Wagon-Based Silage Yield Mapping System

W. S. Lee[1], J. K. Schueller[2], T. F. Burks[1]

[1]Department of Agricultural and Biological Engineering, University of Florida, Gainesville, Florida, 32611. wslee@ufl.edu

[2]Department of Mechanical and Aerospace Engineering, University of Florida, 32611.

ABSTRACT

A silage yield mapping system was developed using a DGPS receiver, load cells, a header switch, Bluetooth modules for wireless data transmission, and a moisture sensor. A total of 13 loads of silage crops were harvested during tests in commercial silage fields. The masses of the empty and full silage wagon were measured with a platform scale before and after harvesting, and were compared with load cell measurements in the silage yield mapping system. The system yielded errors less than 5.0% of the total harvested crop, compared with measurements by a platform scale. A Bluetooth module (wireless transmission) was successfully implemented to transfer moisture sensor information to a host computer. A silage yield map was created for a site-specific crop management.

Keywords: Bluetooth, Precision agriculture, Silage, Yield mapping, Wireless communication.

1. INTRODUCTION

Yield mapping systems for grains and other crops are commercialized and are being used for managing fields site-specifically to increase profit and ultimately protect the environment. Although there is a commercial system to give a hardcopy of the amount harvested as measured by feedroll displacement (Deere & Company, 2005), there is no commercial system currently available for silage yield mapping. This research explores the feasibility of developing a silage yield mapping system and its development.

Farm fields are conventionally managed without considering their variability of nutrients, moisture, soil organic matter, pH, texture, etc. Precision farming carefully tailors soil and crop management to fit the different conditions found within each field.

Yield monitoring and yield mapping have been widely researched and commercialized for various crops over the last one and one-half decades. Yield mapping during grain harvesting (e.g., de Baerdemaeker et al., 1985; Schueller and Bae, 1987; Searcy et al., 1989) has been extensively studied and adopted. Some examples of yield mapping for other crops include cotton (Wilkerson et al., 1994), potatoes (Campbell et al., 1994), sugar beets (Demmel et al., 1998), tomatoes (Pelletier and Upadhyaya, 1999), and citrus (Schueller et al., 1999). Yield mapping of dry forages has been demonstrated on round balers (e.g., Wild et al., 1994; Rottmeier, 1996; Behme et al., 1997; Wild 1998; Shinners et al., 2000).

Silage is an important crop throughout the world to provide feed for animals including dairy cattle. Yield mapping for silage is very valuable and important first step to initiate site-specific crop management or precision farming, in order to know the magnitude of yield variability, and to produce more, and higher quality and better planning of animal feed.

Despite their importance, there has been significantly less work on developing yield monitoring and mapping systems for silage crops, especially in North America. Common silage crops in North America include corn (maize), alfalfa, various grasses, sorghum and oats. In 2002, a total of 3.0 million ha were harvested for silage corn in the U. S. and the production was about 105 million tons (USDA NASS, 2004).

Some of the earliest work on silage yield mapping was performed in Belgium at the Katholieke Universiteit Leuven. Their early work (e.g., Vansichen and de Baerdemaeker, 1993) demonstrated corn silage yield ranging from 1.2 to 4.8 kg/m^2 in a 1.2 ha field. Their system measured torques of the base unit and the material blower using strain gages, somewhat similar to the efforts at Purdue University (e.g., Schueller et al., 1985) to measure flow rates in grain combines. The KU-Leuven forage harvester blower torque gave a higher coefficient of determination to the mass of harvested crop than the base unit torque, but did not work well when operating near full capacity. Their later work (e.g., Missotten et al., 1997) used a curved plate flow sensor (similar to what was used in their grain combine work). As the tested machine did not have a blower (it was a “cut-and-throw” rather than “cut-and-blow” chopper in North American terminology), the material flow speed in the spout where the measurement occurred was determined with a radar sensor. The system was reported to work well.

Researchers at Silsoe College in the U.K. have developed a yield mapping system for root and forage crops based upon instrumenting a high-sided trailer with load cells and a differential GPS receiver (Godwin and Wheeler, 1997; Godwin et al., 1999). To remove unwanted noise, the data was subjected to analog signal filtering and subsequent numerical processing. Operation of a 3 m direct cut forage harvester in 6.3 ha field found mixed rye grass yields ranging from 26 to 35 t/ha.

Development and field testing of yield mapping on a John Deere 6810 self-propelled forage harvester was conducted by researchers at the Technische Universität München (Auernhammer et al., 1995; Auernhammer et al., 1997). A mass flow sensor based on the radiometric principle using Americium 241 was used with a radar sensor to determine flow speed. The unit was tested on over 140 ha of maize and 20 ha of grass silage. Over 2,000 tonnes of maize were harvested in 416 trailer loads in 22 fields. The accuracy of the system for harvesting corn for silage showed a standard deviation of the relative errors of 3.3%. This error is similar to the error levels determined in field tests by Demmel (2001) for different yield measurement systems in combine harvesters. The highly varying material stream when harvesting grass silage caused the grass errors to be two to three times higher.

