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Stem bending force and hydraulic system pressure sensing for predicting napiergrass yield during harvesting

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ABSTRACT

Napiergrass, which resembles sugarcane in stature and cultivation practices, is emerging as a candidate bioenergy crop. However, limited studies investigating harvesting and yield sensing of napiergrass are available. This study investigated stem-bending force, and the hydraulic pressures of basecutter, chopper and elevator drives in a John Deere 3522 sugarcane billet harvester as indicators of napiergrass yield. The coefficients of determination (R^2) between napiergrass yield and hydraulic pressures were 0.73, 0.88 and 0.81, respectively for the basecutter, chopper and elevator drives. The highest correlation ($R^2 = 0.92$) was found between stem-bending force and napiergrass yield. The yield prediction errors were 4.9% and 8.6% for the calibration and validation plots with the stem-bending force yield sensor. Cross-validation, in which each harvested row was treated as a data point, showed that the average yield prediction errors were 10.9% and 11.8% for the calibration and validation data sets. Yield maps were also generated employing the stem-bending yield sensor. In addition, it was expected that the stem-bending yield sensor could be utilized to control harvester operation such as travel speed. Further studies would be needed to extend the stem-bending concept to other thick stemmed crops.

1. Introduction

Many crops are being investigated for producing cellulosic ethanol in the United States. Napiergrass [*Pennisetum purpureum* (L.) Schum.], also known as elephantgrass, is used as a fodder crop and is being considered as a candidate bioenergy crop in Florida and Georgia (Knoll et al., 2012; Singh et al., 2013; Richard and Anderson, 2014). It resembles sugarcane in stature and in methods of propagation. Yields of between 30 and 60 Mg ha^{-1} yr^{-1} of DM have been observed in southern and central Florida (Richard and Anderson, 2014). High crop moisture and intermittent rains posed challenges in mowing and baling of napiergrass (Mislevy and Fluck, 1992). However, limited studies are available for napiergrass harvesting employing sugarcane harvesting machinery. Similarly, limited studies are available for napiergrass yield sensing, although development of that technology can play an important role in implementing precision agriculture and reducing harvesting cost (Mathanker and Hansen, 2014).

Many sensing approaches have been studied to measure yield of bioenergy crops. A patent was granted in which the yield sensor predicted results by measuring impingement force, forage volume, and drive load (Shinners, 2002). Five different types of sensors were mounted on a forage harvester and sensed data were correlated with timothy grass yield (Savoie et al., 2002). Bale weights were measured for estimating mass-flow rate through a large square baler (Shinners et al., 2003). Similarly, torque and hydraulic pressure drop were recorded to measure the grass mass flow (Wild et al., 2005). The influence of conveyer belt parameters on grass mass flow was also investigated (Wild and Ruhland, 2007). The conditioner power was correlated with alfalfa yield ($R^2 = 0.73$) (Kumhála et al., 2007). A weighing plate mounted on a sugarcane harvester predicted sugarcane yield with an accuracy of 89% (Mailander et al., 2010). A fiber optic yield monitoring system was developed for sugarcane billet harvesters (Price et al., 2011). Grass heights measured with an ultra-sonic sensor predicted biomass yield with an accuracy of 78.6% (Fricke et al., 2011). Mathanker et al. (2014a) developed a "look-ahead" yield sensing

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system that converted the bending load of *miscanthus* stems to a measure of yield (Fig. 1a).

Various options for napiergrass yield sensing were explored, and it was proposed to investigate stem bending force and the hydraulic pressures of the basecutter, chopper, and elevator drives as indicators of napiergrass yield. The specific objectives of this study were to: (a) develop a napiergrass stem-bending yield sensor, (b) measure hydraulic pressures of basecutter, chopper, and elevator drives, (c) determine the correlations between sensed parameters and napiergrass yield, and (d) calculate the yield prediction accuracy and generate yield maps with the stem-bending yield sensor.

2. Materials and methods

A stem-bending yield sensor was developed to fit a John Deere 3522 sugarcane billet harvester (John Deere, Thibodaux, LA) based on the concept (Fig. 1a) advanced by Mathanker et al. (2014a) for a mower-conditioner. Four S type load cells with a maximum load rating of 990 N (Transducer Techniques, Temecula, CA) were fitted between two parallel pipes to form a push bar. The push bar was installed between the crop dividers as shown in Fig. 1b about 1.2 m above the ground and 1.5 m ahead of the basecutter. It was fitted without modifying the functioning of the knockdown rollers.

