Estimates of tillage effects on saturated hydraulic conductivity

Y. CHEN[1], S. TESSIER[2] and J. GALLICHAND[2]

[1]Department of Biosystems Engineering, University of Manitoba, Winnipeg, MB, Canada R3T 5V6; and [2]Département des sols et génie agroalimentaire, Univeristé Laval, Québec, QC, Canada G1K 7P4. *Received 2 July 1997; accepted 15 June 1998.*

Chen, Y., Tessier, S. and Gallichand, J. 1998. **Estimates of tillage effects on saturated hydraulic conductivity**. Can. Agric. Eng. 40:169-177. Soil saturated hydraulic conductivity (K_s) is needed to simulate many water transport related processes in soil, such as water erosion, surface runoff, and water supply to plants. In this study, data reported in the literature relating K_s to tillage practices published during the past 25 years were compiled, pooled, and regressed to obtain relationships between K_s and soil variables. The data showed that soil bulk density (ρ_b) is a major factor influencing K_s for general tillage conditions. When specific tillage treatments are considered, K_s is principally related to soil organic matter (OM) for no-till soil; K_s is also affected by the clay and silt contents for plowed soils. Based on data compiled from the literature, several equations that incorporate tillage practice and basic soil variables were proposed to estimate K_s. These equations were evaluated with field data from Quebec soils where the dominant textures were sandy. Large differences in K_s values between the field data and the prediction values were found due to variable soil characteristics and tillage conditions. Evaluations of three previously-published models for K_s prediction were also performed using the Quebec field data and none of them was in close agreement with the measurements. However, results from Campbell's model were significantly correlated to the field data, although the model under-predicted K_s. This model was calibrated with the measured Quebec data used in this study for prediction of field K_s for sandy soils.

La conductivité hydraulique saturée (K_s) est un paramètre, nécessaire pour simuler les processus de transport de l'eau, comme le ruissellement et l'apport de l'eau aux racines des plantes. Dans cette étude, les données retrouvées dans les rapports de recherche sur la K_s en fonction du travail du sol, publiés durant les dernières 25 années, ont été compilées, classées et étudiées afin de dégager des relations entre la K_s et les variables du sol. Ces données illustrent que la masse volumique apparente (ρ_b) est un facteur majeur qui influence la K_s pour les conditions générales de travail du sol. Pour un système de travail du sol précis, la K_s est principalement associée à la matière organique (OM) pour le semis direct, alors qu'elle est plutôt dépendante des teneurs au argile et limon pour le labour (charrue à versoirs). Ce recensement a permis de proposer plusieurs équations qui intègrent l'influence des systèmes de travail du sol et les variables du sol pour estimer la K_s. Ces équations ont été vérifiées à l'aide d'observations prises au champ au Québec où la texture dominante du sol était sableuse. De grandes différences entre les valeurs de K_s observées et les valeurs prédites ont découlé des conditions contrastantes entre le champ et les données publiées. Une évaluation de trois modèles publiés pour la prédiction de la K_s a été aussi accomplie avec ces mêmes observations au champ. Aucun de ces trois autres modèles n'ont été en meilleur accord avec ces observations. Cependant, les prédictions du modèle de Campbell était plus étroitement corrélées aux observations au champ, malgré une sous-estimation de K_s. Ce modèle a ensuite été calibré avec ces observations pour prédire la K_s des sols sableux.

INTRODUCTION

The saturated hydraulic conductivity (K_s) is an important variable for a wide spectrum of physical and solute transport processes. For example, modeling soil water erosion and surface runoff requires K_s as input (Williams 1994). The accessibility of water for roots also depends on the soil properties, which include K_s (Brown et al. 1992). Tillage operations affect soil structure in different ways (Brady 1990). For instance, conventional plowing yields a looser soil structure than no-tillage which leaves the soil matrix relatively intact (Chen 1993). This results in differences in the number, shape and size distribution of the soil pores and these differences change K_s (Hubbard et al. 1994). Thus, understanding of the tillage effects on K_s can help producers to chose the most adequate tillage practices which reduce runoff and erosion, improve root zone aeration and route water to plants.