Research at the University of Bonn (Kromer et al., 1999; Schmittmann et al., 2000) developed and tested flow rate sensing alternatives on forage harvesters. They classify sensing techniques as measuring either power requirements, mass flow rates, or volumetric flow rates. They applied systems to measure compression roller displacement, crop layer thickness in spout, crop stream contour, crop stream discharging speed, and crop impact force in the spout of a self-propelled harvester with windrow pickup.

Another German group researching forage harvesting yield mapping is the Institut für Agrartechnik Bornim in Potsdam (Ehlert and Schmidt, 1995; Ehlert, 1999). They also used the feed roller clearance and found a correlation with throughput in spring barley, wilted grass, and corn (maize). One field of spring barley had yields ranging from less than 5 t/ha to more than 13 t/ha.

Researchers at the University of Wisconsin have also developed sensors to measure silage flow rate and moisture content in a forage harvester (Barnett and Shinners, 1998). They have also measured flow rate during windrowing (Shinners et al., 2000), and implemented different sensor systems to measure mass-flow on both hay and forage equipment (Shinners et al., 2003). They reported the average absolute mass-flow prediction errors of 13.4%, 12.3%, and 1.4% for a windrower, a forage harvester, and a large square baler, respectively.

Investigators from Université Laval and Agriculture Canada have studied the power requirements of self-loading coarse chopping (Tremblay et al., 1991) and sensors to measure flow rates and moisture contents (Martel and Savoie, 1999). In the latter, sensors measured feedroll displacement, crop impact force on hinged plate above blower, frequency drop of capacitance-controlled oscillator near the end of the spout, and the number of light beam interruptions in the spout. The impact plate and feedroll displacement was well-correlated with flow rate. Oscillator frequency was affected by both flow rate and moisture.

The moisture content of the silage being harvested is of importance for various reasons. It affects the quality of the feed and its capability to be stored. It is also necessary to determine dry matter (DM) yields as silage is usually composed of large and variable amounts of moisture. It has been demonstrated that moisture content of silage can be measured in static sample conditions by infrared gauging in the U.K. (Percy, 1991) and electromagnetic fields in Germany (Snell et al., 2001).

1.1 Objectives

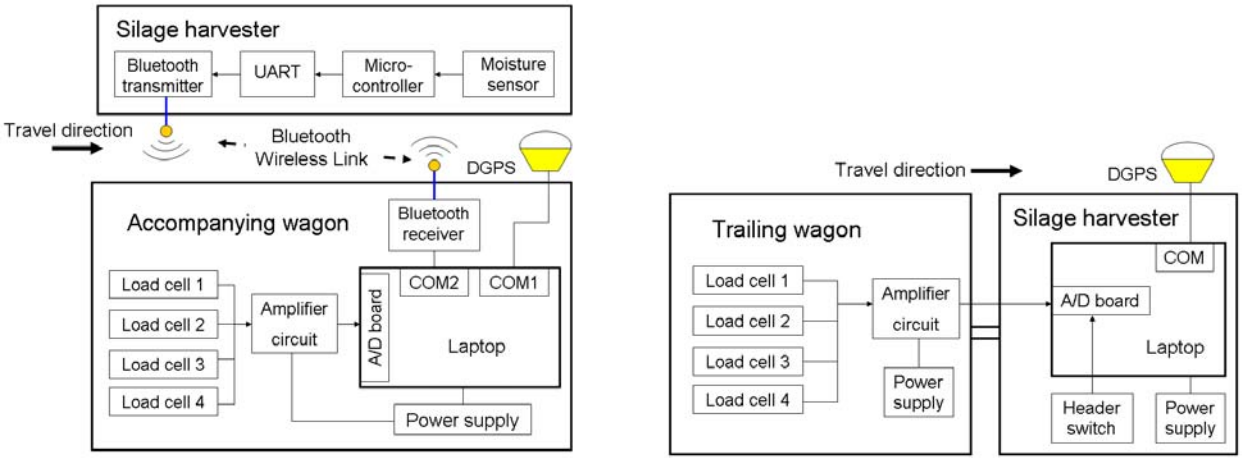
The overall goal of this research was to develop a real-time yield mapping system for silage crops, which could continuously measure instantaneous yield at a specific field location during harvesting operations. In this research, a load cell measuring system was installed on a silage wagon instead of on a harvester, and a wireless communication device was implemented using Bluetooth technology to explore an application of wireless data transportation of moisture concentration of harvested silage.

2. MATERIALS AND METHODS

2.1 Positioning and Harvesting System

A DGPS (Differential Global Positioning System) receiver (model AgGPS 132, Trimble Inc., Sunnyvale, CA, USA) with a U. S. Coast Guard beacon antenna was installed at the center of a forage harvester (model Hesston 7165, Hesston Corp., USA) with a two-row header. A silage wagon (model 970, Gehl Company, West Bend, WI, USA) was used to receive the harvested and chopped silage crop.

