Prediction of Disc Harrow Draft Force Based on Soil Moisture Content, Tillage Depth and Forward Speed

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Abstract: As accurate knowledge of draft force is useful for optimal matching of power unit (usually tractor) to tillage implement, this study was conducted to predict draft force (DF) of a double action disc harrow (pull-type) based on soil moisture content (SMC), tillage depth (TD) and forward speed (FS) of the implement. For this purpose, DF of the double action disc harrow was measured at three levels of SMC (11.27, 17.04 and 22.87%), four levels of TD (4, 8, 12 and 16 cm) and four levels of FS (3.05, 4.30, 5.89 and 7.15 km/h). Results of DF measurement at SMCs of 11.27 and 22.87% were utilized to determine multiple-variable regression models and results of DF measurement at SMC of 17.04% were used to verify selected model. The paired samples t-test results showed that the difference between the DF values predicted by selected model and measured by field tests were not statistically significant and to predict draft force of double action disc harrow based on soil moisture content, tillage depth and forward speed of the implement, the multiple-variable regression model DF = 397.2 - 4.920 SMC + 7.250 TD + 2.470 FS^2 with R^2 = 0.89 can be strongly suggested.

Key words: Draft force % Disc harrow % Soil moisture content % Tillage depth % Forward speed % Modeling % Prediction

INTRODUCTION

Tillage involves the movement of soil from one place to another [1, 2]. In conventional farming tillage may consume a major portion of the farm's energy budget. The most convenient method to estimate a given implement's energy requirement is to measure the force required to pull the tillage implement at a desired forward speed [3-5]. The force required to pull a tillage implement through the soil is called draft force. When a tillage implement is pulled through the soil, the power unit (usually a tractor) must overcome draft forces created by soil resistance. The direction of the draft force is in the direction of travel [6].

Accurate knowledge of draft force is useful for optimal matching of power unit to tillage implement [7]. However, draft force varies greatly due to numerous factors that influence it. Since a large number of factors influencing draft requirement and various potential combinations of tillage devices exist, it is prohibitively expensive to test all implements in all conditions for every soil type. Therefore, determining which variables have the greatest influence on the draft requirement for tillage with the most common tillage tools would greatly enhance the process of matching power units to tillage implements [8].

The objective of a large body of existing work has been to study the draft force of a given tillage implement under certain soil conditions and/or operating parameters [4, 5, 9-19]. The ASAE standard D497.4 describes draft force as a function of implement type, soil type, implement width, tillage depth and forward speed [6]. A number of other properties such as static and dynamic component of soil shear stress, soil-metal friction coefficient, soil density and implement geometry are also necessary to consider when analyzing draft force [8, 10, 12, 20]. However, most work that has been done on draft force in the past was focused on specific draft and has concluded that tillage depth is the primary determinant of the amount of force required to pull an implement through soil, with speed often having a significant effect [8, 12, 15, 16, 19].

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As soil moisture content, tillage depth and forward speed of the implement have the greatest influence on the draft requirement for tillage with the most common tillage tools, this study was conducted to predict draft force (DF) of a double action disc harrow (pull-type) based on soil moisture content (SMC), tillage depth (TD) and forward speed (FS) of the implement.

MATERIALS AND METHODS

Experimental Site: Experiments were conducted at the Agricultural Research and Experimental Farm of Shahid Beheshti Technical School at Sari, Mazandaran Province, Iran. The experimental site was located at latitude of 36° 31' N and longitude of 53° 25' E and was 16.4 m above mean sea level.

Soil Sampling and Analysis: A composite soil sample from 48 points was collected from 0-20 cm depth and analyzed in the Laboratory for particle size distribution (sand, silt and clay). The soil in the experimental site was clay. The clay soil was consisted of 49.5% clay, 35.0% silt and 15.5% sand.

Tillage Implement: One commercial double action disc harrow (pull-type) with width of 255 cm was used in this study. This implement was representative of the standard secondary tillage implement most commonly used for seedbed preparation in Iran. It consisted of four groups with 28 discs, each 36 cm in diameter.