Tillage effects on soil structure are generally limited to the surface 300 mm zone (Gantzer and Blake 1978), where the induced change in K_s is most pronounced. The root environment within this depth is also critical for plant development (Mielke et al. 1984). Therefore, it is important to investigate soil water conditions in this upper root zone.

Field measurements in many studies have shown different conclusions on the variation of K_s with tillage operations. Hubbard et al. (1994) reported that tilled soils exhibit greater K_s values than no-till soils, whereas Culley et al. (1987) had concluded the contrary. However, Gregorich et al. (1993) found no significant difference in K_s between these two tillage practices. These studies demonstrate the difficulty to qualitatively generalize the effects of tillage on K_s, because the response of a soil to tillage varies with soil variables. In addition, K_s measurements for obtaining a large data set are often tedious and time consuming, and it would be most advantageous to be able to estimate K_s from easily measured soil variables, such as bulk density (ρ_b), organic matter (OM) and textural variables. Furthermore, the estimations of K_s for agricultural soils need to incorporate tillage effects.

The objectives of this study were: (i) to develop models which incorporate the effects of tillage types into the estimation of K_s based on data from the literature, and (ii) to evaluate the suitability of the proposed models and the selected previously-published models for estimating K_s of sandy soils in Portneuf region of Quebec.

REVIEW OF LITERATURE

Various equations to estimate saturated hydraulic conductivity, K_s have been developed. In those equations, K_s is estimated using soil bulk density (ρ_b), porosity, textural variables, or combinations of these variables. It is better to avoid using the porosity to estimate K_s as the porosity is difficult to determine. Tietje and Hennings (1996) compared the five published equations and pointed out large differences in prediction accuracy owing to the contrasting conditions from which the equations were developed. Published equations will need to be evaluated for their effectiveness in predicting the influence of tillage on K_s. Five previously-published equations were reviewed by Tietje and Hennings (1996), six listed in Table I and three typical equations using textural variables, ρ_b, or both are reviewed in the following sections and evaluated in this study with the measurements from Quebec soils. (Note that all equations have been converted to a common set of units of K_s in mm/h and ρ_b in Mg/m^3.)

Table I. Descriptions of equations established in the literature and used to estimate saturated conductivity, K_s (mm/h) from bulk density, ρ_b (Mg/m^3), pore space, ϕ (m^3/m^3), effective porosity, ϕ_e (m^3/m^3) and macroporosity, p (m^3/m^3).

Author(s)	Texture class	Equation	R^2	N	Other description
Culley et al. 1987	Clay loam	$K_s = 4149\ \phi^{2.63}$	0.52	unknown	For moldboard plow
		$K_s = 525\ \phi^{1.09}$	0.36	unknown	For no-tillage
Franzmeier 1991	Various	$K_s = 18000\ \phi^{3.21}$	0.86	14	
Kenny and Saxton 1988	Silt loam	$K_s = 42\ \rho_b^{-10.2}$	0.57	37	No validation
Mbagwu 1995	Various	$K_s = 42\ e^{8p}$	0.94	18	
		$K_s = 1872\ \rho_b^{-6.28}$	0.77	18	

R^2 = coefficient of determination N = number of data points

Campbell's model

Tillage can produce significant macroporosity (Sutikto and Chikamori 1993). For this reason, it is useful to compare measured saturated conductivity of tilled soils with estimated saturated conductivity of uniform soils. Campbell (1985) estimated saturated conductivity with clay and silt contents for uniform soils using:

$$K_s = C\exp(-0.069\,clay\% - 0.037\,silt\%) \qquad (1a)$$

where:

K_s = saturated hydraulic conductivity (mm/h) and
C = regression constant (mm/h).

A relationship incorporating ρ_b in addition to silt and clay contents also was suggested by Campbell (1985):

$$K_s = C\left(\frac{1.3}{\rho_b}\right)^{1.3b} \exp(-0.069\,clay\% - 0.037\,silt\%) \qquad (1b)$$

where:

ρ_b = soil bulk density (Mg/m^3) and
b = a function of soil pore size distribution obtained from the soil moisture characteristic curve, ranging from 2 to 24 for typical soils.

