Energy requirements and depth stability of two different moldboard plow bottoms in a heavy clay soil

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INTRODUCTION

The moldboard plow has historically been the most important primary tillage implement in agriculture. As draft animals were replaced by tractors in the twentieth century, tillage operations grew in scale, speed, and efficiency. Mechanization provided the means by which labour inputs could be substituted by capital inputs, enabling each unit of labour to become technically more productive, covering more acreage in the same amount of time (Stonehouse 1991). Judiciously used, the moldboard plow can be an effective tool for mechanical weed control (Buhler and Oplinger 1990), seedbed preparation, and promotion of surface warming and upper profile drainage in spring (Logan et al. 1991). However, moldboard plowing ranks among the highest energy consuming primary tillage operations (ASAE 1992). The larger tractor axle weight required to provide the traction and draft requirements of wider moldboard plows can also result in significant soil compaction (Plouffe et al. 1994). Moreover, the practice of running two tractor wheels in the open furrow is partially responsible for plow pan development (Chaplin et al. 1986) and sub-soil compaction (Barnes and Maddux 1991). Finally, deep plowing (more than 150 mm) is blamed for surface organic matter dilution within the tilled layer (Logan et al. 1991).

A research program was initiated to study the tillage requirements for sustainable agriculture under Eastern Canada conditions. A key part of this program was to investigate the suitability of existing moldboard plows for shallow plowing. The findings from a first study are presented herein.

OBJECTIVES

The overall objective of this study was to establish the difference in draft force, fuel consumption, and operating depth stability between a cylindrical (short) and a helical (long) bottom commonly used. In addition, the relationships between plowing depth, operating speed, and bottom type on draft force were to be determined.

LITERATURE REVIEW

Numerous studies have dealt with modelling the power requirements of moldboard plows. Such models use parameters such as plowing depth and bottom width (spacing), speed of...
operation, and soil and bottom characteristics. ASAE (1992) indicates that draft varies linearly with plowing depth and bottom width. Bogotopov and Kravchuk (1984) and Gill and Vanden Berg (1968) suggest the idea of an optimum cutting width which implies non-linearity of the draft/width relationship. The cutting width also alters the degree of pulverization; plowed clod size is proportional to cutting width (Gill and Vanden Berg 1968). Within the range of operating speed (5 to 10 km/h) covered by ASAE (1992), the draft-speed relationship is quadratic due to the acceleration imparted to the soil during furrow inversion (Kermis 1978; Bernacki et al. 1972).

On theoretical grounds, Kermis (1978) proposed an approach to high-speed moldboard plow design by altering the conventional helical moldboard so that relatively low soil acceleration occurs during furrow slice turning resulting in a lower effect of speed on draft. The angle of the moldboard tail, $\theta_t$, and share wing, $\theta_s$, (Fig. 1) both affect soil trajectory and acceleration (Suministrado et al. 1990). A low approach angle for these two components results in lower acceleration of the soil mass moving over the moldboard, and thus reduces draft requirements (Eradat Oskoui et al. 1982; Bernacki et al. 1972). Klenin et al. (1985) stated that most of the resistance is due to soil cutting by the share. They established that the draft increases by 30 to 40% if the share is blunt. In that regard, Gill and Vanden Berg (1968) promoted the use of a self-sharpening edge.

Draft resistance may be deduced by theoretical analysis for several situations. Gebresenbet (1992) and Mil’tsev (1974) proposed mathematical models that include the geometric parameters of the plowing tools and the physical and mechanical properties of the soil. However, the variability of soil properties encountered in the field limits their use. Goryachkin’s equation (Eradat Oskoui and Witney 1982; Bernacki et al. 1972) is among the most widely used for moldboard plow draft prediction, possibly due to the physical meaning of its parameters:

$$ D_t = fG + K_ohb + eabx^2 $$  \tag{1}

where:

- $D_t =$ total draft force (kN),
- $f =$ coefficient of plow friction,
- $G =$ plow weight (kN),
- $K_o =$ coefficient of static resistance (kN/m$^2$),
- $a =$ plowing depth (m),
- $b =$ plowing width (m),
- $e =$ factor depending on lateral directional angle, and
- $s =$ plowing speed (km/h).

The first term on the R.H.S. of Eq. 1 is related to the resistance due to friction, component of the rolling resistance of the plow wheel, the sliding of plow parts against the soil, etc. Bernacki et al. (1972) suggested values of 0.3 to 0.5 for the plow friction coefficient, $f$. Klenin et al. (1985) proposed higher values ranging from 0.5 to 1.0 for the plowing of compact and loose soil, respectively. The second term corresponds to the energy required to cut the soil slice. Values for the static coefficient, $K_o$, range from 20 to 80 kN/m$^2$ for sandy (light) to clay (heavy) soils, respectively (Bernacki et al. 1972). The last term accounts for the energy required to accelerate the soil mass moving over the moldboard and to throw it aside and forward. The factor, $e$, depends mainly on the lateral directional angle, $\theta_t$ (Fig. 1) at the moldboard tail (Söhne 1960)

$$ e = K_1 (1 - \cos \theta_t) $$ \tag{2}

where $K_1 =$ dynamic resistance constant (kN/m$^2$)($\times$km/h)$^2$.

