PRESION AGRICULTURE AS APPLIED TO NORTH AMERICAN HAY AND FORAGE PRODUCTION

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ABSTRACT

This research developed systems to measure mass-flow of hay and forage using a self-propelled windrower, self-propelled forage harvester and large square baler in order to generate yield maps of hay and forage production.

The windrower was used to collect mass-flow and yield data in alfalfa using systems to measure: (1) impact force at the swath forming shield; (2) crop volumetric flow past the swath forming shield; (3) conditioning roll speed; (4) platform pitch; and (5) pressure of platform drive motor. Some sensors systems were promising but even the most promising will require further evaluation because the average absolute mass-flow prediction error and 90th percentile error were 13.4 and 26.4%, respectively, above the desired maximum of 5 and 10%.

The forage harvester was used to collect mass-flow and yield data in wilted alfalfa and whole-plant corn silage using systems to measure: (1) feedroll displacement; (2) crop impact force in the spout; (3) blower speed; and (4) depth of material in the spout. The accuracy of these sensors was much better in whole-plant corn silage than in wilted alfalfa, primarily because the former fed much more uniformly. The average absolute and 90th percentile errors were 12.3 and 24.2%, respectively, for wilted alfalfa, and 4.4 and 7.4%, respectively, for whole-plant corn silage.

The large square baler was used to collect mass-flow and yield data in dry alfalfa using sensor systems to measure: (1) bale velocity; and (2) dynamic bale weight on the chute. The bale velocity and weight measurement systems were excellent at predicting mass-flow with typical absolute and 90th percentile errors of 1.4 and 3.2%, respectively.

Multi-parameter regression models were developed to predict mass-flow for each of the three machines. These models were then used to create yield maps using the output from selected sensors. The resolution of the yield maps was a function of the width of the harvested strip. The resolution of the yield maps was the best with the windrower and forage harvester in whole-plant corn silage because these machines had the narrowest harvesting widths. The map resolution was less with the forage harvester harvesting wilted alfalfa and with the large square baler because multiple windrows were often merged together to meet the capacity needs of the machines. The developed yield maps were quite capable of showing spatial differences in yield that corresponded very well to differences in elevation, soil type, traffic patterns and fertility. The hay and forage mass-flow sensor systems and yield mapping systems should become a valuable precision farming tool.

KEYWORDS. Hay, Forage, Precision Agriculture, Mass-Flow, Yield, Mapping

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INTRODUCTION

The development of methods to measure yield on hay and forage harvesting equipment has closely followed that of grain harvesting systems, however the development of a workable system for hay and forage crops has proved more difficult. The difficulties in developing these systems can be partially attributed to the very high mass-flow-rates passing through the machines, the short dwell time of a few seconds that the material resides in the machines, and the wide range of physical properties, especially moisture, of the varied hay and forage crops as they progress from cutting to harvest. Also, hay and forage crops may be handled several times from cutting to harvest, leading to problems with non-uniform flow and displacement of the crop from growth to harvest location. Forages such as grasses, alfalfa and corn silage have relatively low value, so they are typically converted to value-added products by feeding them to ruminant animals on the same farm where forage production took place. Spatial knowledge of hay and forage yield and moisture could be used to alter the rate of seeds, fertilizer and animal manure at economically and environmentally sustainable levels. Spatial yield information could also be used for management decisions like rotation scheduling and selection of cultivars for local agronomic conditions. The application rate of silage inoculants and hay preservatives could be optimized based on crop mass-flow and moisture. Spatial yield and moisture information could be used as a basis for payment when hay or forages are harvested on a custom basis. Although reliable and accurate systems to measure hay and forage yield are not yet widely available, these systems obviously have promise to improve hay and forage production systems.