According to Campbell (1985), a value of 141 mm/h for C provides the best fit to data from several sources. However, the author did not mention the number of observations and the correlation coefficients.

Jabro's model

Using the same soil variables, Jabro (1992) gave an equation (with a coefficient of multiple determination (R^2) of 0.68) derived from published data from 350 samples:

$$K_s = 10^{9.56-0.81\log(silt\%)-1.09\log(clay\%)-4.64\rho_b} \qquad (2)$$

Naney's model

Both K_s and ρ_b are recognized as soil structure and texture-related variables (Carter 1987). Therefore, ρ_b can be considered as an important determinant for K_s. A relationship, predicting K_s solely from ρ_b, was derived from approximately 50 data points from three different soils by Naney et al. (1983):

$$K_s = 4590\rho_b^{-22.27} \qquad (3)$$

MATERIALS and METHODS

For the model development, a database was compiled from the published studies in the literature. While there have been many studies reporting K_s, only those associated with tillage studies were used for our purpose. Such literature was searched for the time period from 1990 to 1997 and 28 published studies around the world (Table II) were included in the database. For the model validation, field measurements were taken in 18 fields on 10 Quebec farms.

Description of data base from the literature

The database includes the following variables: mineral particle contents of clay, silt, and sand, OM, ρ_b, K_s, and primary tillage type. Tillage types were classified into seven categories: no-tillage, moldboard plow, chisel, tine, disk, subsoiler, and ridger, which represent most common tillage practices. When not available, mineral particle contents were derived from the soil texture descriptions (Shirazi and Boersma 1984). When OM-values were not available, soil organic carbon was converted into OM by multiplication by a factor of 1.72 (Brady 1990). Soil textures in the data set covered clay contents between 6 and 54%, silt between 9 and 73%, sand between 8 and 83%, and OM between 0.2 and 7%. All data were taken within the 0-300 mm depth range.

Table II. **Description of literature data sources from which the proposed models were developed.**

Authors	Location*	Soil texture	Primary tillage**
Bagherzadeh et al. 1992	Pennsylvania, USA	Silty clay loam	Chisel
Bissett and O'Leary 1996	Dooen, Australia	Clay, sandy loam	Chisel, NT
Brown et al. 1992	Iowa, USA	Silty clay loam	Plow
Carter and Steed 1992	Rutherglen, Victoria	Sandy clay loam	NT, Plow
Chang and Lindwall 1989	Alberta, Canada	Clay loam	NT, Plow
Comia et al. 1994a	Laguna, Philippines	Clay	NT, Plow
Comia et al. 1994b	Säby, Sweden	Clay	Plow, Disk
Coote and Malcolm-McGovern 1989	Ottawa, Canada	Sandy loam, fine sandy loam, loam	NT, Plow
Culley et al. 1987	Minnesota, USA	Clay loam	NT, Plow
Douglas and Goss 1987	Oxfordshire, Gt. Britain	Clay	NT, Plow
Fritz et al. 1995	Minnesota, USA	Clay loam	Tine
Gantzer and Blake 1978	Minnesota, USA	Clay loam	NT, Plow
Goss et al. 1984	Göttingen, West Germany	Clays, silt loam	Plow
Gregorich et al. 1993	Ontario, Canada	Clay loam	NT, Plow
Heard et al. 1988.	Indiana, USA	Silty clay loam, silt loam	Plow, Chisel, Ridger, NT
Horne et al. 1992	Palmerston North, New Zealand	Silt loam	Plow, Disk, NT
Hubbard et al. 1994	Georgia, USA	Sandy clay loam	Plow, Chisel, NT
Johnson et al. 1989	Michigan, USA	Clay	Plow, Chisel
Kenny and Saxton 1988	Washington, USA	Silt loam	NT, Plow, Chisel
Liebig et al. 1993	Nebraska, USA	Silty clay loam	Ridger
Mielke et al. 1984	NB, USA	Loam	Plow, Subsoiler, NT
Murphy and Rieke 1994	N/A	Loamy sand	NT, Tine
Murphy et al. 1993	N/A	Loamy sand	NT, Tine
Pagliai et al. 1995	Lazio, Italy	Silt loam	Disk
Pierce et al. 1992	Michigan, USA	Loam	Chisel, Subsoiler, NT
Rizvi et al. 1987	Iowa, USA	Loam	Chisel, NT
Simmons and Cassel 1989	North Carolina, USA	Loamy sand	Chisel, Subsoiler, Disk

*N/A = the information is not available from the source.