Two harvesting system set-ups (figure 1) were used for testing the silage yield mapping system: a two-vehicle system (silage harvester and a wagon accompanied on harvester's side, each pulled separately) and a one-vehicle system (a tractor-pulled silage harvester and a wagon connected to the harvester).



(a) Two-vehicle system.

(b) One-vehicle system.

Figure 1. Silage yield mapping system diagram.

For some test, a header position switch was made with a micro-switch (model DC3, Cherry Corp., Pleasant Prairie, WI, USA) and used to indicate whether harvesting operation was being conducted. A program was written with Visual C++ (Microsoft Corp., Redmond, WA, USA) to read serial ports for GPS and Bluetooth data, and the load cells and header switch.

2.2 Load Cell and its Calibration

Four 4500 kg shear beam type load cells (model 65023, Measurement Specialists, Huntsville, AL, USA) were used to continuously monitor mass of the wagon. The load cells were installed on the four corners of the bottom of the wagon's silage box (figure 2). Prior to their use, the load cells were calibrated with a universal testing machine (model 66120B-03, MTS Systems Corporation, Eden Prairie, MN, USA).

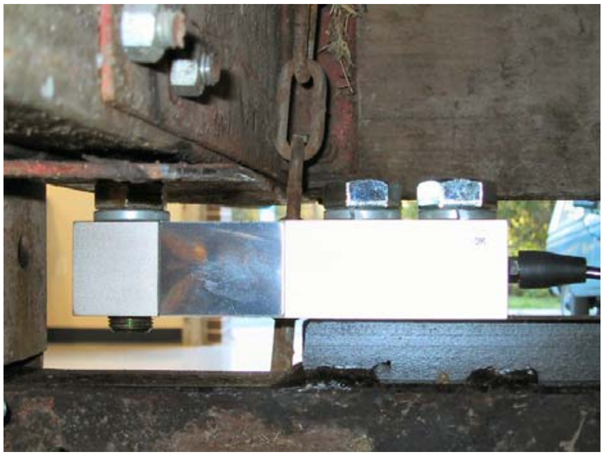


Figure 2. Load cell installed on the four corners of the bottom of the wagon's silage box.

2.3 Data Acquisition System

A 12-bit multifunction PCMCIA I/O board (model DAQCard-AI-16E-4, National Instruments, Austin, TX, USA) was used to acquire and digitize continuous mass of the silage harvested. Analog signal conditioning modules (model 5B38, National Instruments, Austin, TX, USA) were used to amplify signals from the load cells. A Pentium 450 MHz portable PC was used as a host computer for data acquisition from the load cells and the moisture sensor. A Bluetooth evaluation kit (model Intelli*BLUE* Callisto, BrightCom Tech., Carlsbad, CA, USA) was used to implement a wireless link between moisture information from a moisture sensor in the silage chopper and a host computer in the pickup truck towing the wagon when the two-vehicle system was used. The device contained two Bluetooth boards (RS-232 dongles), USB powering cables, and serial cables. The data transmission rate was set to 115 Kbps between the two RS-232 dongles used as a transmitter and a receiver.

2.4 Moisture Sensor

A capacitance type moisture sensor (model FP-1, AgriChem Inc., Ham Lake, MN, USA) was mounted in an opening made in the middle of a spout of the silage chopper along the travel path of harvested silage. A microcontroller (model MSP430F149, Texas Instrument Inc., Dallas, TX, USA) was used to digitize moisture sensor information (figure 3).

Prior to its use, the moisture sensor was calibrated with chopped silage samples from a silage field. The silage samples were obtained in a field, stored in plastic bags and brought to a laboratory. The silage samples were placed on top of the moisture sensor. This stationarily simulated the dynamic passage of silage past a sensor in the silage chopper spout. The samples were dried in an oven at 103°C for 24 hours to determine moisture concentration based on the standard method for forage moisture measurement (ASAE S358.2 DEC99).

