Accuracy of hay moisture sensing systems for round alfalfa bales

by

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Abstract

Moisture measurement is critical when baling alfalfa into round bales for feed. If alfalfa is too wet or too dry, it can greatly diminish the alfalfa crop's feed quality and cause economic loss to producers. Therefore, monitoring of alfalfa moisture content while baling is critical for producers to maintain hay quality and maximize profits. Currently, there are several different types of moisture sensing technologies available for round balers. But, concerns exist regarding their accuracy and repeatability during hay baling. Therefore, objectives of this project are to 1) Establish a protocol for coring methodology to assess the variation of moisture within a round alfalfa hay bale, and 2) Compare and contrast sensing accuracy and repeatability of different hay moisture sensing technologies. A coring methodology was established to determine the average moisture within a round bale based upon the way a sensor in a round baler chamber would determine the bale moisture; by looking at the moisture contents along the round bale diameter. This method was then compared with the more traditional method of using radial cores only to determine the whole bale moisture content. A sensor testing stand was developed to perform comparative testing between the sensors on the same alfalfa hay bale and collect core samples of material immediately after it was formed. Six commercially available moisture sensors were selected to measure moisture at four pre-determined locations on hay bales. After the sensor measurements, core samples were extracted from the exact same locations to determine actual moisture using oven-drying method. The moisture measurements were conducted during three growth stages and bales were formed with three approximate moisture contents of 10%, 15% and 20%. Six different cuts of alfalfa of the same variety were used to capture all the measurements. A seventh cut was also performed for moisture measurements with the alfalfa baled at 15% and the same growth stage, but different baler compression cylinder pressures (250, 400, and 800psi). Actual moisture content was across different sampling locations were compared to understand moisture distribution and establish coring protocol. Sensor and oven-dried measurements were compared to determine accuracy and repeatability of sensing technologies. Results showed that sensors and oven-dried measurement varied for all the sensors for every growth stage and baling moisture levels, with one sensor exhibiting lowest variability in its readings. The comparison identified the most accurate and reliable sensor among the ones currently available. A second year of testing was also conducted to validate the

research from the first year of testing. Future research needs to be conducted to identify correlation between the testing stand readings and actual hay baler moisture sensor readings.

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My research would not have been possible without the help and support of various people. First, I would like to thank my major professor, Dr. Ajay Sharda and my committee, Dr. Doohong Min, Dr. Daniel Flippo, Dr. Deon Van Der Merwe, and Dr. Krishna Jagadish for their guidance and advice throughout this research project. Second, I would like to thank my fellow Kansas State BAE Machinery Systems graduate students for their help conducting my testing. Without their assistance, this testing wouldn't have been possible. Finally, I would like to thank my family, friends, and God for their support of me throughout this experience.

Chapter 1 - Introduction

Moisture measurement is critical when baling alfalfa (Medicago sativa) into hay bales for feed. If alfalfa is too wet, it can heat up the inside of the bale and spoil the alfalfa. But if the alfalfa is too dry, the leaves can fall off which lowers the feed quality of the alfalfa. Therefore, the monitoring of alfalfa moisture content while baling is critical for producers to minimize feed value losses and get top dollar for their alfalfa. Currently, there are several different types of moisture sensing technologies available for round and square balers. There hasn't been any direct comparison testing with moisture sensors comparing moisture readings on the same round hay bales. If a producer intends to implement a commercial sensor, they will choose one based upon price, or by a recommendation instead of basing their decision on results from comparison testing for accuracy and repeatability.

This thesis will provide the direct comparison necessary for farmers to be able to compare the accuracy of commercially available moisture sensors. To be able to directly compare the sensors, a testing procedure needed to be established. A description of the fields tested, and the weather data will be given in the rest of chapter one. Chapter two focuses on developing this testing procedure. When moisture sensors take readings from the bale chamber, the sensor takes readings at different diameters of the round hay bale. Most previous research focuses on taking 5 to 9 cores along the radial side of the bale to determine the average bale moisture and then compare those to the sensor readings. Using moisture contents along the different points along the bale diameter could improve sensor accuracy and give a visualization of how the moisture varies within a single alfalfa bale.