Three 69 MPa pressure sensors (Model Z, Honeywell, Columbus, OH) were fitted to the inlets of the hydraulic motors operating the basecutter, chopper, and elevator of the John Deere 3522 sugarcane billet harvester. The technical specifications of the hydraulic motors are given in Table 1. A GPS (Global Positioning System) unit (1-EGPS-200-P-2, Hottinger Baldwin Measurements Inc., Marlboro, MA) was used to record latitude and longitude of the harvester at 1 s intervals. The load cells and pressure sensors were sampled at 200 Hz and averaged values at 1 s intervals were recorded using a data acquisition system (1-ECPU-PLUS-COM-2, Hottinger Baldwin Measurements Inc., Marlboro, MA). The load cell values were offset to account for residual forces experienced due to working of the harvester components. The offset was determined by measuring the load cell values when the harvester was at headlands.

The second ratoon napiergrass crop (variety: PI 300086; row spacing: 1.5 m; row length: 250 m; location: Lorida (27.3433°N, 81.2212°W), Florida) was harvested by employing the John Deere 3522 dual-row sugarcane harvester (Fig. 2) using green harvesting techniques. Average harvester speed was 4.6 km h^{-1} and efforts were made to maintain a consistent cutting height of 50 mm. The billeted napiergrass crop was collected in a calibrated weigh wagon and weight recorded at the end of each crop row. The weight of green biomass collected from each row was divided by the row area to determine the yield. All the observed yield data in this study are reported on a wet basis and the average moisture

Table 1
Technical specifications of the hydraulic motors that operated the basecutter, chopper, and elevator of the John Deere 3522 sugarcane billet harvester.

S. No.	Parameter	Base-cutter	Chopper	Elevator
1.	Type	Axial piston	Radial piston	Disc valve
2.	Relief pressure (MPa)	34.5	34.5	24.1
3.	Flow rate (L s^{-1})	3.30	3.30	1.84

content of the harvested crop was 64.3%. The pressure values recorded at 1 s intervals were averaged for each row. In contrast, the bending force values for a row were added to obtain an accumulated bending force following the procedure described by Mathanker et al. (2014a). In determining the correlations between yield and sensed parameters, a row was treated as a data point.

The yield prediction errors [(predicted–observed) × 100/observed] were determined for the stem-bending yield sensor following two approaches. In the first case, the single row data points from two plots were used to calibrate the model and the single row data points from the third plot were used to validate it. The calibrated linear model and recorded GPS coordinates were used to generate yield maps for the three plots. In addition, the yield prediction errors for each row of the three plots were calculated.

In the second case, cross-validation was carried out by randomly allocating the row data points into calibration and validation data sets. For this approach, a model was "trained" utilizing the calibration data set and tested for validity using the validation data set. Twenty random runs were made following the methodology of Mathanker et al. (2011). Average prediction errors and root mean square errors for the twenty random runs were calculated.

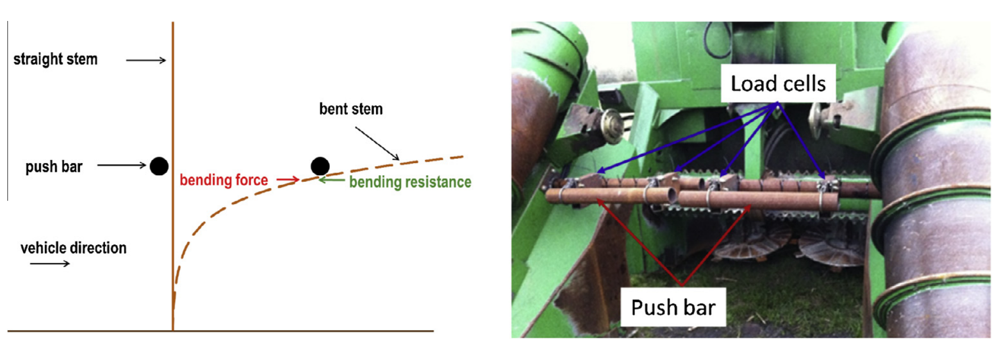
3. Results and discussion

Section 3.1 presents correlations between the sensed parameters and napiergrass yield on a wet weight basis. Section 3.2 presents detailed analysis for the stem-bending yield sensor.

3.1. Yield and sensed parameter correlations

The correlations between the sensed parameters and napiergrass yield (Mg ha^{-1}) are shown in Fig. 3. Among the sensed hydraulic pressures, the chopper pressure showed the highest correlation (Fig. 3b). The sensed bending force showed the best correlation among all four sensing approaches evaluated.

A reasonable coefficient of determination (R^2 = 0.73) was found between the basecutter pressure and yield. In addition to yield, it is expected that the basecutter pressure would depend on cutting height. In commercial sugarcane harvesting applications, operators actually use basecutter pressure to determine the appropriate



(a) (b)

Fig. 1. (a) Concept diagram of stem bending force sensing system; (b) stem-bending force yield sensor fitted to a John Deere 3522 sugarcane harvester.