992	MI, USA	Riddles loam	CT (chisel), NT
Singh and Malhi, 2006	AB, Canada	Black Chernozem, Gray Luvisol	CT (rotary tiller), NT
Siri-Prieto et al., 2007	AL, USA	Dothan loamy sand	CT (chisel, disk harrow), NT
Tessier et al., 1997,	QC, Canada	Orthic Gleysoil	CT (plow, cultivator)
Taboada et al., 1998	Argentina	Sandy loam	CT (plow, disk harrow), NT
Unger and Fulton, 1990	TX, USA	Pullman clay loam	NT, CT (sweep plow)

Unger and Jones, 1998	TX, USA	Pullman clay loam	NT
Vetsch and Randall, 2002	MN, USA	Port Byron silt loam	NT, CT (chisel)
Voorhees, 1983	MN, USA	Nicollet silty clay loam	CT (plow, chisel, disk harrow)
Wilkins et al., 2002	OR, USA	Walla silt loam	NT, CT (plow)

[1]CT = Conventional tillage; NT = No tillage.

2.1.2 Data classification

Data were divided into two main categories: no-tillage and conventional tillage. Within conventional tillage, the type of implement and number of passes varied from one data source to another. These, however, were not differentiated, and all data were put in one pool for this category. This was considered not to significantly affect the objectives of this study because of the following support facts. The general purpose of conventional tillage is to create favorable seedbed for plant growth. This may be achieved with one tillage operation or a combination of tillage operations. However, the tillage process remains similar, i.e. changing soil structure by ways of breaking large aggregate clods and back-filling the large void spaces. Given these facts, the change in soil structural parameters (such as soil porosity) is limited within a certain range, regardless of the tillage implements used and the number of passes.

2.1.3 Range of soil depth

In the data sources, measurements were performed at different depths. Data, however, within the tillage depth of interest (200 mm) were included in this study. Tillage depths were often limited to 200 mm for most conventional tillage practices. Thus, only the data within this depth ranges were included in the dataset of conventional tillage. For the no-tillage dataset, data in the same depth range as the conventional tillage were included, so that comparisons could be made between the two tillage systems.

2.1.4 Final database

The final database had two datasets: one for conventional tillage and the other for no-tillage. Each dataset included values of the following variables at different soil depths within 0-200 mm soil profile: CI, clay, silt, and sand fractions, moisture content, and bulk density. Not all of these variables were available in all the data sources selected. In the case of missing soil textural variables, they were derived from the general soil textural class description (Shirazi and Boersma, 1984). For other missing variables, they were treated as missing data.

2.2 Field measurement

In this study, field data were collected to validate the regression equations generated from the literature data. Field measurements were performed at five farms in Manitoba, Canada (Table 2). The first four farms listed in Table 2 had both no-till fields and conventionally tilled fields. Measurements were performed in 2006 in those fields. The fifth farm (Oakville) in Table 2 had existing research plots established for another study; plots of no-tillage and conventional tillage were used for measurements of this study during 2006-2008.

Table 2 Summary of field conditions, Manitoba, Canada

Location	Date of measurement	Number of fields/plots[1]	
		NT	CT
St. Agathe	Sept. 27, 2006	1	1

Winnipeg	Sept. 28, 2006	1	1
Carman	Oct. 2, 2006	1	2
Brandon	Oct. 3, 2006	8	1
Oakville	June 19, 2006	1	1
	Oct. 14, 2006	1	1
	May 12, 2007	3	2
	May 23, 2008	0	3
	May 27, 2008	8	3
	June 20, 2008	0	3

[1]NT = No tillage; CT = Conventional tillage.

