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Article

Multilevel modelling of the draft force required by seeder-fertilizers

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Abstract

The high production costs in agriculture have guiding the adoption of farming systems and new management techniques as well as the sizing of agricultural machinery. In this regard, planning entails knowledge on the efficiency according to the energy requirements parameters, so the farmer shall consider the characteristics of the soil on which the implement operates. The performance assessment of sowing-fertilize machines shows the effect of some variables on the draft requirement, so the experimental conditions, which might lead to different outcomes of implement operation, must be regarded. Therefore, it is necessary obtain metanalytical estimates to integrate the results available in the literature. Grounded on systematic review, this study aimed to model the draft imposed by sowing-fertilizing machines considering fixed effects, mainly soil characteristics, and random effects associated to the selected experiments. It was found that the best models according to information criteria may not always meet the assumptions as normality of the distribution of residuals and homoscedasticity. The variables such as bulk density of soil, stubble conditions, depth of fertilizer placement, and speed could accurately explain the draft requirement with mean squared deviation of 2.93 whereas the referred evaluator for the ASABE standard was 63.51. Forthcoming works may analyze the repeatability of the models considering different seeders under diverse configurations and operation conditions

Keywords: ASABE, cultivation, meta-analysis, soil properties

Introduction

The adoption of farming systems and new management techniques has mainly focused on the reduction in energy requirements in agricultural operations in face of increased production costs in agriculture. The proper use of machines and implements enables the rural producer to reach better operational performance through the increase of effective field capacity and better fuel efficiency (Furlani et al., 2013; Tricai et al., 2016).

According to the American Society of Agricultural and Biological Engineers (ASABE), the draft force required by precision seeders moving through the field with a prepared seedbed is 900 N ± 25% per row (drawn-seeding only) and 3,400 N ± 35% per row (seeding, fertilizing and herbicide application). Through technical standards, the model used by ASABE reports the draft force, after using machine-specific parameters, considering the number of rows and soil textural classification (ASABE, 2011).

However, the traction efficiency is affected by the presence of previous crop's stubble (Kamimura et al., 2009; Altikat et al., 2013; Ahmad et al., 2015), tillage management practices (Furlani et al., 2008; McLaughlin et al., 2008), soil characteristics (Collins & Fowler, 1996; Canakci et al., 2009; Cepik et al., 2010), furrow depth (McLaughlin et al., 2008; Cepik et al.,

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2010; Palma et al., 2010; Rinaldi et al., 2010), and opener design (Collins & Fowler, 1996; Hasimu & Chen, 2014).

Furthermore, the draft force required by seeders may possibly display different behaviors depending upon field conditions. Its estimation may be associated with high coefficient of variability, which is recognized as a source of error in performance comparison on implements due to different soil characteristics (Collins & Fowler, 1996).

In this regard, it was pertinent to make a systematic review supported by statistical techniques to appraise findings from several empirical studies for the purpose of calculating estimates that summarize their data. The application of that methodology implies a rigorous alternative to descriptive reviews of the literature, explained not only by the bias minimization but also the increase in the statistical power of the primary researches (Sacks et al., 1996; Koretz & Lipman, 2017).

Thus, one may generate multilevel models that incorporate both fixed and random effects. The fixed effects are reproducible covariates and the random ones denote levels of variation besides the deviation of each observation normally incorporated to regression models (Bates et al., 2015).

Therefore, the aim of this study is to estimate the draft force required by seeder-fertilizer machines considering 379 observations from research papers collected through systematic review of the literature. The equations were obtained by maximum likelihood and the models of evaluation were selected by Corrected Akaike Information Criterion.

Material and Methods

This study initiated with the systematization of a dataset obtained from literature review that encompassed publications in indexed journals, dissertations, theses and research bodies' technical reports. Those studies described the tractive effort required under certain operational conditions of the experiments.

At that point the criteria of data collection were tightened up and each observation was depicted according to experimental area characterization, tillage management practices, furrow opener dimensions and design, and some implement adjustments. That enabled it to consider 10 fixed effects such as: relative proportion of soil particle size fractions, moisture content, bulk density of soil, stubble condition, soil penetration resistance, depth of fertilizer placement, and the speed of tractor and implement setup.

The presence of relevant variables in the results of the reviews and detailed description of the methodology and experimental field became initially the main eligibility criteria for primary researches. Among the experiments assessed, 43 were selected and included in the dataset, amounting to 379 observations. Those studies were published between 2000 and 2016.

The general model used to estimate the draft force per row required by a seeder-fertilizer is depicted by Equation 1:

$$Y_{ijk} = X_{ijk}^{T}\beta + s_j + \varepsilon_{ijk} \quad (1)$$

where Y_{ijk} is the k-th observation of the draft force per row, X_{ijk}^{T} is the transposed observations matrix, β is the fixed-effect parameters vector, s_j is the random effect associated to j-th study, and ε_{ijk} is the residual error.