The developed coring methodology was tested on over 100 bales, and compared to the previous methodology of coring along the radial side of the bale. Results indicated that the developed methodology of coring along the diameter yields the same average bale moisture as determined by coring along the radial side of the bale.

Chapter three focuses on the direct comparison of various moisture sensors currently available on the market. A testing stand was developed to directly compare these sensors on the same alfalfa sample bales directly after baling. These tests were completed on two different cuttings for three different growth stages and three different target moisture using the developed testing stand, and the testing methodology described in Chapter 2. This test was repeated for a second year, with an additional unit of one of the sensors mounted in the round bale chamber for direct comparison.

Results indicated that one sensor performed better than the other five sensors for determining the average bale moisture. This sensor was determined to be the best sensor, and is the most recommended for moisture sensor usage. A statistical analysis was performed and showed that sensor performance wasn't based upon growth stage or cut. Future research ideas are discussed in Chapter 4, along with future research ideas.

Testing Site and Weather Description

All testing for the first testing year, 2017, at fields near Wabaunsee, Kansas. The GPS coordinates of this are (39° 9'N, 96° 22'W). A total of 33 acres was planted to WL Alfalfas 372HQ.RR. This alfalfa was planted in the fall of 2012, and has a fall dormancy of this alfalfa is 4.9 (Forage Genetics International, 2017). Typical protein contents from representative whole-bale samples tested with the FOSS DS2500F NIRS Analyzer (Foss, Hilleroed, Denmark) using calibration curves for feed quality (including protein, lignin, and ADF) from the National Forage Testing Association (NFTA) yielded results for the alfalfa protein content varying between 15 and 22 percent, with an average of 18.7% Crude Protein with a standard deviation of 2.30.

Due to a spraying incident in May 2018 (2018 was the second testing year) that killed the alfalfa in the original fields, new field locations were selected within 1 km of the 2017 fields that were similar. The fields contained 40 acres of WL Alfalfas WL 349HQ. This alfalfa has a fall dormancy of 4.4 (Forage Genetics International, 2017), and yielded similar crude protein contents as WL Alfalfas 372HQ.RR when tested. The main difference between the two fields is that the 2017 fields were glyphosate resistant, while the 2018 fields were not.

Table 1.1 shows the 30 year average weather data, the 2017, and the 2018 average weather data (Kansas Mesonet 2017 and 2018). During May, June, and July for both 2017 and 2018, it was dryer and hotter than the normal 30 year average. The rains didn't come until the August and September. The combination of higher temperatures and less precipitation resulted in periods with lower alfalfa regrowth (less tonnage), and some periods where the alfalfa lay idle instead of regrowth. Thus alfalfa tonnage was less, cuttings were delayed, and not all tests had a sufficient number of bales. This resulted in the third alfalfa cutting for 2018 being delayed until August.

Table 1.1: Average Maximum Temperature and Total Rainfall Weather Data from Manhattan, KS for 30 year, 2017, and 2018 testing years by month.

MANHATTAN (Manhattan North Farm) Weather Station						
	30 Year Avg.		2017		2018	
Date	Precip (in)	AvgTmax (°F)	Precip (in)	AvgTmax (°F)	Precip (in)	AvgTmax (°F)
May	5.1	76.7	3.6	76.4	3.8	86.4
June	5.7	86.1	2.9	88.2	2.6	91.6
July	4.4	91.5	1.5	92.6	2.4	92.2
August	4.1	90.2	5.7	84.5	8.4	89.2
September	3.4	81.8	1.3	85.0	8.0	80.1

References

Forage Genetics International, L. (2017). WL 349HQ technical specifications. Retrieved from https://www.wlalfalfas.com/WLAlfalfas/media/PDF/WL-349HQ.pdf?ext=.pdf

Forage Genetics International, L. (2017). WL 372HQ.RR technical specifications. Retrieved from https://www.wlalfalfas.com/WLAlfalfas/media/PDF/WL-372HQ-RR.pdf?ext=.pdf

Kansas Mesonet. (2017). Kansas 2017 Mesonet Historical Data. Accessed 4 December 2018. Retrieved from http://mesonet.k-state.edu/weather/historical