**Plow = moldboard plow; NT = no-tillage.

Literature K_s data were measured by different techniques, such as using a Guelph permeameter, a falling head permeameter, a constant head permeameter, and auger hole methods. Systematic errors might be associated with different methods as reported by Gallichand et al. (1990). However, this was not taken into account because of the limited information from which to compare performance precision of different measurement techniques.

Quebec sites and field measurements

Field measurements were conducted by the authors for model evaluation. The field study area was located in the Portneuf region of Quebec, where coarse soil textures predominate. Soil samples were taken early in the growing season (June 1996) after spring tillage operations in eighteen fields spread over ten farms (Table III). Thirteen of the 18 sites had sandy textures. Three typical, primary tillage treatments were applied at these sites: no-tillage, chisel, and moldboard plow. Paired soil samples were collected from each site, one for determining soil texture and OM and the other for ρ_b and K_s measurements. The undisturbed soil cores (63-mm diameter), for ρ_b and K_s measurements, were taken within the depth of 0-300 mm at three locations within each site. Soil cores, kept in air-tight bags, were taken to the laboratory where Ks was measured by a constant head method (Klute and Dirksen 1986). Samples were then oven-dried at 105 °C for 24 hours to determine dry ρ_b. Soil textures were determined using the hydrometer methods (Gee and Bauder 1986) and OM using a standard extraction method (Schnitzer 1982).

Data analyses

Data obtained from the literature were pooled over all tillage types (referred to as entire data set hereafter) to investigate general effects of tillage on K_s. The same data were also divided into seven sub-data sets, corresponding to the seven tillage types, to examine specific effects of individual tillage type. Regression analyses were performed on the entire data set and each sub-data set. Stepwise regression procedures (Steel and Torrie 1980) were used to determine the best relationship between the independent variables (clay, silt, sand, OM, and ρ_b) and dependent variable (K_s) at a significance level of $p < 0.10$.

Table III. Site descriptions for soil samplings, Quebec, June 1996.

Soil texture	Primary tillage	Number of sites
Clay	No-tillage	1
Clay	Moldboard plow	1
Sandy clay loam	Moldboard plow	1
Sandy clay loam	No-tillage	1
Loam	No-tillage	1
Sandy loam	Chisel	4
Loamy sand	Moldboard plow	5
Loamy sand	Chisel	3
Sand	Chisel	1

Several statistical evaluation procedures were used to test the performance of the models with the field-measured data from this study. The statistics included: correlation coefficient (r) which evaluates the degree of association between measured and predicted values; the absolute mean difference between measured and predicted values (AMD), which evaluates the degree of coincidence; and the relative error (RE) between the measured and the predicted values. The mathematical expressions for the absolute mean difference (AMD) and relative error (RE) between the measured and predicted data are:

$$AMD = \frac{1}{N}\sum_{i=1}^{N}\left|M_i - P_i\right| \tag{4a}$$

$$RE = \frac{100}{N}\sum_{i=1}^{N}\frac{\left|M_i - P_i\right|}{M_i} \tag{4b}$$

where:
N = number of samples,
M_i = ith measurement, and
P_i = ith prediction.

RESULTS AND DISCUSSION

Model development based on literature data

General effects of tillage on K_s Stepwise regression was performed on the entire data set from the literature and all five independent variables (clay%, silt%, sand%, OM%, and ρ_b) were included in the regression. Clay%, sand%, and OM% were not significant and excluded but two variables, ρ_b and silt%, were significantly related to K_s:

$$K_s = 611.27 - 328.15\rho_b - 2.17 silt\% \quad (N = 109, \quad r = 0.50) \tag{5}$$