It is assumed that $\varepsilon_{ijk} \sim N(0,\sigma^2)$, where σ^2 is the residual variance, and $s_j \sim N(0,\sigma_s^2)$, where σ_s^2 is the variance among experiments. All the models were fitted by maximum likelihood, using the lme4 package in R programming environment (Bates et al., 2015).

The best models were selected according to the Corrected Akaike Information Criterion (AICc) (Kletting & Glatting, 2009), depicted by the Equation 2:

$$AIC_c = AIC + \frac{2(k+1)(k+2)}{n-k-2} \quad (2)$$

where k is the number of parameters in the model, and n is the sample size. The first term in Equation 2 is the Akaike Information Criterion (AIC) (Akaike, 1974), which is expressed by equation 3:

$$AIC(\theta) = -2\log[L(\theta)] + 2k \quad (3)$$

where L(θ) is the maximum likelihood function and k is number of fitted parameters to find θ.

Results and Discussion

The technical standard ASAE D497.7 MAR2011 (ASABE, 2011) applied to seeder-fertilizers, after using machine-specific parameters, may be briefly depicted by Equation 4:

$$D = F_i \cdot 1820 \cdot W \quad (4)$$

where D is the implement draft, F_i is a soil texture adjustment parameter, and W is number of rows.

The Figure 1 depicts the relationship between the mean drawbar force in each selected experiment and its corresponding estimate according to ASABE's equation. One may see the data points scattered; some of them does not cluster around the identity line. It indicates clear discrepancy between observed values and its estimates.

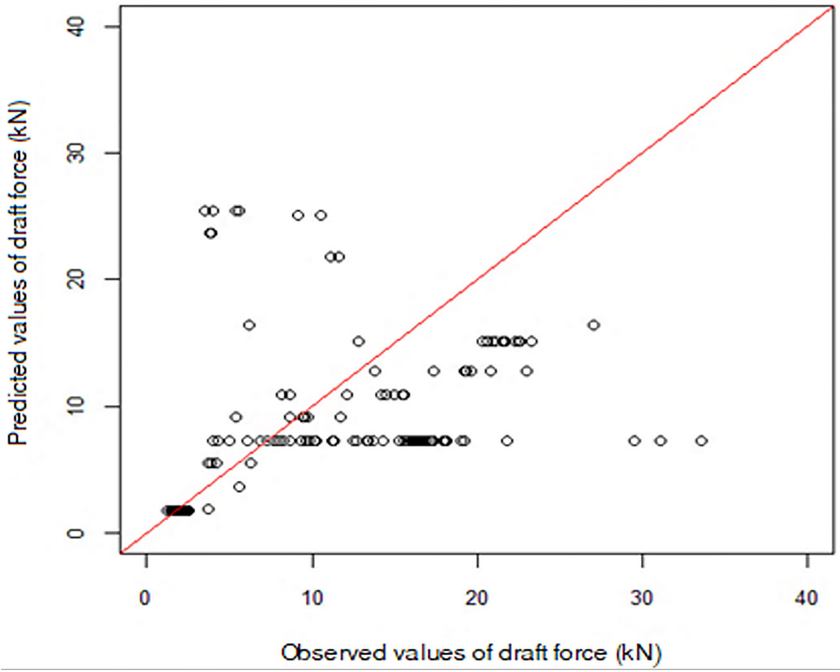

Figure 1. Predicted and observed values of mean drawbar force.

In the experiment conducted by Silveira et al. (2005), for instance, the draft force required to pull a drawn seeder with 14 rows in clay soil was 3.56 kN and 5.61 kN, at the speed of de 5.24 km.h^{-1} e 7.09 km.h^{-1} respectively. However, the drawbar draft according to ASABE would be 25,48 kN, regardless the speed of tractor and implement setup. This value is 453% higher than the highest value observed in that experiment.

It also must highlight that the ASABE's equation tends to underestimate the mean draft requirement. Among the drawn seeders, the expected draft estimated by the technical standard is lower than observed values in 78.3% of the selected observations. Moreover, only 20% of observed values are in the ± 25% expected range in drafts.

The mean squared error (MSE) of the ASABE's model was equal to 63.51. When that statistics is partitioned into components according to the approach of Kobayashi & Salam (2000), the model bias is approximately 3.53, supporting the occurrence of draft estimates systematically lower than observed outputs.

Initially 511 model without interaction effects were generated in order to estimate the mean draft per seeding line comprising all the possible combinations (subsets) of parameters of the global model. Those parameters were estimated by maximum likelihood and sorted by AICc values in ascending order.