Soil cone indices were measured using a Rimik cone penetrometer (Model CP 20, Agridy Rimik Pty. Ltd., Toowoomba, Australia) having cone base area of 129 mm^2 and an apex angle of 30°. The penetrometer was pushed into the soil manually at a speed of about 30 mm s^{-1} (ASABE, 2006b). Measurements were taken at 20 random locations in each field or plot. At each location readings from three randomly selected places were taken at 25 mm intervals up to a depth of 200 mm. Also, soil samples were taken with 50 mm diameter core samplers in the same depth range from six random locations in each field or plot. Soil samples were weighed and oven dried at 105°C for 24 hours and weighed again to determine the dry bulk density and moisture content. Then, the samples were sent to a commercial lab for soil texture analysis.

2.3 Data analysis

Data from the literature were analyzed within the no-tillage dataset and the conventional tillage dataset. First, variations of soil CI with soil depth, textural parameters, bulk density, and moisture content were investigated separately. Secondly, stepwise multiple linear regression procedures were performed on the entire data within each tillage dataset to obtain the relationship between the dependent variable (CI) and the independent variables (depth, textural parameters, moisture content, and bulk density). This procedure screened out the independent variables which did not contribute significantly to the dependent variable. Correlation coefficients were used to evaluate the degree of association between dependent and independent variables. Relative errors were used to assess the agreement of the regression equations with the field measurements.

3 Results and discussion

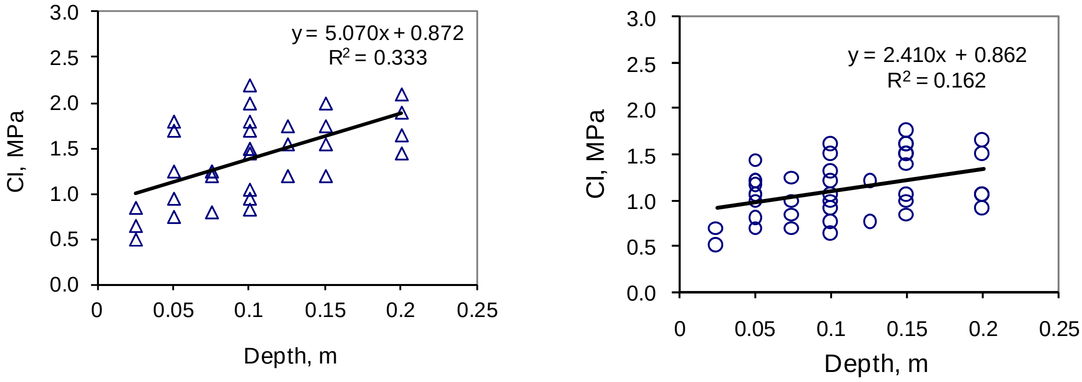
3.1 Trends of the literature data

To examine the variation of CI with soil physical properties, the literature data were plotted between CI and each variable, pooling over all the other variables. Linear trend lines were generated for describing the relationships. The coefficient of determination (R^2) of the trend lines were generally low, which were expected due to greater variability of soil properties among different soils and climate conditions. The intentions were to learn the range of CI variations and the general trends of CI as influenced by different soil physical properties under no-tillage and conventional tillage. The results are discussed in the following sections.

3.1.1 Soil cone index versus soil depth

The literature data showed that overall, no-tillage resulted in higher CI (up to 2.2 MPa) when compared to conventional tillage (up to 1.8 MPa) within the depth profile of 0-200 mm

(Figure 1). Cone indices had a general tendency to increase with soil depth regardless of tillage practices, as reported by Cavalaris and Gemtos (2002). The linear trend line was much steeper for no-tillage than conventional tillage, meaning that CI of no-till soil increased more rapidly with depth (0-200 mm) than that of conventionally tilled soil.