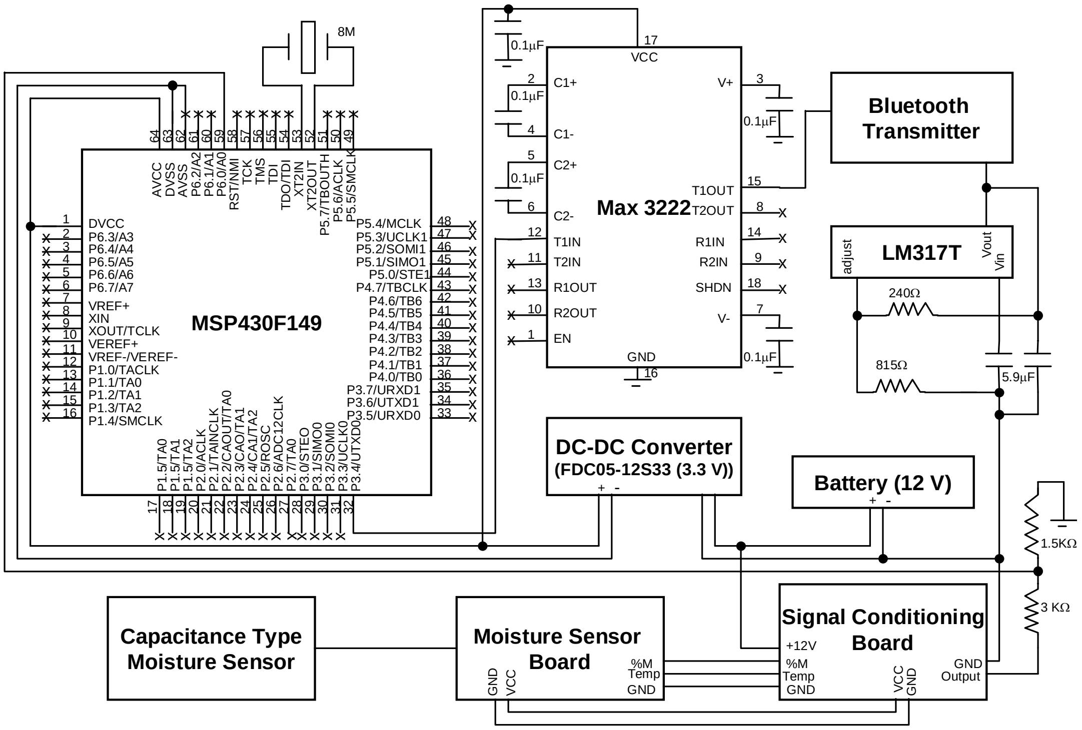


Figure 3. Connection diagram from the moisture sensor to the Bluetooth transmitter.

2.5 Field Testing Of the Silage Yield Mapping System

The silage yield mapping system was tested three times from June 2002 to July 2003 in silage fields located at the Dairy Research Unit (DRU) of the University of Florida in Hague, FL, 15 miles north of Gainesville, FL (table 1). A total of 1.96 ha (4.84 ac) were harvested at 7 different fields.

Table 1. Field testing of the silage yield mapping system.

Date	Crop	Harvested area (ha)	Number of loads	Vehicle system
June 24 & 25, 2002	Corn	0.46	3	Two-vehicle
October 14 & 15, 2002	Sorghum	0.67	3	One-vehicle
July 16 & 17, 2003	Corn	0.83	7	One-vehicle

The following information was recorded at 1 Hz in a file for future data analysis: time, longitude, latitude, each load cell output, and moisture sensor output. The load cell output of an empty wagon was recorded prior to each run. When the wagon became full, it was taken to a permanent platform scale (model 615XL, Central City Scale, Central City, NE, USA) to measure the mass of the wagon and harvested crop. The moisture sensor was used only for the two-vehicle system during the field testing.

Since the platform scale measured the total mass of the wagon and the load cells only weighed the silage box of the wagon, the empty mass of the silage box was needed. The silage box was removed from the wagon's running gear. By weighing the running gear separately on the platform scale, its mass could be subtracted from the total empty wagon mass, giving the empty mass of the silage box.

3. RESULTS AND DISCUSSION

3.1 Load Cell Calibration

The results of load cell calibration over a range of 0 to 4536 kg are shown in table 2. All of them showed a highly linear relationship between load cell raw output and actual mass.

Table 2. Calibration of the load cells.

Load cell no.	Calibration equation (W_i = mass (kg), LC_i = load cell raw output)	RMSE (kg)
1	$W_1 = 894.76 \times LC_1 - 93.95$ ($R^2 = 0.993$)	119
2	$W_2 = 927.18 \times LC_2 - 38.31$ ($R^2 = 0.999$)	52
3	$W_3 = 927.98 \times LC_3 - 54.91$ ($R^2 = 0.998$)	56
4	$W_4 = 921.24 \times LC_4 - 39.32$ ($R^2 = 0.998$)	59

Over the range of field usage for 0 to 1500kg, the load cells were more accurate in their calibration having RMSE's of 41, 16, 17, and 15 kg for the load cells 1 through 4, respectively.

3.2 Moisture Sensor Calibration

An attempt was made to calibrate the moisture sensor with samples from the field, but did not yield an acceptable relationship between moisture sensor output and actual moisture content of the samples. Figure 4 shows one of the calibration results from 25 corn silage samples. The R^2 was 0.31 and the root mean square error was 22.6% wet basis. Moisture data was recorded during the harvesting operation using the Bluetooth module, but was not used to calculate dry yield. The mass and yield described in this paper is for wet crops. Further development and more tests are needed to accurately measure moisture content during harvesting operation.

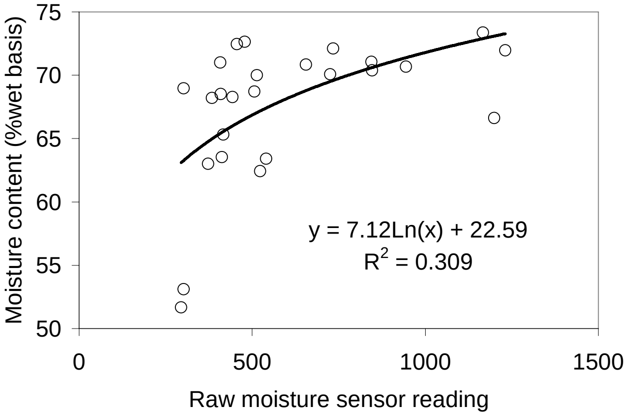


Figure 4. Moisture sensor calibration result.