Soil bulk density can be the only determinant of K_s as observed by Naney et al. (1983). Kenny and Saxton (1988) also indicated that the effects of soil texture and OM on K_s can be reflected by ρ_b. Therefore, we considered estimating K_s from ρ_b only. Data from the literature in Fig. 1 show that K_s values become less with the increase in ρ_b values and a logarithmic relationship was obtained through the regression analysis of the entire data set:

$$K_s = 214.86\rho_b^{-5.324} \qquad (N = 76, r = 0.50) \tag{6}$$

The significant but low r values of Eqs. 5 and 6 reflect the large variability of such a broad data set from various studies in the literature. Saturated hydraulic conductivity often shows a high variability as indicated by Anderson and Cassel (1986), perhaps owing to different measurement techniques (Gallichand et al. 1990), field conditions (Diiwu et al. 1995), and soil characteristics (Rawls et al. 1982).

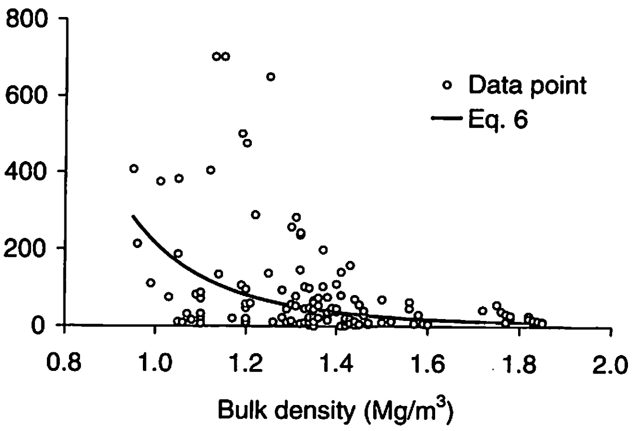

Fig. 1. Distribution of K_s as a function of ρ_b for all tillage conditions. Data points were from the entire literature data set.

Specific tillage effects on K_s Equations 5 and 6 provide a general estimate of K_s over all tillage types. However, different tillage types cause different changes in K_s. Effects of each tillage type on the relationship between K_s and soil variables were investigated based on the sub-data sets. Regression analyses on the sub-data set from no-tillage showed that organic matter plays an important role on the determination of K_s (Fig. 2) with a linear relationship:

$$K_{NT} = -50.85 + 41.79 OM\% \qquad (N = 20, r = 0.56) \tag{7}$$

where K_{NT} = saturated hydraulic conductivity for no-tillage.

Equation 7 was derived from soils with OM ranging from 1.30 to 4.42%. While soil texture is also known to have a dominant effect on K_s (Campbell 1985; Jabro 1992). This was not the case for no-till soils within the data analyzed. From the sub-data set for moldboard plowing, regression analysis showed that both silt% and ρ_b were significant variables affecting K_s for soils with a silt content from 11 to 83%:

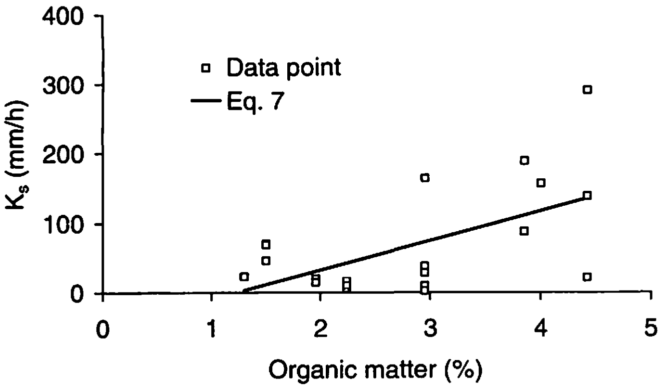

Fig. 2. Variation of K_s with organic matter under no-tillage conditions. Data were from the literature for no-tillage.

$$K_{MP} = 1020.07 - 5.84\,silt\% - 517.54\rho_b \qquad (N = 40, \quad r = 0.66) \qquad (8a)$$

where K_{MP} = saturated hydraulic conductivity for moldboard plowing.