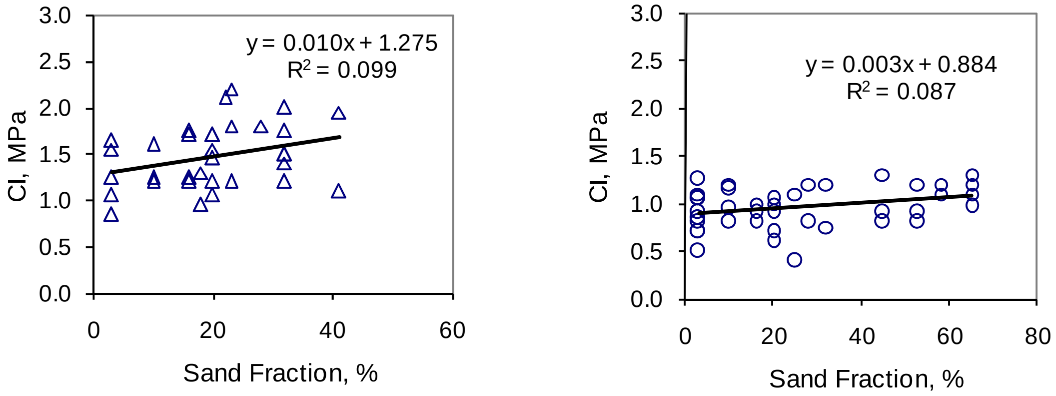


(a) No-tillage (b) Conventional tillage

Figure 1 Soil cone indices (CI) versus soil depth; data were from the literature.

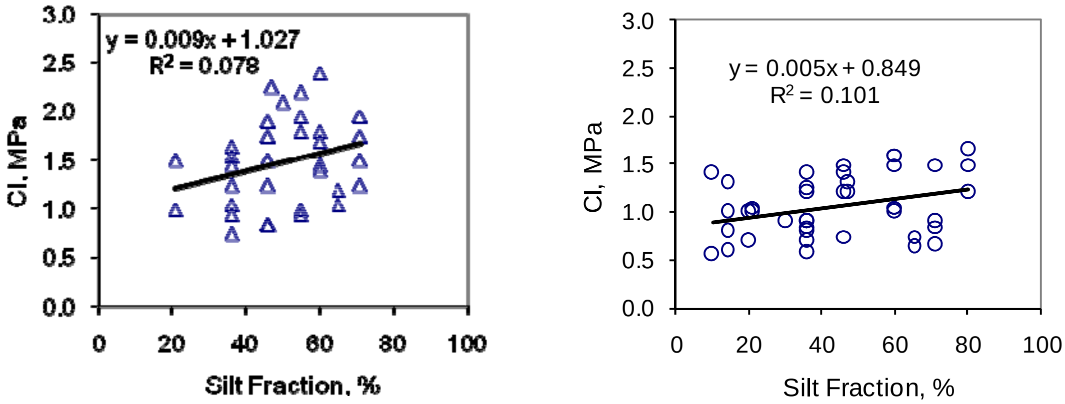
3.1.2 Soil cone index versus soil textural parameters

To provide some insight into effects of soil texture on CI under each tillage system, cone indices and textural parameters in the database were plotted. The range of sand fraction in the no-tillage dataset was 3-41%, and that in the conventional tillage dataset was wider (3-65%) (Figure 2). Values of CI under no-tillage increased with the increase in sand fraction (Figure 2a). Similarly, values of CI under conventional tillage also had a general tendency to increase with the sand fraction (Figure 2b), whereas this trend for conventional tillage was not as obvious as that of no-tillage. Sand particles have relatively higher friction coefficients than silt and clay particles, which may explain the increasing trends of CI with sand fraction. The literature data had a wide range of silt fraction: from 21 to 71% for the no-tillage dataset and from 10 to 80 % for the conventional tillage dataset (Figures 3a and 3b). Trends for the relationships between CI and silt fraction are similar to those between CI and sand fraction. A decreasing trend between CI and clay fraction was observed for both no-tillage (Figure 4a) and conventional tillage (Figure 4b), which was the reverse of trends of CI versus sand and silt fractions. Up to 61% of clay fraction has been found in the literature data.