Research efforts to develop hay and forage yield and moisture monitoring systems have concentrated on three machines: windrowers or mower-conditioners, forage harvesters and balers. Research on cutting equipment has been limited to measuring mass-flow on self-propelled windrowers (Barnett, 1998; Schlesser, 2000; Shinners et al., 2000a; Lehnert, 2002; Huenink, 2003). These systems typically involved relating mass-flow to cutting platform load, conditioning roll displacement or crop impact at the roll exit. Much research has been conducted to measure mass-flow and moisture on the forage harvester (Mains et al., 1984; Vansichen and Baerdemaeker, 1993; Van der Werf et al., 1994; Auernhammer et al., 1995; Minnichoffer, 1996; Godwin and Wheeler, 1997; Barnett and Shinners, 1998; Tietz, 1998; Kromer et al., 1999; Martel and Savoie, 2000; Schlesser, 2000; Forristal and Keppel, 2001; Ehlert, 2002; Savoie et al., 2002; Huenink, 2003). Mass-flow has typically been estimated by relating it to feedroll displacement or lift force, impact force in the spout, and thickness of the material in the spout or it has been measured directly by continuously weighing the contents of the wagon or truck. Research on the large round baler has focused primarily on dynamic weight measurement of the bale during formation (Wild et al., 1994; Behme et al., 1997; and Wild and Auernhammer, 1997). Research performed on a large square baler used volumetric displacement and dynamic bale weight to predict mass-flow-rate (Barnett, 1998; Schlesser, 2000; Shinners et al., 2000b; Sauter et al., 2001; Huenink, 2003). Unfortunately, none of these sensor systems has been developed into a commercially viable yield measuring system that has been adapted to any hay and forage harvesting equipment. Although estimates of the wet-mass and volumetric flow-rates through the machines have correlated well with actual, errors in estimating dry matter yield have been caused by poor performance of sensors to dynamically measure crop moisture during harvest. This problem has created another area of research related to forage yield measuring: dynamic moisture measurement (Kormann and Auernhammer 2000; Shinners et al., 2000b; Eubanks and Birrell, 2001; Snell et al., 2001; Osman et al., 2002; Snell et al., 2002; and Huenink, 2003). Moisture sensors used on the forage harvesters and balers has included conductance, capacitance, near-infrared, and microwave types.
OBJECTIVES

Our general objectives were to conduct research on systems to measure hay and forage mass-flow and yield and to use this information to determine if spatial differences in yield corresponded to known differences in elevation, soil type, moisture, and fertility. Our specific objectives were:

1. To design, fabricate, adapt, and conduct field evaluation of sensor systems to measure mass-flow-rate on a windrower, a forage harvester and a large square baler.
2. To develop multi-parameter mathematical yield prediction models based on the raw data of mass-flow-rate as a function of sensor output.
3. To collect additional sensor data and to use the developed model to produce yield maps of hay and forage crops based on the new sensor data.
4. To assess the accuracy of the sensor systems and to determine if spatial differences in yield corresponded to known field variations.

SENSOR SYSTEMS AND PROCEDURES

Data Acquisition

The data acquisition system contained two sub-systems: (1) GPS system to record the location data and (2) data acquisition system to record the individual sensor data. For the location sub-system, a laptop computer equipped with ESRI ArcPad™ 6.0 software was used to collect the GPS data from a StarFire™ receiver at five samples per second. To record sensor data, a laptop computer equipped with National Instruments LabVIEW® 6.0, NIDAQCard™-700, and NIDAQ driver 6.9.1 software was used. The sensor system had a sampling rate of 100 Hz and every 20 points were averaged to give a recorded sampling rate of 5 Hz. All sensor data was passed through a first order low pass Butterworth filter at a cutoff frequency of 1 Hz. The GPS system was sampled at 5 Hz. In order to make the two data streams compatible, the data files were linked by time. Before data acquisition, both systems were synchronized to GMT.

Windrower

Sensors placed on the windrower included: (1) pressure sensor to measure load at platform drive motor; (2) speed pick-up to measure conditioning roll speed, (3) capacitive liquid inclinometer to measure platform pitch, (4) load cell to measure crop impact on swath forming shield, (5) rotary potentiometers to measure crop volumetric flow past the swath forming shield and (6) radar to measure ground speed. The platform load sensor performance was erratic and not a good predictor of mass-flow. Roll speed was well correlated with mass-flow because greater mass-flow resulted in greater motor load and lower volumetric efficiency. Crop impact force on, or volumetric flow past, the swath shield was a function of mass-flow, roll exit speed and inclination, so the output of three separate sensors was needed to estimate mass-flow.