Soil organic matter is a major tillage-related variable affecting soil structure properties, such as ρ_b, for various tilled soil conditions (Sharifat and Kushwaha 1996). However, in our case, OM proved less significant and was not retained as an independent variable in Eq. 8a. The regression analysis was performed again on selected data points with OM higher than 3.5%, resulting in a significant effect of OM on K_s:

$$K_{MP} = -195.62 - 13.84\,clay\% + 243.26\,OM\% \qquad (N = 13, \quad r = 0.82) \qquad (8b)$$

Equation 8b was derived from soils with clay content from 10 to 50% and can not be applied to soils with higher clay content.

No significant relationships between K_s and soil variables were found for chisel, tine, disk, subsoiler, and ridger. Since no-tillage and moldboard plow reflect two extremes in tillage intensity, their effects on K_s provide a useful assessment of the hydraulic characteristics in relation to the other tillage operations.

Model evaluations with field measurements

The proposed models derived from the literature data, represented by Eqs. 5 to 8 and the previously-published models (Eqs. 1 to 3) were evaluated using the Quebec field data for soil texture, OM, ρ_b, and K_s determined in this study. Laboratory measured values of K_s from undisturbed soil samples range from 80 to 1390 mm/h with an average of 580 mm/h and a standard deviation of 310 mm/h.

Evaluation of proposed models Measured soil variables, regardless of tillage types, were inserted into Eqs. 5 and 6. The estimated values of K_s were then compared with the measured values of K_s, resulting in a weak correlation with r = 0.29 and -0.08, for Eqs. 5 and 6, respectively (Table IV). Equation 5 yielded slightly higher values of K_s than Eq. 6, but both of them underestimated K_s. Values of AMD and RE for Eq. 5 were 469 mm/h and 76%, whereas for Eq. 6 these values were 540 mm/h and 84%, respectively.

Separate measurements for no-tillage and moldboard plow tillage were used to evaluate K_{NT} and K_{MP} in Eqs. 7 and 8. The predictions gave AMD and RE values of 550 mm/h and 75% for no-tillage and 375 mm/h and 61% for moldboard plow. Equation 8a was in better agreement with measurements compared to the other equations and was significantly correlated with the measured values (r = 0.37).

The predicted results from Eqs. 5 and 6 proposed for all tillage derived from the field measurements with relative errors (RE) of 76% and 84%. This may be due to the fact that 70% of the measurements were taken from sandy soils (Table III). Thus, the predicted values would be expected to underestimate the measurements, because only 11% of the literature data were obtained from sandy soils (Table II). The deviation between the measurement and the prediction may also indicate the inadequacy of using a single equation to describe field K_s resulting from various tillage types.

However, smaller relative errors were obtained between the models developed for moldboard plow and the measurements. The variability was in accordance with that reported in the previous studies (Anderson and Cassel 1986; Jabro 1992). Because the proposed models were derived from field observations of various soil textures, it is presumed that they can be used for estimating K_s over a wide range of soil textures. However, further tests with field data from various soil textures are needed for this assumption.

Evaluation of previously-published models The three previously-published models (Eqs. 1 to 3) were evaluated and none of them was in close agreement with our field data (Table IV). The associated values of AMD range from 570 to 784 mm/h and those of RE from 88 to 290%. As the soil structure modifications induced by tillage are mostly reflected in ρ_b, neglecting the ρ_b effect as in Campbell's Eq. 1a might not adequately account for the influence of tillage on K_s. However, the models which integrate ρ_b, as an input, as in Eqs. 1b, 2, and 3, also failed to fit the measured data from this study.

Field data from sites 5 and 8 (Table IV), possessing similar soil textural variables and ρ_b values of 1.31 and 1.13 Mg /m^3, respectively, were used to demonstrate model differences. In Campbell's model, K_s values varied slightly with changes in soil texture and ρ_b. In Jabro's and Naney's models, K_s values fluctuated greatly with ρ_b due to the heavy weight of ρ_b in these equations. For a 16% increase of ρ_b, the value of K_s decreases about 54% (from 78 to 36 mm/h) for Campbell's Eq. 1b, about 84% (from 1546 to 245 mm/h) for Jabro's model and by 97% (from 333 to 11 mm/h) for Naney's model.