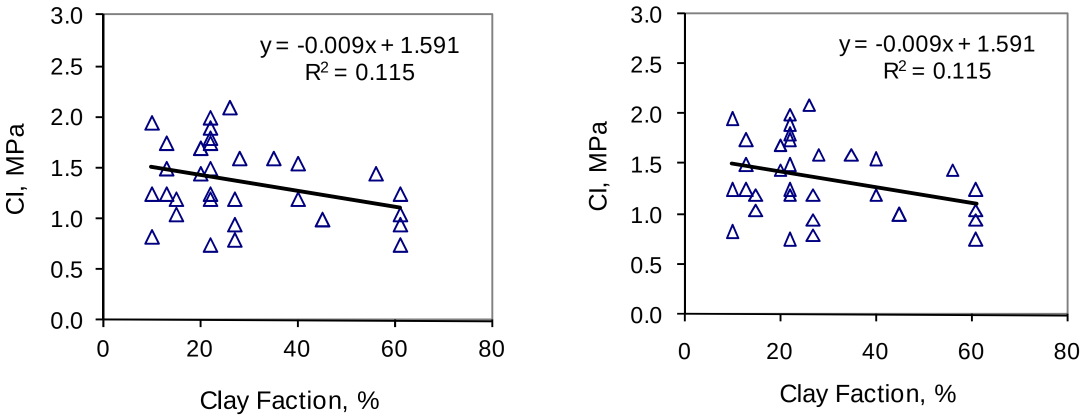
(a) No-tillage (b) Conventional tillage

Figure 2 Soil cone indices (CI) versus sand fraction of the soil; data were from the literature.



(a) No-tillage (b) Conventional tillage

Figure 3 Soil cone indices (CI) versus silt fraction of the soil; data were from the literature.

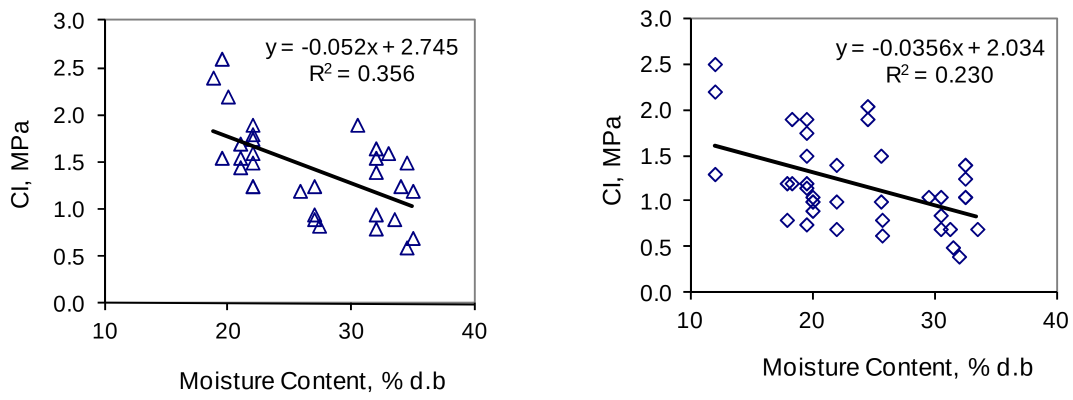


(a) No-tillage (b) Conventional tillage

Figure 4 Soil cone indices (CI) versus clay fraction of the soil; data were from the literature.