Söhne (1960) proposed a simplified equation based on Goryachkin’s model for specific draft force, $D_s$, which basically neglects the plow friction resistance.

$$ D = K_o + e^2 $$ \tag{3}

ASAE (1992) uses Eq. 3 for predicting moldboard plow draft in different soil types. The coefficients $K_o$ and $K_1$ are known to increase from light to heavy soils (coarse to fine texture). Soil conditions and characteristics such as density and water content dramatically affect draft force. ASAE (1992) suggests that either an increase of 1% by mass in soil moisture or a decrease of 0.1 Mg/m$^3$ in soil dry bulk density results in a plowing draft decrease of 10%. Eradat Oskoui and Witney (1982) also demonstrated that the strength of agricultural topsoils depends on the soil water content and density. They suggested the use of a cone penetrometer to relate soil strength to soil water content and density.

Vertical forces acting on the bottom could influence the plow stability considerably. These forces include the weight of the plow, the weight of the soil volume being lifted by the moldboard, the component from the tractor hitch and the force resulting from a sharp/dull share (Smith and Wilkes 1976). The interaction between these components does not result in a uniform surface pressure along the bottom. Gebresenbet (1989) and Bernacki et al. (1972) located the highest surface pressure on the share point and the moldboard wing.
In addition, surface pressure on the sharepoint was found proportional to speed and depth (Gill and Vanden Berg 1968). The Conservation Management Systems (CMS 1990) reported better stability for the bottom equipped with a sharepoint. The same source reported inadequate operation at depth less than 125 mm without a sharepoint on the bottom tested.

MATERIALS AND METHODS

Experimental site and design

The experiment was conducted 21-22 October 1991 on a Sainte-Rosalie clay soil (Typic Humaquept, very-fine, mixed, frigid, 45% clay, 23% sand, 5.9% OM) located at Saint-Simon (Québec). Residue conditions were typical of a barley crop harvested in August. Volunteer cereal regrowth was up to 0.3 m. To characterize initial soil conditions, soil samples were taken at eight locations in the field using core cylinders of 60 mm diameter and 64 mm height. Soil core tubes were inserted into the soil at 40 and 140 mm depths in each location. The soil cores were oven dried at 105°C for 24 h. The average dry bulk density ($\rho_b$) and volumetric water content ($\theta_v$) were 1.27 Mg/m³ and 36%, respectively.

The experimental design was a modified split-split plot (Steel and Torrie 1980) with the bottom shape as the main plot unit (MPU) within the three replicates. Five depths were randomized within the MPU and five speeds within each sub plot unit (SPU). The target depths and speeds retained for the study ranged between 120 to 250 mm and 3.5 to 7.5 km/h, respectively, covering the range encountered for most field conditions. Each plot had a width of one plowing swath (1.8 m) by 14 meters long.

Interchanging of bottoms required approximately three hours, therefore the field layout design was modified, as a compromise, to save time. The long and narrow field (420 m x 36 m) was separated in two halves along its length, and one bottom shape assigned to each section. In the 140-200 mm depth interval, both the mean $\rho_b$ (1.37 vs 1.25 Mg/m³), and $\theta_v$ (39.2 vs 36.5%) were higher on the field area where the short bottom was operated. According to ASAE (1992), a draft increase would be expected with an increase in $\rho_b$ or a decrease in $\theta_v$. In this specific case with higher $\rho_b$ and $\theta_v$, these two influences may well cancel each other. The average values for the 40-200 mm profile were not different. Hence, the assumption of homogeneity between plots for the long and short bottom is reasonable.

Description of implements

A semi-mounted variable-width plow with four bottoms (model 7500, J.I. Case Co., Racine, WI) was used for all tests. (Mention of trade names or company names does not imply endorsement of those products by the authors or institutions they represent.) Two sets of bottoms were studied, 1) the Case-IH “Super Chief”, high speed model HSCXK-25 and 2) the model HSES manufactured by Kverneland (Klepp AS, N-4344 Kverneland, Norway) and supplied by J.I. Case as an optional bottom (Fig. 2). The geometric characteristics of each bottom, referring to Fig. 1, are presented in Table I. The bottom spacing was set to 450 mm, for a 1.8 m plowing swath. Rolling coulters were used but trashboards and jointers were removed. The short and long bottoms were factory fitted with share cutting widths ($W_s$) of 470 and 360 mm, respectively.