Campbell's Eqs. 1a and 1b might not correctly predict the saturated hydraulic conductivity of a soil containing macropores having large hydraulic radii, because when saturated, it conducts water much faster than a uniform soil. Under many of our field conditions, macroporosity resulting from tillage treatments is likely a dominant factor in conduction of free water. Thus, higher values of measured K_s were expected than those predicted from Eqs. 1a and 1b. This was consistent with that found by Sutikto and Chikamori (1993). This effect of macroporosity can be clearly illustrated by the sites 8 and 10 (Table IV). There was no difference in the Campbell's Eq. 1a values for K_s (34 mm/h) for each of the two sites, but K_s exhibited marked differences in the measured values (884 and 1391 mm/h).

Table IV. **Soil physical properties and associated saturated hydraulic conductivity values*, K_s, (mm/h) measured and those predicted from three previously published models and proposed models.**

Site No.	Soil texture	Clay %	Silt %	Sand %	OM %	ρ_b Mg/m^3	K_m	K_{C1a} Eq. 1a	K_{C1b} Eq. 1b	K_{Ja} Eq. 2	K_{Na} Eq. 3	K_p Eq. 5	K_p Eq. 6	K_p Eq. 7	K_p Eq. 8a	K_p Eq. 8b
No-tillage																
1	Loam	20.7	41.2	38.1	3.4	1.01	415	7	74	1352	3678	190	204	91	257	345
2	Sandy clay loam	26.8	20.9	52.3	6.2	1.69	197	10	1	1	0	11	13	208	23	942
3	Clay	65.2	27.4	7.3	4.0	1.32	342	1	0	21	10	119	49	116	177	-
Chisel																
4	Sandy loam	17.3	29.4	53.2	3.5	1.25	377	14	20	166	32	137	65	95	201	416
5	Loamy sand	12.0	13.5	74.5	2.7	1.31	797	37	36	245	11	152	51	62	263	295
6	Sand	6.0	9.5	84.5	1.8	1.37	696	66	54	366	4	141	40	24	256	159
7	Sandy loam	13.3	19.8	66.9	3.2	1.17	560	27	52	718	139	184	93	83	299	399
8	Loamy sand	13.3	13.9	72.8	3.1	1.13	884	34	78	1546	333	210	112	79	354	374
9	Sandy loam	17.3	17.9	64.8	5.0	1.23	473	22	33	308	46	169	71	158	279	781
10	Sandy loam	15.3	9.6	75.1	2.7	1.20	1391	34	56	804	79	197	81	62	343	249
11	Loamy sand	13.3	12.2	74.5	3.5	1.28	871	36	40	346	21	165	58	95	286	472
Moldboard plow																
12	Loamy sand	16.0	11.5	72.5	3.0	1.46	576	31	15	41	1	107	29	75	197	313
13	Loamy sand	15.3	10.1	74.5	2.6	1.09	787	34	98	2498	673	232	136	58	397	225
14	Loamy sand	15.3	9.6	75.1	2.7	1.19	632	34	60	943	105	200	85	62	348	249
15	Loamy sand	13.3	14.2	72.5	2.8	1.11	681	33	83	1783	449	216	123	66	363	301
16	Loamy sand	12.0	10.9	77.1	4.0	1.05	124	41	126	4692	1549	243	166	116	413	611
17	Sandy clay loam	21.3	14.2	64.5	4.8	1.47	773	19	7	24	1	98	28	150	176	677
18	Clay	65.2	27.4	7.3	4.0	1.33	512	1	0	19	9	115	47	116	172	-
AMD								589	570	784	740	469	540	520	349	366
RE								94	88	290	182	76	84	75	42	81
Correlation coefficient with K_m								0.41**	0.11	-0.16	-0.27	0.29	-0.08	-0.53	0.37**	-0.23

*K_m measured values; K_{C1a} and K_{C1b} calculated from Eqs. 1a and 1b (Campbell 1985); $_{Kja}$ calculated from Eq.2 (Jabro 1992); K_{Na} calculated from Eq. 3 (Naney et al. 1983)
AMD = Absolute mean difference; RE = Relative error; ** Significant at $p < 0.10$