3.1.3 Soil cone index versus soil moisture content and bulk density

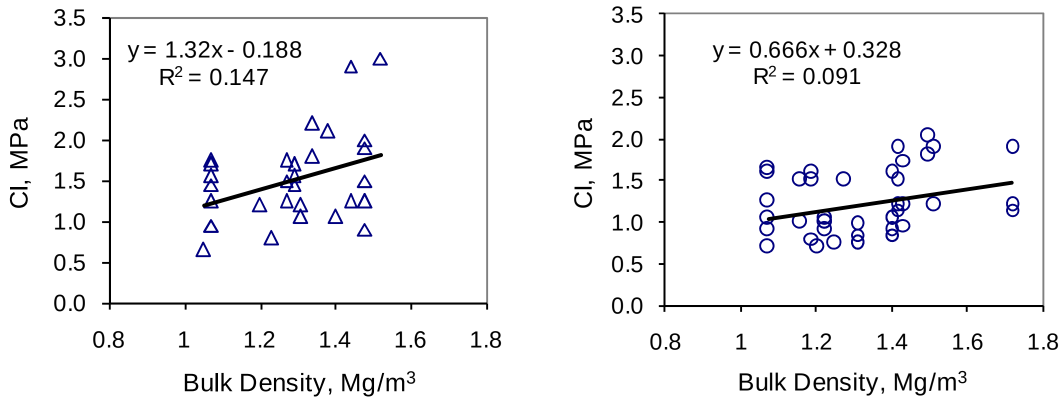
The literature data covered soil moisture content ranging between 18.8 and 34.5% for no-tillage and between 12 and 32.5% for conventional tillage. Values of CI decreased with the increase in moisture content (Figure 5a and Figure 5b), meaning that drier soil results in higher CI, which is in agreement with the findings from other researchers (Ayers and Perumpral, 1982; Busscher et al., 1997; Earl, 1996; Mapfumo and Chanasyk, 1998). The CI trend of no-tillage had a steeper slope, compared to that of conventional tillage, which suggested a greater sensitivity of CI to moisture content in no-till soil. This effect of moisture content on CI may partially explain the aforementioned effects of soil textural parameters on CI. As compared with clay soils, sandy soils have lower water holding capacity and therefore are possibly drier, when other conditions are the same. The potentially dry conditions of sandy soils, together with their high friction coefficients, may have contributed to the increasing trends of CI with sand fraction. Whereas the potentially wet conditions of clay soils may be attributable to the decreasing trends of CI with clay fraction.



(a) No-tillage (b) Conventional tillage

Figure 5 Soil cone indices (CI) versus soil moisture content; data were from the literature.

Soil bulk density in the database varied from 1.05 to 1.52 Mg/m^3 for no-tillage and 1.08 to 1.72 Mg/m^3 for conventional tillage (Figure 6a and Figure 6b). Contrary to the effect of moisture content on CI, values of CI tended to increase with the increase in bulk density under both tillage systems. This is in agreement with previous investigations (Blanchar et al., 1978; Cruse et al., 1981; Stitt et al., 1982; Cassel, 1983; Voorhees, 1983) who reported that CI varied directly with bulk density. Again, data for no-tillage had a steeper slope than those for conventional tillage, meaning that CI of no-till soil is more sensitive to the variation in bulk density.



(a) No-tillage (b) Conventional tillage

Figure 6 Soil cone indices (CI) versus soil bulk density; data were from the literature.

3.2 Regression equations for estimations of soil cone index

Stepwise multiple linear regression analysis was performed to obtain the regression equations showing the relationships between CI and the physical properties. Such regressions were performed separately for the no-tillage and conventional tillage datasets. The results based on the no-tillage dataset showed that CI was not significantly related to clay and silt fractions as well as bulk density, but CI varied significantly with soil depth, sand fraction, and moisture content. Thus, the final regression equation for no-tillage is as follows. The correlation coefficient (r) of the equation was 0.61.

$$CI_{NT} = 2.185 + 0.016\,(sa) - 0.053(mc) + 0.0051(d) \quad (1)$$

Where, CI_{NT} is soil cone index for no-tillage system (MPa); *sa* is sand fraction (%); *mc* is moisture content (%); *d* is depth (mm).

For conventional tillage, the regression analysis identified that only clay fraction and depth were significantly related to CI. The final regression equation for conventional tillage is as follows. The correlation coefficient (r) was 0.47.

$$CI_{CT} = 0.916 - 0.013(cl) + 0.0054(d) \quad (2)$$

Where, CI_{CT} is soil cone index for conventional tillage (MPa); *cl* is clay fraction (%).