Field Methods: There was no crop growth and the field was left fallow. Prior to performing the experiments, the field was irrigated by using a sprinkler irrigation system. Soil samples were collected and weighed during the experiments to determine soil moisture content. The samples were placed in an electric oven maintained at 110° C for 48 hours. The dried soil samples were reweighed and the soil moisture contents were calculated on a dry weight basis. A factorial experiment based on randomized complete block design (RCBD) with three replications was used to evaluate the effect of soil moisture content (SMC), tillage depth (TD) and forward speed (FS) of the implement on draft force of double action disc harrow (pull-type). Three SMC (11.27, 17.04 and 22.87%), four TD (4, 8, 12 and 16 cm) and four FS (3.05, 4.30, 5.89 and 7.15 km/h) were used in a combination resulting in a total of 48 treatments. The treatments were randomly distributed in the field tests.

Experimental Procedure: An experimental block 75 m long by 5 m wide was used for each treatment. A small block of approximately 15 m long by 5 m wide in the beginning of each tested block was used to enable the tractor and implement to reach the required tillage depth and forward speed. Tillage depth was measured as the vertical distance from the top of the undisturbed soil surface to the implement's deepest penetration. During field operations, the tractor was operated at the same tillage depth but at different forward speeds. A Universal 650 tractor with 48.5 kW and in good condition was used in all the experiments. The implement draft force, tillage depth and forward speed during field operations were measured and recorded by an onboard data logger in the tractor cab.

Data Acquisition System: The data acquisition system consisted of a data logger, a towed linkage load cell, a depth position transducer and a fifth wheel. The towed linkage load cell used to measure implement draft force was calibrated prior to the experiments using a specially built calibration rig. A performance test program was developed and documented for the data logger to scan the transducers every second during field operation. Therefore, the number of readings made in each treatment depended on the forward speed of the tractor. To begin the field tests, the depth wheels lever was adjusted to lower the implement corresponding to the tillage depth. Then the tractor was accelerated to the required forward speed with a known gear range before entering the first test block. Data acquisition was activated by pressing the push button switch on the activity unit as the tractor passed the flag marking the beginning of the first test block. Data acquisition continued until the end of the test block. After finishing the first test block, the tractor was again driven straight toward the second test block with a different forward speed and the process was repeated. Similar procedure was repeated for other treatments. Results of draft force measurement at soil moisture contents of 11.27 and 22.87% (Table 1) were utilized to determine multiple-variable regression models and results of draft force measurement at soil moisture content of 17.04% (Table 2) were used to verify selected model.

Regression Model: A typical multiple-variable regression model is shown in equation 1:

$$Y = C_0 + C_1 X_1^r + C_2 X_2^s + C_3 X_3^t \tag{1}$$

Table 1: Results of draft force measurement (three replications) at soil moisture contents of 11.27 and 22.87% used for determining multiple-variable regression models

Soil moisture content (%)	Tillage depth (cm)	Forward speed (km/h)	Draft force of double action disc harrow (kgf)		
			R_1	R_2	R_3
11.27	4	3.05	381	387	387
		4.30	412	413	414
		5.89	425	429	431
		7.15	466	466	472
	8	3.05	410	414	415
		4.30	458	463	465
		5.89	466	482	483
		7.15	570	575	586
	12	3.05	418	418	421
		4.30	463	467	474
		5.89	479	483	487
		7.15	579	583	590
	16	3.05	503	504	505
		4.30	533	533	534
		5.89	545	456	553
		7.15	588	589	591
22.87	4	3.05	353	354	359
		4.30	376	385	386
		5.89	394	395	400
		7.15	431	436	438
	8	3.05	370	372	377
		4.30	407	409	414
		5.89	423	424	426
		7.15	492	493	494
	12	3.05	376	379	382
		4.30	415	416	418
		5.89	430	430	431
		7.15	498	500	503
	16	3.05	423	424	426
		4.30	450	451	453
		5.89	465	465	466
		7.15	503	504	508

Table 2: Results of draft force measurement (three replications) at soil moisture content of 17.04% used for verifying selected model