The Bluetooth module transmitted data from the moisture sensor to the host computer and it worked very well in the field environment. One limitation of its application was that both Bluetooth dongles needed to be within the specified range (about 10 m apart). When the silage chopper and the accompanying wagon in the two-vehicle system made a turn at the end of a row, a disconnection was experienced. However, this limitation was easily corrected with a modification to the operating software, which did not require the connection establishment while turning.

3.3 Field Testing Of the Yield Mapping System

Figure 5 shows accumulated mass and its 21-point moving average of an example load of silage corn harvested on July 16, 2003. The harvester was operated at a constant speed of about 8 km/h and data was recorded at 1 Hz. Due to the ground condition and machinery vibration, the mass signal is noisy.

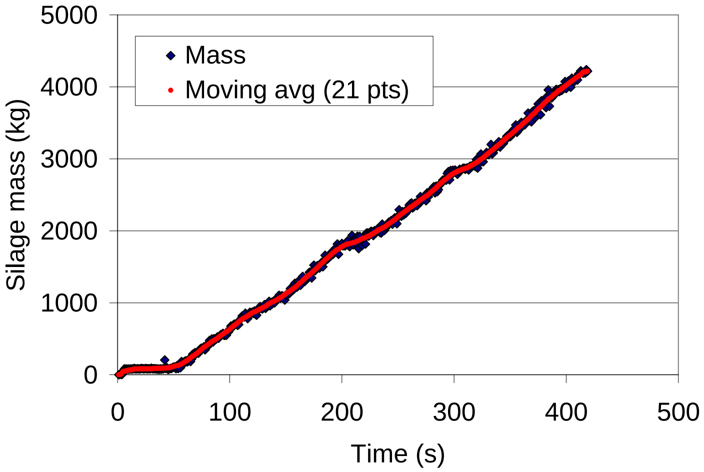


Figure 5. Accumulated mass of silage corn harvested and its 21-point moving average.

3.4 Comparison Of Accumulated Mass

A total of 13 wagon loads of silage were harvested during the testing of the yield mapping system. At the end of each load, the wagon's total mass was measured on the platform scale. Table 3 shows the comparison of wagon mass measured by the platform scale and load cells. In order to compare the mass measured by the platform scale and load cells, the platform scale result has the 590 kg running gear mass already subtracted (third column in table 3). The reported load cell masses were the averages of the last 5 records measured by the load cells. Errors were calculated between the two measurements and were found to be in the range of 0.0% to 4.90%, which are comparable to performances of typical grain yield mapping systems. Figure 6 shows a strong relationship (R^2 = 0.987) between the measurements. If only the corn silage tests from 2002 and 2003 are considered, the R^2 value increases to 0.9963, and all errors in total load mass are less than 2%.

Yield maps are widely used to discover yield variability, diagnose production problems, and optimize management practices. However, yield data often show incorrect values or systematic errors (Blackmore and Moore, 1999; Beck et al., 2001), which should be subsequently processed to filter and remove extreme values. Figure 7a shows a histogram of unfiltered sorghum silage yield (2,563 data points) harvested on October 2002, which contains zero yield data points and extremely high values. In Florida, typical average silage yield is approximately 43,000 kg/ha and yield more than 90,000 kg/ha would be unrealistic (C. G. Chambliss, personal communication, Gainesville, FL., 14, December 2004). Therefore, in order to create a yield map in this study, 268 zero yield data points and 268 yield data points greater than 90,000 kg/ha were removed. Figure 7b shows a histogram of filtered sorghum silage yield (2,027 points).

Table 3. Comparison of wagon mass measured by a platform scale and load cells.

Harvesting date & crop	Load No.	Silage mass measured by the platform scale (kg)	Silage mass measured by load cells (kg)	Error (%)
June, 2002 Corn	1	4586	4569	-0.37
	2	4604	4514	-1.95
	3	5924	5986	1.05
October, 2002 Sorghum	1	4663	4892	4.90
	2	4454	4565	2.47
	3	4137	4118	-0.46
July, 2003 Corn	1	3497	3565	1.94
	2	4187	4184	-0.07
	3	4146	4146	0.00
	4	4985	5033	0.96
	5	4037	4039	0.05
	6	4291	4271	-0.47
	7	5670	5686	0.28