Given the limitations of the database mentioned above and the variability of CI data (Heiming, 1987), the correlation coefficients 0.47 to 0.61 for no-tillage and conventional tillage, respectively, may be considered reasonable. The Equation 1 and Equation 2 clearly indicate that soil depth is a significant factor in determining CI, regardless of tillage types. Mixed results were obtained for no-tillage and conventional tillage, in terms of the effects of other variables.

3.3 Validations of the regression equations

Soil CI and other soil properties measured in this study are shown in Table 3. The sites for the measurements covered the ranges of soil texture from 4 to 80 % for sand fraction, from 8 to

48 % for silt fraction, and from 12 to 77 % for clay fraction, the range of soil moisture content from 17 to 42%, the range of bulk density from 0.92 to 1.45 Mg m^{-3}. These wide ranges of soil properties were considered to be good for validating the regression equations.

Table 3 Results of field measurements in Manitoba, Canada

Field Location	Tillage type[1]	Field/plot No.	Textural parameter Sand	Silt	Clay	Depth	Bulk density	Moisture content	Cone index
			%	%	%	mm	Mg/m^3	%	MPa
Brandon	NT	1	34	33	33	200	1.14	28.10	1.81
	NT	2	16	42	42	200	1.26	30.39	1.62
	NT	3	31	36	33	200	1.41	26.09	2.20
	NT	4	32	33	35	200	1.21	29.66	1.98
	NT	5	31	36	33	200	1.07	30.61	1.63
	NT	6	36	32	32	200	1.31	23.15	2.23
	NT	7	16	48	36	200	1.23	25.83	2.43
	NT	8	34	30	36	200	1.25	27.82	1.87
	CT	1	16	42	42	200	1.09	31.42	1.35
Carman	NT	1	60	15	25	200	1.43	27.30	1.78
	CT	1	80	8	12	200	1.31	17.14	1.58
	CT	2	76	8	16	200	1.24	21.80	1.21
Winnipeg	NT	1	4	42	54	200	1.41	33.48	1.48
	CT	1	4	42	54	200	1.28	32.63	1.37
ST Agathe	NT	1	4	19	77	200	1.13	34.39	1.32
	CT	1	4	19	77	200	0.98	35.52	1.29
Oakville	NT	1	4	19	77	200	1.32	31.49	1.26
	NT	2	4	19	77	50	0.94	42.15	0.18
	NT	3	4	19	77	100	1.10	37.41	0.58
	NT	4	4	19	77	150	1.22	37.97	0.78
	NT	5	4	19	77	200	1.30	33.25	0.98
	NT	6	4	19	77	50	0.97	33.03	0.14
	NT	7	4	19	77	100	1.16	40.36	0.64
	NT	8	4	19	77	150	1.15	38.70	0.90
	NT	9	4	19	77	200	1.34	32.04	1.04
	NT	10	4	19	77	50	0.92	42.15	0.10
	NT	11	4	19	77	100	1.09	39.64	0.59
	NT	12	4	19	77	150	1.20	38.43	0.94
	NT	13	4	19	77	200	1.20	33.43	1.10
	CT	1	4	19	77	200	1.07	31.92	1.05
	CT	2	4	19	77	50	1.01	27.13	0.43
	CT	3	4	19	77	100	1.10	37.21	1.04
	CT	4	4	19	77	150	1.27	35.76	1.10
	CT	5	4	19	77	200	1.24	34.83	1.09
	CT	6	4	19	77	50	1.14	21.69	0.17
	CT	7	4	19	77	100	1.42	30.19	0.62
	CT	8	4	19	77	150	1.41	29.39	0.83
	CT	9	4	19	77	200	1.45	27.54	1.04
	CT	10	4	19	77	50	1.13	25.02	0.20
	CT	11	4	19	77	100	1.35	32.16	0.68