The Figure 2 displays the lower AICc values found in each subset of models, with the same number of parameters. One may see that the lowest AICc value corresponds to a model with 5 independent variables, that is, min[AICc(k=5)] = 110.7729. For models with more than 5 coefficients, the penalty term has more weight.

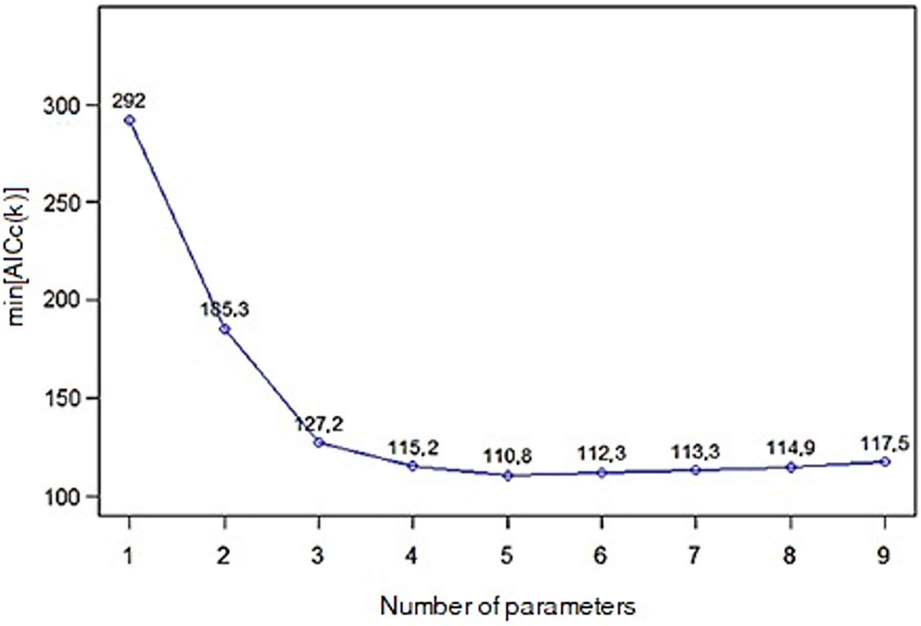

Figure 2. Minimum AICc and number of parameters

The models with only one independent variable have rather discrepant AICc values. The highest one was 788.6244, when the fixed effect was only the speed whereas the lowest value (AICc = 292.0220) corresponds to the model in which the only independent variables was the depth of fertilizer placement.

The Table 1 presents the coefficient estimates of the 10 best models selected according to the lowest AICc values.

Table 1. Model coefficients

Model	AICc	b [1]	Fixed Effects [2]								
			ARE	SIL	ARG	UMI	DEN	RCUL	RPEN	PADU	VEL
F323	110.77	1.027	-3.090	-	-	-	0.346	0.012	-	0.129	0.059
F358	112.01	2.647	-	2.264	-	-	-1.780	0.019	-	0.130	0.059
F458	112.27	2.399	-	7.272	-	-	-2.916	0.008	0.441	0.129	0.059
F437	112.80	1.367	-1.906	-	-	-	-0.433	0.012	0.222	0.130	0.059
F434	113.15	0.123	-2.003	-	-	2.166	0.324	0.010	-	0.129	0.059
F414	113.28	1.088	-3.034	0.791	-	-	0.175	0.012	-	0.129	0.058
F429	113.28	1.879	-3.825	-	-0.791	-	0.175	0.012	-	0.129	0.058
F450	113.28	-1.946	-	3.825	3.034	-	0.175	0.012	-	0.129	0.058
F478	113.28	1.088	-3.034	0.791	-	-	0.175	0.012	-	0.129	0.058
F455	113.39	-0.208	-	1.147	-	4.241	-0.446	0.009	-	0.129	0.059

[1] Intercept [2] Sand fraction (ARE), silt fraction (ARE), clay fraction (ARG), moisture content (UMI), bulk density (DEN), stubble condition (RCUL), soil penetration resistance (RPEN), depth of fertilizer placement (PADU), and speed (VEL)

As it may be appreciated, the effects such as bulk density (DEN), stubble conditions (RCUL), depth of fertilizer placement (PADU), and speed (VEL) are in all models above (Table 1). Those models, however, did not meet the normality assumptions through Lilliefors test so interaction effects must be regarded.

For this purpose, 8,490 models with interaction were generated. The Table 2 presents 5 models, with lowest AICc values, that did not have the hypothesis of normality of the residues rejected according to Lilliefors test.