A 97 kW, instrumented tractor was used for data collection (McLaughlin et al. 1993). This tractor was equipped with transducers and an on-board data logger for measuring tractor and tillage implement operating parameters, such as fuel consumption, wheel and ground speed, axle torque, and draft. Transducer signals were recorded at a scan rate of 100 Hz. Signals from strain gage transducers were filtered prior to recording with a six pole low pass filter with a corner frequency of 10 Hz. A separate data file was created for each plot. Periodically the plow was unhitched and a data file was logged under static no-load (zero) conditions. These zero data files provided a check for instrumentation drift.

Experimental procedure and analysis

The plowing depth was set by interchanging clip-on cylinder stops on the tractor three-point hitch hydraulic booster cylin-

![Fig. 2. Picture of the long (left) and short (right) bottoms used for the study.](image)
and the draft data from the hitch instrumentation were deemed unreliable. Fortunately, the axle torque, which is closely related to implement draft, exhibited no drift. Implement draft was thus estimated by subtracting tractor rolling resistance from the axle draft (quotient of axle torque and rolling radius). An approximation of the mean rolling resistance was known from a separate field experiment conducted at similar conditions (corn stubble) where axle torque and hitch draft were recorded while plowing. A value of 9.8 kN was thus subtracted from axle draft to estimate the implement draft.

RESULTS AND DISCUSSION

Energy requirements

$D_s$ and fuel consumption between the two bottom types were significantly different (Table II). The short bottom $D_s$ was 12% higher with a 6% higher fuel consumption (on average) than the long model over the range of depths and speeds considered. Proportionality between fuel consumption and draft should theoretically remain the same for any change in depth. However, different gear ratios were used to obtain the range of speeds considered. The engine was therefore operating at different efficiencies over the range of ground speeds. Thus, it would be difficult to accurately predict draft from fuel consumption given the speeds selected. In spite of this, the results of the analysis showed similar trends for fuel consumption and $D_s$.

Given the apparently different behaviors of the short and long bottoms and the limitations of the field layout, data for both bottoms were treated separately to obtain relationships between plowing depth and speed, and draft force. $D_s$ was significantly affected by the operating depth for both bottoms and the draft data from the hitch instrumentation were deemed unreliable. Fortunately, the axle torque, which is closely related to implement draft, exhibited no drift. Implement draft was thus estimated by subtracting tractor rolling resistance from the axle draft (quotient of axle torque and rolling radius). An approximation of the mean rolling resistance was known from a separate field experiment conducted at similar conditions (corn stubble) where axle torque and hitch draft were recorded while plowing. A value of 9.8 kN was thus subtracted from axle draft to estimate the implement draft.

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Speed also affected $D_s$ for both bottoms (Fig. 4). Contrast analysis revealed that speed had only a linear effect on $D_s$ with the long model, but had linear and cubic effects on $D_s$ for the short bottom. The absence of a quadratic effect of speed may be due to the limited range of speeds tested.

This non-linear behavior of $D_s$ with depth was subsequently neglected and regression equations for draft and plowing speed and depth based on Goryachkin’s model (Eq. 1) were developed for comparison with ASAE’s general equation for $D_s$ (Eq. 3). The plow friction term, $f G$, was dropped to obtain Eqs. 4 and 5 for the short and long bottoms, respectively. These equations agree with a previously reported equation for Decatur clay loam (Eq. 6), the closest soil type listed in the ASAE Standards to the Sainte-Rosalie clay soil studied.

$$D_s = 68.7 + 0.42 s^2 \quad \text{(short)}$$  
S.E. (8.7) (0.11) \hspace{1cm} (4)

$$D_s = 59.5 + 0.37 s^2 \quad \text{(long)}$$  
S.E. (7.3) (0.10) \hspace{1cm} (5)

$$D_s = 60 + 0.53 s^2 \quad \text{(Decatur clay loam - ASAE, 1992)} \hspace{1cm} (6)$$

The underlying relation between $D_s$ and width and depth indicates that total draft increases rapidly with depth for a given width. The intercepts also agree with the suggested range reported by Bernacki et al. (1972) for $K_o$ (Eq. 3) that is 20 to 80 kN/m$^2$ for light to heavy (coarse and fine texture) soil, respectively. Despite the high variability between measured and regression data (Fig. 4), the non-linearity of $D_s$ against speed behavior translates into a fairly small quadratic coefficient, $c$.

$R^2$ values of 0.59 and 0.60 for Eqs. 4 and 5, respectively, were significantly different from zero based on the model with 24 df (Steel and Torrie 1980). However, a lack of fit analysis, using model residuals and experimental error, revealed that these equations (Eqs. 4 and 5) do not fit the data. In addition, regression equations using the operating parameter (depth and speed) levels reported previously for each bottom did not provide a model that fits the data adequately. Therefore, it is suggested that other parameters, in addition to plowing depth and speed, should be included in the prediction model for $D_s$. This statement agrees with the conclusion of Gebresninet (1992) and Eradat Oskoui and Witney (1982).