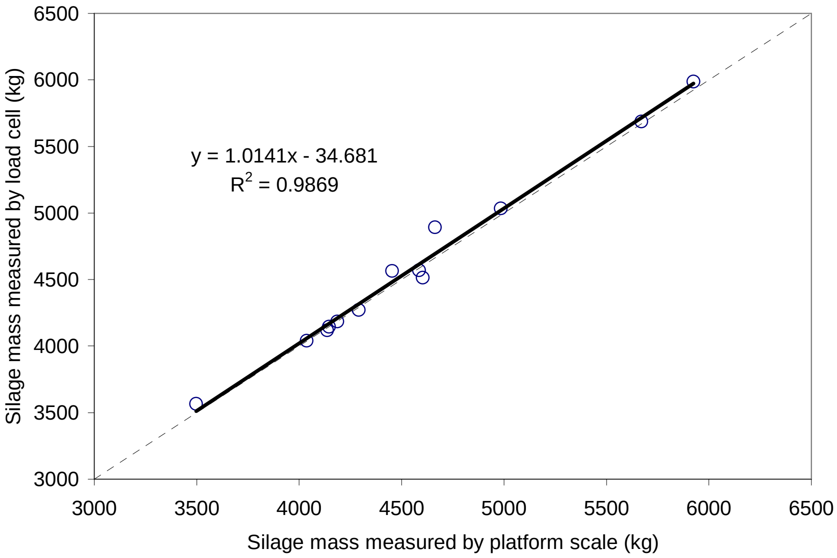
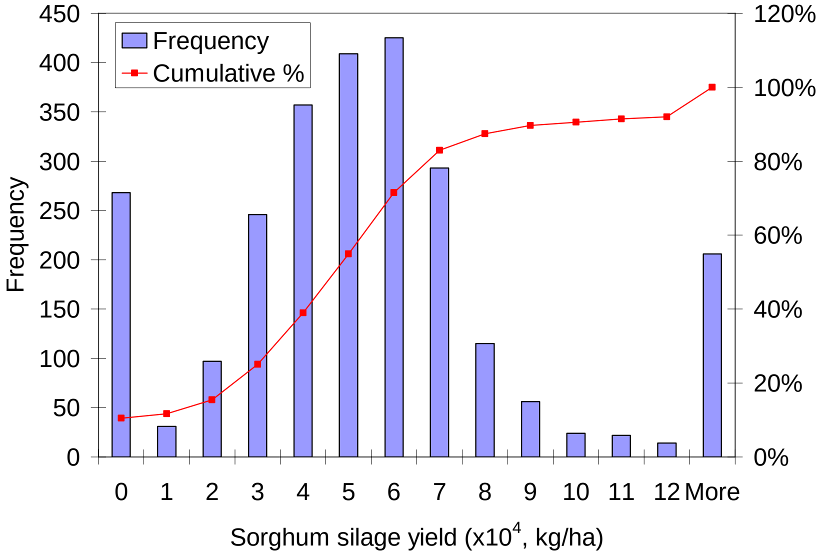
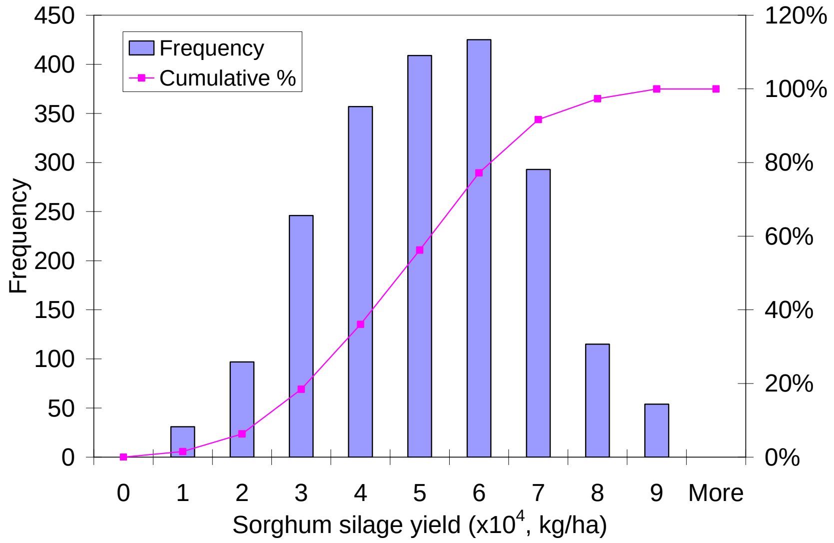


Figure 6. Silage mass measured by load cell vs. silage mass measured by a platform scale.

Figure 8 shows a sorghum yield map of a field where the system was tested on Oct. 14-15, 2002. Each point in this map is a 21-point moving average, which is approximately equal to 63 m^2 harvested area, as the average travel speed was 2.0 m/s and the swath of the harvester was 1.5 m. The harvester was pulled by a tractor around the field clockwise. The mean yield was 46535 kg/ha and the standard deviation was 11387 kg/ha. Yield variability is clearly visible in the map, which indicates site-specific crop management of the field would be needed. The northeast and southwest portions have substantially lower yields than the other portions. In addition, there sometimes was substantial variability between two-row passes.



(a) Unfiltered yield (2,563 data points)



(b) Filtered yield (2,027 data points)

Figure 7. Histogram of sorghum silage yield harvested on October 2002.