The lowest AIC value was 67.85; the highest, 69.40 (Table 2). The lowest mean squared deviation (MSE) was 2.801 and the highest, 2.933. As far as the adjusted coefficient of determination is concerned, at least 93% of the experimental data could be explained by those models. The Table 3 displays the coefficient estimates of those models.

The model F8150, for example, is the most parsimonious and has easy applicability in the field. That model is depicted by Equation 5:

Table 2. Model selection criteria

Model [1]	P-value [2]	MSE	Adjusted R^2	AICc
F8150	0.066	2.933	0.934	67.85
F1537	0.061	2.823	0.938	68.09
F5382	0.107	2.801	0.937	68.22
F1544	0.054	2.823	0.937	68.40
F7252	0.062	2.827	0.936	69.40

[1] The models are sorted by AICc values in ascending order. [2] Lilliefors test

Table 3. Coefficient estimates of the models with interaction effects

Model	Intercept	Fixed Effects [1]							
		ARE	SIL	DEN	RCUL	PADU	VEL	Interactions	
F8150	-1.494	-	-	1.666	-0.192	0.641	0.081	RCUL·PADU 0.020	DEN·PADU -0.386
F1537	-6.188	-1.820	-	4.659	0.006	0.965	0.121	VEL·ARE -0.100	DEN·PADU -0.553
F5382	2.535	-	3.398	-1.182	-0.303	0.171	0.063	RCUL·PADU 0.031	PADU·SIL -0.691
F1544	-5.876	-	0.524	3.991	0.007	0.978	0.187	VEL·SIL -0.430	DEN·PADU -0.560
F7252	-5.663	-1.676	-	4.238	0.072	0.931	0.082	RCUL·ARE -0.153	DEN·PADU -0.531

[1] Sand fraction (ARE), silt fraction (ARE), bulk density (DEN), stubble conditions (RCUL), depth of fertilizer placement (PADU), and speed (VEL)

$$Flin = -1.494 + 1.666 \cdot Den - 0.192 \cdot Rcul + 0.641 \cdot Padu + 0.081 \cdot Vel + 0.020 \cdot Rcul \cdot Padu - 0.386 \cdot Den \cdot Padu \quad (5)$$

where Flin is the draft force per row ($kN.row^{-1}$), Den is the bulk density of the soil ($Mg.m^{-3}$), Rcul is the mass of stubble on the surface per area ($t.ha^{-1}$), Padu is the working depth of the fertilizer furrow opener (cm), and Vel is the speed of tractor-implement setup ($km.h^{-1}$).

The variables of that model are associated to measure unities customarily used in the field and in the literature. As one may see, the variable bulk density has the greatest effect on mean draft force whereas the effect of the mass of surface stubble on draft requirement is minimal.

That equation also may be used to calculate the mean drawbar force requirements, multiplying Flin by the number of the rows in the seeder-fertilizer. The mean draft force was not specifically modelled because the maximum likelihood algorithm had failed to converge for most of models. In some extent, the great discrepancy between the number of rows and the other effects may have caused the non-convergence.

As for meeting the normality assumptions (Figure 3), one may observe the distribution of residuals for the selected model (Equation 5) closer to the normality than the models without fixed effects interactions. The histogram of residuals does not have skewness or outliers.

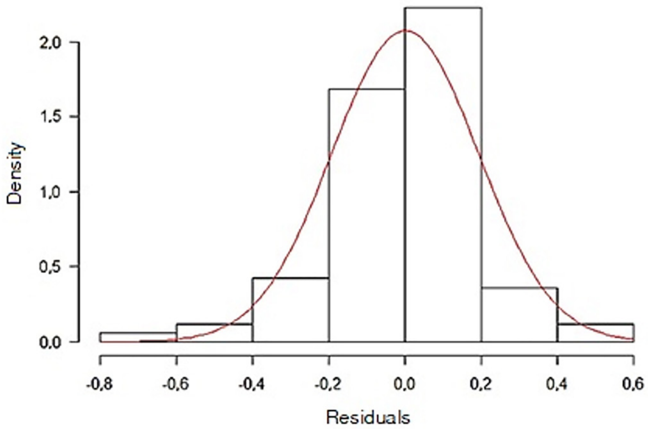

Figure 3. Histogram of the model F8150

Conclusions

The model proposed in this study to predict the draft force per row presented lower error, when compared with ASABE's equation. The mean squared error of the generated model was 2.93 whereas the referred evaluator for the ASABE standard was 63.51. Additionally, the coefficients set out in the model present the influence of other variables that must be regarded in the draft prediction, such as bulk density of the soil, mass of stubble on the surface per area, working depth, and speed.

Lastly, the information criteria were efficient in model selection alternatively to the use of statistical significance. However, follow-up studies must validate the model through new experiments under diverse planter adjustments and soil conditions.

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