Crops harvested were either alfalfa or an alfalfa and grass mixture. Twelve fields were cut in 1st through 4th cutting. Two types of tests were conducted: (1) tests where the field was sectioned into cells of 100 to 150-m length to calibrate the sensor output; or (2) tests where entire fields were cut for mapping. Each calibration test cell or windrow was marked for identification after cutting and samples were hand collected to determine DM content. After a day of wilting, a forage harvester and a weighed-container forage wagon were used to harvest and determine the weight of material from each calibration test cell or windrow. No merging took place prior to harvest. Samples were hand collected from the wagon from each calibration cell or windrow for DM determination.

Forage Harvester

Sensors placed on the forage harvester included: (1) linear potentiometer to measure feedroll displacement; (2) speed pick-ups to measure feedroll and blower speed, (3) load cell to measure crop impact at the transition radius of the spout, (4) ultrasonic sensor to measure thickness of crop stream in spout, and (5) radar to measure ground speed. Feedroll displacement was well correlated to mass-flow at high throughputs, but less well correlated at low throughputs because displacement was quite small. Conversely, crop thickness in the spout was well correlated at low
throughputs when the crop stream was well defined, but poorly correlated at high throughputs when the spout became filled with material. Crop impact force was a function of mass-flow and blower exit speed, so output from two separate sensors was needed to estimate mass-flow.

Crops harvested were either wilted alfalfa or whole-plant corn silage. Twenty alfalfa fields in 1st through 4th cutting and 13 fields of corn silage were harvested. Again, two types of tests were conducted: (1) tests where the field was sectioned into cells of 100 to 300-m to calibrate the sensor output; or (2) entire fields for mapping. Long calibration cells were required in order to insure the harvester was operating at equilibrium conditions. Anywhere from three (1st cutting) to seven (4th cutting) windrows were merged prior to harvesting wilted alfalfa in order to produce typical throughputs for the forage harvester. A 10 Mg-capacity forage wagon with a weighed-container was used determine the weight of material from each calibration test cell or windrow. Samples were hand collected from each calibration cell or windrow for DM determination.

**Large Square Baler**

Sensors placed on the baler included: (1) star wheel driven encoder to measure bale displacement rate; (2) load cells in the bale chute to measure bale weight, and (3) radar to measure ground speed. Proximity sensors were used at the spring-loaded expansion restrictors and the needles to measure slice count and beginning and end of individual bale formation, respectively. The star wheel was located at the rear of the chamber to eliminate backlash from hay re-expansion.

Crops harvested as dry hay using either alfalfa or an alfalfa and grass mixture. Eight fields were baled in 2nd through 4th cutting. Two types of tests were conducted: (1) tests where the field was sectioned into cells to calibrate the sensor output; or (2) entire fields for mapping. A calibration cell was the distance required to form one bale. Anywhere from two (2nd cutting) to three (4th cutting) windrows were merged prior to baling in order to produce typical throughputs for the baler. When baling to calibrate sensors or develop yield maps, each bale was tagged for identification, weighed on a platform scale and bored to collect samples for DM determination.

**Data Analysis**

Sensor output collected during each calibration test cell was averaged, the average paired with actual mass-flow and multi-parameter regression analysis performed with mass-flow and sensor output as the dependent and independent variable, respectively. The accuracy of the mass-flow prediction equations was expressed by determining an absolute and 90th percentile error from actual. The desired accuracy was 5 and 10%, respectively.

**RESULTS**

**Windrower**

Roll speed alone tended to be a good predictor of mass-flow, producing less variation than impact force on the swath shield because the inertia of the platform components produced some system damping that reduced noise in the roll speed signal. The load cell to measure impact force was vulnerable to dynamic loading from ground irregularities that compromised sensor accuracy. The crop volumetric flow as measured by potentiometers on the swath shield was well correlated with mass-flow when the sensor output was combined with platform inclination and roll speed (fig. 1). The average and 90th percentile error of predicted from actual mass-flow was higher than desired, especially at low throughputs (fig. 2). However, data smoothing techniques in the mapping software still allowed spatial variations to be identified. The mapping software was configured to use an inverse distance weighted smoothing scheme using 12 interpolation points per cell. A typical yield map created at cutting shows low yield concentrations at the upper and lower left side of the map (fig. 3). The yield depression at these locations was caused by high traffic patterns, as these locations were entrances to the field. The NE corner of the field was elevated and consisted of thinner soil, so yield was adversely affected by low water holding capability. The entire south edge of the field was not planted to alfalfa and grass was the dominant crop, so yield was depressed at this location. The average whole-field error between predicted and actual wet-mass yield all fields cut and mapped was about 5%.
Figure 1. Predicted versus actual wet-flow-rate for alfalfa cut with windrower.