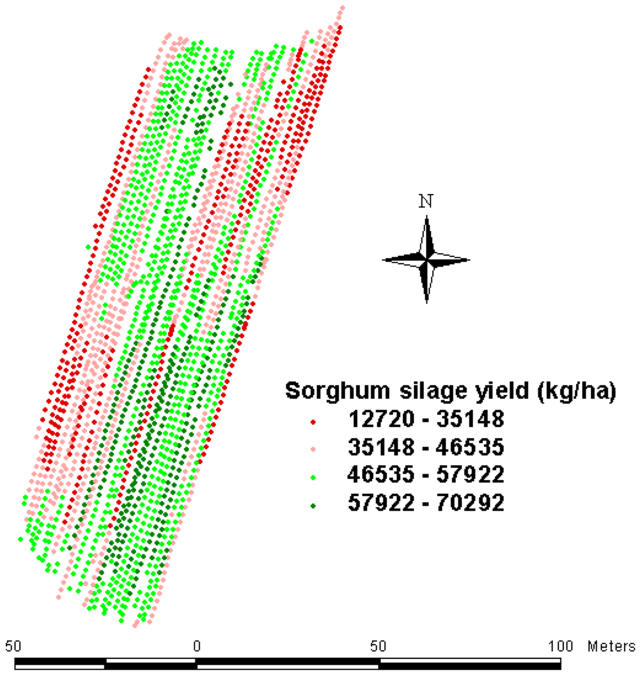


Figure 8. Sorghum silage yield map.

4. CONCLUSIONS

This research was conducted to develop a silage yield mapping system using a DGPS receiver, load cells, Bluetooth modules, a moisture sensor, and a header switch. Accomplishments from this research include:

- A yield mapping system for silage was developed and tested in commercial silage fields three times during a two year period. The system yielded errors of mass measurements in the range of 0.0% to 4.90% of total harvested crop, compared with measurements by a platform scale. The coefficient of determination (R^2) between silage masses measured by the platform scale and measured by the load cells was 0.987.
- A Bluetooth module (wireless transmission) was successfully implemented to transmit moisture information from a moisture sensor to a host computer during harvesting operation. The operation range of the Bluetooth module was about 10 m. Further development of the moisture sensor is needed.
- A silage yield map was created for site-specific crop management. This yield map can be used for precision agriculture similar to the use of yield maps for other crops and situations.

5. ACKNOWLEDGEMENTS

The authors would like to thank Palaniappan Annamalai, Ismail Bogrekci, Juan Herrera, Larry Miller, G. Harmon Pearson, and staff members at the Dairy Research Unit in the University of Florida for their assistance in this research. The assistance of Dr. Markus Demmel of the Bayerische Landesanstalt für Landwirtschaft (Bavarian State Research Center for Agriculture) with portions of the literature review and Prof. John Davidson and George Lopp of the University of Florida Department of Civil and Coastal Engineering with the load cell calibration is gratefully acknowledged. This research was supported by the Florida Agricultural Experiment Station, and approved for publication as Journal Series No. R-10651.

6. REFERENCES

Auernhammer, H., M. Demmel, P.J. M. Pirro. 1995. Yield measurement on self-propelled forage harvesters. ASAE Paper No. 951757. St. Joseph, Mich.: ASAE.

Auernhammer, H., M. Demmel, P.J. M. Pirro. 1997. Durchsatz- und Ertragsmessungen im selbstfahrenden Feldhäcksler. VDI-Tagung Landtechnik. VDI-Berichte 1356. 135-138.

Barnett, N. G., and K. J. Shinners. 1998. Analysis of systems to measure mass-flow-rate and moisture on a forage harvester. ASAE paper No. 981118. St. Joseph, Mich.: ASAE.

Beck, A. D., S. W. Searcy, and J. P. Roades. 2001. Yield data filtering techniques for improved map accuracy. *Applied Engineering in Agriculture* 17(4): 423-431.

Behme, J. A., J. L. Schinstock, L. L. Bashford, and L. I. Leviticus. 1997. Site-specific yield for forages. ASAE Paper No. 971054. St. Joseph, Mich.: ASAE.

Blackmore, S., and M. Moore. 1999. Remedial correction of yield map data. *Precision Agriculture* 1(1): 53-66.

de Baerdemaeker, J., R. Delcroix, and P. Lindemans. 1985. Monitoring the grain flow on combines. Proceedings of Agrimation I. Chicago. February 25-28. pp. 329-338.

Campbell, R. H., S. L. Rawlins, and S. Han. 1994. Monitoring methods for potato yield mapping. ASAE Paper No. 94-1584. St. Joseph, Mich.: ASAE.

Deere & Company. 2005. New 7000 series John Deere self-propelled forage harvesters: AMS, electronics & sensors. Available at: http://www.deere.com/en_GB/agricultural_equipment/spfh/7000_ams.html. Accessed 26, August, 2005.

Demmel, M. 2001. Ertragsermittlung im Mähdrescher – Ertragsmessgeräte für die lokale Ertragsermittlung. DLG Merkblatt 303. DLG-Frankfurt, 20 p.