CT	12	4	19	77	150	1.41	31.66	0.92
CT	13	4	19	77	200	1.42	31.52	1.04

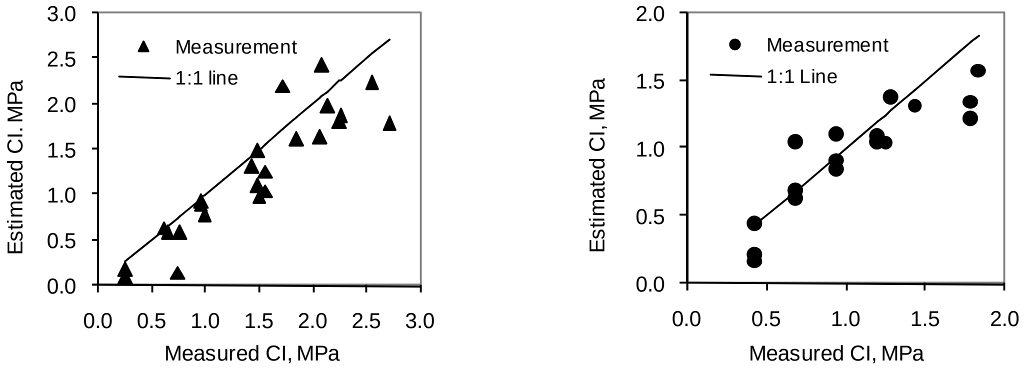
[1]NT = No tillage; CT = Conventional tillage.

Equations 1 and 2 were applied to the field conditions of this study. The measured values of soil textural parameters, moisture content, and bulk density under no-tillage and conventional tillage listed in Table 3 were inserted into the corresponding equation to estimate CI, which were compared with the measured CI values listed in Table 3. The agreement between estimations and measurements was evaluated by the relative error defined as follows:

$$RE = \frac{|M_i - E_i|}{M_i} \text{ x } 100 \qquad (3)$$

Where, RE is relative error (%); M_i is ith measurement; E_i is ith estimation.

The 1:1 lines (Figures 7a and 7b) show that measurements and estimations had similar trends, although data from measurements scattered around estimations. In general, the equations overestimated CI at lower values and under estimated at higher values. For no-tillage, the RE between estimations and the corresponding measurements was ±20% and lower. The equation for conventional tillage gave closer estimations when compared to the equation for no-tillage; the RE between estimation and the measurement ranged ±18% or lower.



(a) (b)

Figure 7 Comparisons of estimated and measured soil cone index (CI); (a) No-tillage (b) Conventional tillage.

4 Conclusions

The literature data for no-tillage and conventional tillage systems showed similar trends, in terms of variations of soil cone index with the selected soil physical properties. For both tillage systems, the general trends were that higher soil cone indices occurred at the greater soil depth and bulk density; cone indices decreased with increasing moisture content and clay fraction and with decreasing sand and silt fractions. No-till soil was more sensitive to those soil properties than conventionally tilled soil. The regression equations obtained from the literature data showed that soil cone indices of no-tillage were significantly related to soil sand fraction, moisture content, and tillage depth, whereas for the conventional tillage CI was significantly related to clay fraction and tillage depth. Good agreement was observed between the predicted values using regression equations and measured values (11 out of 24 data points for no-tillage and 13 out of 18 data points for conventional tillage) represented by relative errors of 20% or lower. However, at some other data points, the equations exhibited greater discrepancies from the field measurements, which may be indicative of the nature of soils variability and the variations of the data sources used for the development of the equations.

This study provided important insight into the variations of soil cone index with soil physical properties. However, it must be noticed that soil cone index may also vary with other factors, such as the cropping systems, the climate, and time since tillage. The information on those factors was, however, not considered due to the limited number of published data. Also, the results are applicable only to the depth of 0-200 mm. The regression equations obtained from the literature data may not be used for the purpose of CI predictions.

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