Figure 2. Predicted wet-flow-rate versus error for alfalfa cut with windrower.

Figure 3. Typical yield map for an alfalfa-grass mixture cut with windrower (area – 5.24 ha; actual yield – 68.2 MT; predicted yield – 68.1 MT)
Forage Harvester

Depending upon throughput, feedroll displacement, crop impact at spout radius and depth of material in the spout were all well correlated with mass-flow. However, the former and latter outputs were not used in prediction models because their outputs were too varied at low or high throughputs, respectively (see procedure section). Therefore, the mass-flow prediction model only used inputs for blower speed and spout impact force (fig. 4). The average and 90th percentile error of the predicted from actual mass-flow was well within the desired range for corn silage (fig. 5), but was higher for wilted alfalfa (12.3 and 24.3%, respectively). Multiple windrows of wilted alfalfa were merged before harvest and this led to non-uniform windrows and thus non-uniform feeding into the harvester, which caused more variability in the sensor output. A windrow of wilted alfalfa may have had as much as 25-m of merged material, so 50 neighboring points were interpolated in the mapping software in order to produce a smoothed map. This reduced resolution for the maps of wilted alfalfa yield. A typical yield map of corn silage shows two distinct strips in the center of the field where research on fertility had been conducted several years past (fig. 6). The low yield portion on the east side of the field was due to previous traffic at the exit to the field when it was in alfalfa production. The high yield strip at the west side was due to beneficial effects of an adjacent soybean field. The average whole-field error between predicted and actual wet-mass yield for all fields harvested and mapped was about 6 and 2% for wilted alfalfa and corn silage, respectively.

![Figure 4](image_url)  
Figure 4. Predicted versus actual wet-flow-rate for corn silage harvested with forage harvester.

![Figure 5](image_url)  
Figure 5. Predicted wet-flow-rate versus error for corn silage harvested with forage harvester.
Figure 6. Typical yield map for corn silage harvested with forage harvester (area – 2.22 ha; actual yield – 68.5 MT; predicted yield – 70.9 MT).

Large Square Baler
The use of dynamic bale weight and speed of bale formation produced a very accurate estimate of mass-flow rate through the baler (fig. 7). The average and 90th percentile error of the predicted from actual mass-flow were well within the desired range (fig. 8). A typical yield map of dry alfalfa shows a high yield area in the center right portion of the field where water drained to from a ridge at the center left of the field where yields were low (fig. 9). Localized high and low yield spots at the north and south edges of the field were due to raking techniques. This field was baled in 3rd cutting and the developed yield map was very similar, indicating the robustness of the developed sensor systems and prediction models (Huenink, 2003). The average whole-field error between predicted and actual dry-mass yield of all fields baled and mapped was slightly over 2%.

Mapping at Cutting and Chopping or Baling
Yield was mapped from several fields at both cutting and chopping or cutting and baling to determine if similar spatial yield patterns could be identified. In general, the yield patterns were similar, but the reduced map resolution produced by merging windrows before chopping or baling tended to mask some of the yield differences observed at cutting.

Figure 7. Predicted versus actual dry-flow-rate for alfalfa hay baled with large square baler.
Sensor systems to measure mass-flow on hay and forage equipment were successfully implemented. Mass-flow was measured when cutting with a self-propelled windrower, when chopping with a self-propelled forage harvester and when baling with a large square baler. Predominant crops harvested were alfalfa and whole-plant corn silage.

Multi-parameter regression models using inputs from several sensors on each machine were developed to predict mass-flow. The error of the predicted mass-flow was greatest for the windrower and least for the baler. Reduced accuracy of mass-flow prediction occurred when crop was not fed uniformly into the machine.

Yield maps produced using the developed mass-flow prediction models were quite capable of showing spatial differences that corresponded very well to differences in elevation, soil type, traffic patterns and fertility.

Hay and forage mass-flow sensor systems and yield mapping should become a valuable precision farming tool when sensors to accurately determine crop moisture during harvest are developed.
REFERENCES