Demmel, M., Auernhammer, H., Rottmeier, J.: Georeferenced Data Collection and Yield Measuerement on a Self Propelled Six Row Sugar Beet Harvester. ASAE St. Joseph 1998, Paper No. 98 3103

Ehlert, D., and H. Schmidt. 1995. Ertragskartierung mit Feldhäcksler. *Landtechnik* 50(4): 204-205.

Ehlert, D. 1999. Ertragskartierung in selbstfahrenden Feldhäcksler. *Landtechnik* 54(2): 84-85.

Godwin, R. J., and P. N. Wheeler. 1997. Yield mapping by mass accumulation rate. ASAE Paper No. 971061. St. Joseph, Mich.: ASAE.

Godwin, R. J., P. N. Wheeler, M. J. O'Dogherty, C. D. Watt, and T. Richards. 1999. Cumulative mass determination for yield maps of non-grain crops. *Computers and Electronics in Agriculture*. 23: 85-101.

Kromer, K.-H., O. Schmittmann, and A. M. Osman. 1999. Crop yield monitoring on forage harvesters. ASAE Paper No. 991051. St. Joseph, Mich.: ASAE.

Martel, H., and P. Savoie. 1999. Sensors to measure forage mass flow and moisture continuously. ASAE Paper No. 991050. St. Joseph, Mich.: ASAE.

Missotten, B., B. Broos, G. Stubbe, and J. de Baerdemaeker. 1997. A yield sensor of forage harvesters. In J.V. Stafford, ed. *Precision Agriculture ‘97. Vol. II: Technology, IT, and Management.* Oxford: BIOS Scientific Publisher. pp. 529-536.

Pelletier, G., and S. K. Upadhyaya. 1999. Development of a tomato load/yield monitor. *Computers and Electronics in Agriculture* 23(2): 103-118.

Percy, R. A. 1991. Measurement of moisture content of silage by on-line infrared gauging. *Process Control and Quality* 1: 185-186.

Rottmeier, J. 1994. Statische und dynamische Gewichtsermittlung in Fahrzeugen und Maschinen zur Futterernte. Dissertation. Technische Universität München. Forschungsbericht Agrartechnik (VDI-MEG) 294. 138 pp.

Schmittmann, O., A. M. Osman, and K.-H. Kromer. 2000. Durchsatzmessung bei Feldhäckslern. *Landtechnik* 55(4): 286-287.

Schueller, J. K., and Y. H. Bae. 1987. Spatially attributed automatic combine data acquisition. *Computers and Electronics in Agriculture* 2: 119-127.

Schueller, J. K., M. P. Mailander, and G. W. Krutz. 1985. Combine feedrate sensors. *Transactions of the ASAE* 28(1): 2-5.

Schueller, J. K., J. D. Whitney, T. A. Wheaton, W. M. Miller, and A. E. Turner. 1999. Low-cost automatic yield mapping in hand-harvested citrus. *Computers and Electronics in Agriculture* 23(2): 145-154.

Searcy, S. W., J. K. Schueller, Y. H. Bae, S. C. Borgelt, and B. A. Stout. 1989. Mapping of spatially-variable yield during grain combining. *Transactions of the ASAE* 32(3): 826-829.

Shinners, K. J., N. G. Barnett., and W. M. Schlesser. 2000. Measuring mass-flow-rate on forage cutting equipment. ASAE Paper No. 001036. St. Joseph, Mich.: ASAE.

Shinners, K. J., B. M. Huenink, and C. B. Behringer. 2003. Precision agriculture as applied to North American hay and forage production. In *Proc. The International Conference in Crop Harvesting and Processing*, Louisville, KY., 9-11 February, 2003. ASAE Publication Number 701P1103e, ed. Graeme Quick.

Snell, H. G. J., C. Oberndorfer, and W. Lücke. 2001. Fast determination of the moisture content of chopped maize using electromagnetic fields. ASAE Paper No. 01-3084. St. Joseph, Mich.: ASAE.

Tremblay, D., P. Savoie, and R. Thériault. 1991. Self-loading wagon power requirement for coarse chopping of forage. *Canadian Agricultural Engineering* 33: 31-38.

United States Department of Agriculture (USDA) National Agricultural Statistics Service (NASS). 2004. Crop production 2003 summary.

Vansichen, R., and J. de Baerdemaeker. 1993. A measurement technique for yield mapping of corn silage. *Journal of Agricultural Engineering Research* 55: 1-10.

Wild, K. J. 1998. Satellitengestützte Arbeitszeiterfassung und Ertragsermittlung in Rundballenpressen. Dissertation. Technische Universität München. Forschungsbericht Agrartechnik (VDI-MEG) 325. 228 pp.

Wild, K. J., H. Auernhammer, and J. Rottmeier. 1994. Automatic data acquisition on round balers. ASAE Paper No. 94-1582. St. Joseph, Mich.: ASAE.

Wilkerson, J. B., J. S. Kirby, W. E. Hart, and A. R. Womac. 1994. Real-time cotton flow sensor. ASAE Paper No. 94-1054. St. Joseph, Mich.: ASAE.