Differences in energy requirement are likely related to bottom geometry. The short model had a share angle, $q_s$, and moldboard angle, $\theta_s$, of 45° and 47° compared with 39° and 31° for the long bottom, respectively (Table I). Suministrado et al. (1990) attributes more importance to $\theta_s$. This characteristic of the bottom affects largely the soil slice trajectory. A higher $\theta_s$ increases the shear stress induced onto the soil slice while lifting and pushing it aside, and also promotes lateral acceleration of the soil slice, throwing it further aside with a greater impact speed. As $\theta_s$ increases, the coefficients, $K_o$ and $c$, effectively increase (Eq. 3). This would largely explain the higher $K_o$ and $c$ for the short bottom (Eq. 4) when compared to the long model (Eq. 5). Eradat Oskoui et al.
(1982) reported similar behavior with two bottoms tested on three soil series (sandy loam, sandy clay loam, and a clay loam). Conversely, CMS (1990) reported higher $D_5$ for a long bottom than a short model in three different stubble fields (clay and clay loam).

$W_s$ can have a marked influence on plow draft requirements (Gill and Vanden Berg 1968), especially when shares are blunt. In this experiment, both shares were new but lower $W_s$ were used for the long bottom (360 vs 470 mm) and a point was factory installed on the latter model. These differences in share configuration may partly explain the higher energy demand recorded for the short bottom.

**Plow stability**

A major concern for shallow plowing is depth stability. Uneven plowing depth affects plant growth directly since it affects the quality of the final seedbed. Uniform tillage depth is required to produce an adequate and level seedbed to favor seedling emergence.

Plow stability was evaluated from the plowing depth SD within each plot. This value is essentially a measure of plowing depth variations over the 14 meter plot length. Differences in SD among depths and bottom types were not significant. Nevertheless, plow stability was generally better at greater depths (Fig. 5). At these depths, Gebresenbet (1989) reported a higher surface pressure on the share and moldboard that would agree with this behavior. The long bottom SD seems rather independent of plowing depth with a lower negative linear regression slope of 0.04 compared to 0.13 for the short model. The sharepoint on the long bottom had a steeper angle than the share to help penetration in shallow conditions. However, dividing the SD with its corresponding plowing depth gives the coefficient of variability (CV). Pooling the SD of both bottoms together (Fig. 5), a CV of 14% compared to 5% was found, at depths of 140 mm and 220 mm, respectively. This stresses the need for a better depth control system for the plow designs intended for shallow conditions.

In agreement with the results of Gebresenbet (1989) and Patterson et al. (1980), an increase in speed tended to decrease operating depth. For a given depth setting, a 10 mm decrease in plowing depth was recorded as speed increased from 4.5 to 7.5 km/h. Increase in speed changes the resultant soil force acting on the bottom thus varying the operating depth. The draft component increases with speed due to the greater acceleration of soil, while the vertical force component remains nearly constant. Hence, the resultant soil force vector has a lower angle against the bottom and the bottom will reduce its depth if the angle of the line of pull is not reduced (Morling 1979).

**CONCLUSIONS**

Higher energy requirements and better plowing depth stability were found with the helical (long) bottom compared to the cylindrical (short) model. More specifically, the following conclusions were drawn from this study.

Specific draft force ($D_5$) and fuel consumption for the long bottom are respectively 12% and 6% lower than for the short model plow bottom. Differences in plowing depth standard deviation (SD) among depths and bottom types are not significant. However, SD is highly dependant on plowing depth, especially for the short bottom. Higher SD was found when operating at shallow depths for both bottoms. Coefficient of variability (CV=SD/mean) for both bottoms increases from 5% to 14% as plowing depth decreases from 220 mm to 140 mm. This indicates that increasing difficulties are encountered in maintaining a constant depth with shallow plowing (less than 150 mm).

The short and long bottoms present different relationships for plowing depth and operating speed on $D_5$. Specific draft has a non-linear behaviour with plowing depth for both bottoms. However, speed shows a linear influence on $D_5$ for the long bottom and a non-linear influence for the short model. Regression equations following Goryachkin’s model were developed for each bottom. A lack of fit analysis revealed that none of these equations adequately fit the draft data. Typical field variability was such that simple $D_5$ models based on plow operating parameters of depth and speed do not adequately explain the measured draft data.

Finally, we conclude that, on the basis of $D_5$ and SD, the long bottom shows promise for shallow plowing under Eastern Canadian conditions. The higher CV noted for shallower depths demonstrates the need for a better depth control system on the moldboard plow.

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