Soil moisture content (%)	Tillage depth (cm)	Forward speed (km/h)	Draft force of double action disc harrow (kgf)		
			R_1	R_2	R_3
17.04	4	3.05	363	367	380
		4.30	389	398	410
		5.89	403	410	426
		7.15	448	451	460
	8	3.05	388	392	399
		4.30	431	435	442
		5.89	440	444	454
		7.15	511	518	528
	12	3.05	391	398	408
		4.30	431	438	445
		5.89	449	455	464
		7.15	519	525	534
	16	3.05	458	463	471
		4.30	485	491	503
		5.89	501	507	519
		7.15	541	545	555

Table 3: Three multiple-variable regression models and their relations

Model No.	Model	Relation
1	$DF = C_0 + C_1\ SMC + C_2\ TD + C_3\ FS$	$DF = 339.8 - 4.920\ SMC + 7.250\ TD + 25.02\ FS$
2	$DF = C_0 + C_1\ SMC + C_2\ TD^2 + C_3\ FS$	$DF = 370.3 - 4.920\ SMC + 0.350\ TD^2 + 25.02\ FS$
3	$DF = C_0 + C_1\ SMC + C_2\ TD + C_3\ FS^2$	$DF = 397.2 - 4.920\ SMC + 7.250\ TD + 2.470\ FS^2$

where:

Y	=	Dependent variable, for example draft force (DF) of double action disc harrow
X_1, X_2, X_3	=	Independent variables, for example soil moisture content (SMC), tillage depth (TD) and forward speed (FS) of the implement, respectively
r, s, t	=	Power of the independent variables
C_0, C_1, C_2, C_3	=	Regression coefficients

In order to predict draft force of disc harrow from soil moisture content, tillage depth and forward speed of the implement, three multiple-variable regression models were suggested and all the data were subjected to regression analysis using the Microsoft Excel 2007. Three multiple-variable regression models and their relations are shown in Table 3.

Statistical Analysis: A paired samples t-test and the mean difference confidence interval approach were used to compare the draft force values predicted by selected model with the draft force values measured by field tests. The Bland-Altman approach [21] was also used to plot the agreement between the draft force values measured by field tests with the draft force values predicted by selected model. The statistical analyses were also performed using the Microsoft Excel 2007.

RESULTS AND DISCUSSION

The p-value of independent variables and coefficient of determination (R^2) for the three multiple-variable regression models are shown in Table 4. Among the three models, model No. 3 had the highest R^2 value (0.89). Moreover, this model totally had the lowest p-value of independent variables among the three models. Based on the statistical results model No. 3 was selected as the best model, which is given by equation 2:

$$DF = 397.2 - 4.920\ SMC + 7.250\ TD + 2.470\ FS^2 \qquad (2)$$

Draft force of the double action disc harrow was then predicted for SMC of 17.04% at four levels of TD (4, 8, 12 and 16 cm) and four levels of FS (3.05, 4.30, 5.89 and
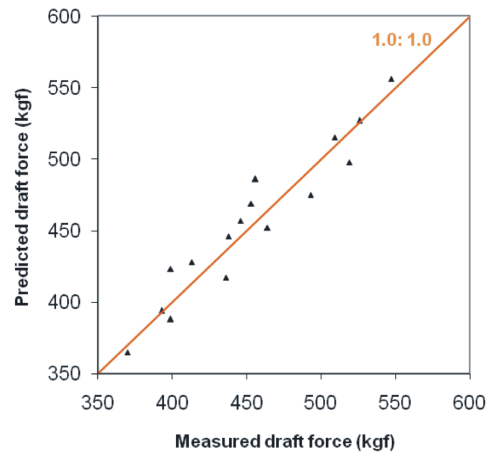

Fig. 1: Measured draft force by field tests and predicted draft force by model No. 3 with the line of equality (1.0: 1.0)
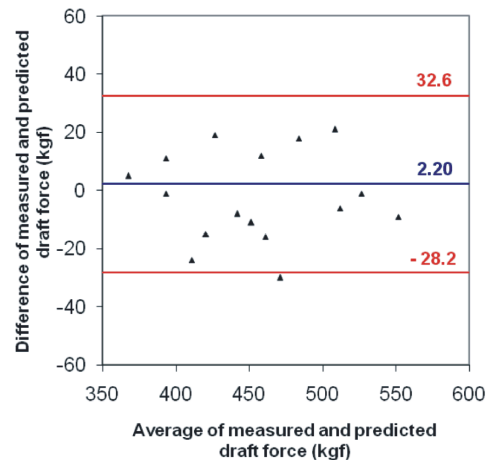