Correlation analyses showed that Campbell's Eq. 1a was significantly correlated to our field measurements ($r = 0.41$) at $p<0.1$ level. It would be useful to recalibrate the coefficient C in Eq. 1a for tilled soils with our field measurements of K_s and textural conditions. A new value of 2682 mm/h for C was obtained from the regressions. Fig. 3a and 3b show the relationships between the saturated hydraulic conductivity and (a) clay and (b) silt contents. Equations for the field measurements or for those values calculated from the recalibrated equation appear to posses similar correlation coefficients. However, the AMD between the K_s values calculated using the recalibrated equation and those measured (Table IV) was reduced 63% and the RE 40% compared to using a coefficient C of 141 mm/h suggested by Campbell (1985) for uniform soils. The recalibration was based on the field data from sandy soils; therefore, the recalibrated equation might be suitable only for sandy soils. Also, the recalibrated equation was not tested on different data sets.

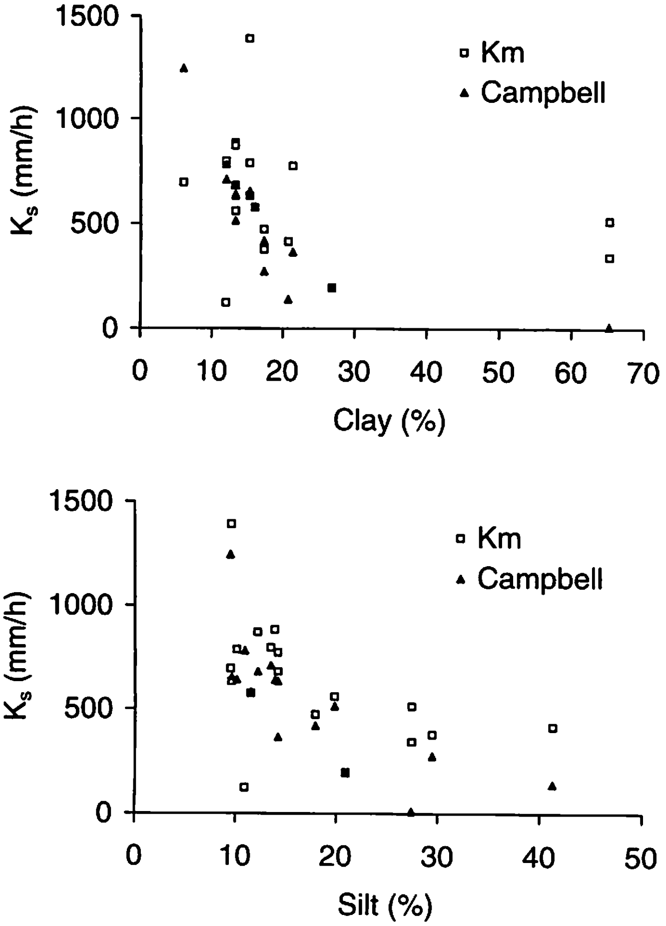

Fig. 3. Calibrations of Campbell's equation (Eq. 1) with K_s values measured from sandy soils in Quebec, as influenced by (a) clay and (b) silt contents.

CONCLUSIONS

In general, both ρ_b and soil textural variables are significant variables which reflect overall effects of tillage on saturated hydraulic conductivity, K_s. For specific tillage type, such as no-tillage and moldboard plow, organic matter also plays an important role in the determination of K_s.

The models developed from the literature data underestimated field measurements from Quebec soils where the dominant texture classes were sandy. The model developed for moldboard plow resulted in closer predictions to measurements. However, as Eqs. 5 to 8 were derived from data sets where only those showing an association with tillage were retained, the models can still be useful for predicting tillage effects on K_s. Additional tests for a wider range of soil types are required.

The three previously-published models tested did not respond similarly to the effects of varying soil texture classes and ρ_b on K_s. Campbell's model was less sensitive to the changes in either soil textural class or in ρ_b compared to the Jabro's and Naney's models where the coefficient of bulk density has greater weight. The predictions of K_s using the selected previously-published models differed greatly from the measured Quebec field data. However, the Campbell's equation, which included only clay and silt as independent variables, was significantly correlated to the field data taken from sandy soils in Quebec. This equation was recalibrated with the field data and the recalibrated equation is proposed for tilled, sandy soils. However, the recalibrated equation was not tested by another set of field measurements.

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