Fig. 2: Bland-Altman plot for the comparison of measured draft force by field tests and predicted draft force by model No. 3; the outer lines indicate the 95% limits of agreement (-28.2, 32.6) and the center line shows the average difference (2.20)

7.15 km/h) using the multiple-variable regression model No. 3. The draft force values predicted by model No. 3 were compared with the draft force values measured by field tests and are shown in Table 5. A plot of the draft force values predicted by model No. 3 and the draft force values measured by field tests with the line of equality (1.0: 1.0) is shown in Fig. 1. Moreover, a paired samples

Table 4: The p-value of independent variables and coefficient of determination (R^2) for the three multiple-variable regression models

Model No.	p-value					R^2
	SMC	TD	TD^2	FS	FS^2	
1	4.54E-22	1.64E-25	---	7.46E-31	---	0.88
2	5.81E-21	---	9.42E-24	1.60E-29	---	0.86
3	2.95E-23	8.47E-27	---	---	1.12E-12	0.89

Table 5: Soil moisture content, tillage depth, forward speed and draft force of double action disc harrow used in evaluating model No. 3

Soil moisture content (%)	Tillage depth (cm)	Forward speed (km/h)	Draft force of double action disc harrow (kgf)		Average of measured and predicted draft force (kgf)	Difference of measured and predicted draft force (kgf)
			Measured by field tests	Predicted by model No. 3		
17.037	4	3.05	370	365	368	5
		4.30	399	388	394	11
		5.89	413	428	421	-15
		7.15	453	469	461	-16
	8	3.05	393	394	394	-1
		4.30	436	417	427	19
		5.89	446	457	452	-11
		7.15	519	498	508	21
	12	3.05	399	423	411	-24
		4.30	438	446	442	-8
		5.89	456	486	471	-30
		7.15	526	527	526	-1
	16	3.05	464	452	458	12
		4.30	493	475	484	18
		5.89	509	515	512	-6
		7.15	547	556	551	-9

Table 6: Paired samples t-test analysis on comparing draft force determination methods

Determination methods	Average difference (kgf)	Standard deviation of difference (kgf)	p-value	95% confidence intervals for the difference in means (kgf)
Field tests vs. model No. 3	2.20	15.5	0.5806	-6.10, 10.5

t-test and the mean difference interval approach were used to compare the draft force values predicted by model No. 3 with the draft force values measured by field tests. The Bland-Altman approach [21] was also used to plot the agreement between the draft force values measured by field tests with the draft force values predicted by model No. 3. The average draft force difference between two methods was 2.20 kgf (95% confidence intervals for the difference in means: -6.10 kgf and 10.5 kgf; P = 0.5806). The standard deviation of the draft force difference was 15.5 kgf (Table 6). The paired samples t-test results showed that the draft force values predicted by model No. 3 were not significantly different than the draft force values measured by field tests. The draft force difference values between two methods were normally distributed and 95% of these differences were expected to lie between μ-1.96F and μ+1.96F, known as 95% limits of agreement [22-25]. The 95% limits of agreement for comparison of the draft force values determined by field tests and model No. 3 was calculated at -28.2 kgf and 32.6 kgf (Fig. 2). Thus, the draft force values predicted by model No. 3 may be 28.2 kgf lower or 32.6 kgf higher than the draft force values measured by field tests. The average percentage difference for the draft force values predicted by model No. 3 and measured by field tests was 2.9%.

CONCLUSIONS

It can be concluded that the multiple-variable regression model DF = 397.2 - 4.920 SMC + 7.250 TD + 2.470 FS^2 with R^2 = 0.89 can be strongly recommended to predict draft force (DF) of double action disc harrow (pull-type) based on soil moisture content (SMC), tillage depth (TD) and forward speed (FS) of the implement.

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