Kansas Mesonet. (2018). Kansas 2018 Mesonet Historical Data. Accessed 4 December 2018. Retrieved from http://mesonet.k-state.edu/weather/historical

Kansas Mesonet. (2018). Kansas 30-Yr Average Mesonet Historical Data. Accessed 4 December 2018. Retrieved from http://mesonet.k-state.edu/weather/historical

Chapter 2 - Developing a Procedure to Determine Round Alfalfa Hay Bale Average Moisture Content

Abstract

Moisture measurement is critical when baling alfalfa into round bales for feed. If alfalfa is too wet or too dry, it can greatly diminish the alfalfa crop's feed quality and cause economic loss to producers. Therefore, monitoring alfalfa moisture content while baling is critical for producers to maintain hay quality and maximize profits. Currently, there are several different types of moisture sensing technologies available for round balers. These sensors are typically mounted on the hay baler where they can see hay being packed in the round bale chamber as the bale is growing in size. The current methodology used for obtaining actual moisture contents to compare with the whole bale average sensor reading involves taking 5 to 9 cores from the radial side of a round bale. The current method does not provide any detail on how accurate the sensing technology is at the different points during bale formation. Hay producers would desire to have moisture sensors that output accurate moistures during hay bale formation. Currently, there is no established and tested methodology to collect hay samples to compare it to actual sensor response based on position testing as the bale is forming. An improved methodology is needed when testing different hay moisture sensors for accuracy and repeatability. Therefore, the objectives of this project are to 1) Establish a protocol for coring methodology to assess the variation of moisture within a round alfalfa hay bale based on measurements by position on the flat face of the round bale, and 2) To compare this developed methodology with previous methodology of using radial cores and whole bale averages. Core samples were extracted from locations along different diameters of a round bale to determine actual moisture using oven-drying method. The moisture measurements were conducted during three growth stages and bales were formed with three approximate moisture contents of 10%, 15% and 20%. Six different cuts of alfalfa of the same variety were used to capture all the measurements. These tests were repeated for a second year to confirm the first year's results. A seventh cut was also performed in the first year of testing for moisture measurements with the alfalfa baled at 15% and the same growth stage, but different baler compression cylinder pressures of 1.72, 2.76, and 5.52MPa (250, 400, and 800psi). The results for both years showed that the average whole bale moisture *and standard deviation are almost nearly identical when comparing the cores taken along the different diameters of a round bale versus taking radial cores along the radial side of the bale. The results thus suggested that taking cores along the diameter of the bale for position based moisture measurements results in the same average moisture content as taking radial cores to determine average bale moisture. The proposed coring methodology could provide a baseline protocol to assess whole bale actual moisture and also to accurately compare moisture measurements in round hay bales by position.*

Introduction

Alfalfa (Medicago sativa) is one of the most common forages used to feed cattle and other livestock. Every year, millions of tons of alfalfa are sold within the United States or exported to other countries. In 2017, 55.1 million tons (with an average value of $140/ton resulting in a total revenue of $7.71 billion) of alfalfa was produced in the United States.(USDA, National Agricultural Statistics Service, 2018). Moisture measurement is critical when baling alfalfa into hay bales for feed. If alfalfa hay is too wet (>22%), it can heat up the inside of the bale and spoil the alfalfa and cause instantaneous combustion of the hay when stored. But if the alfalfa is too dry (<12%), the leaves can fall off which lowers the feed quality of the alfalfa. Therefore, monitoring of alfalfa moisture content while baling is critical for producers to bale the hay within the desired moisture range of 13% to 17% moisture content to minimize feed value losses and maximum economic benefit for their alfalfa. (Rich, 2017).

Currently, there are several different types of moisture sensing technologies available for round and square balers. To be able to directly compare different moisture sensors, there needs to be an accurate method determining the moisture content with the moisture sensor’s readings throughout the formation of a hay bale. The rest of this introduction will explain the hay-making process, previous bale coring methodology, and the objectives of this project.

When hay is formed, it first goes through the following process of swathing which cuts the hay down, and typically has conditioner rollers on it that crush the stems of the crop to allow the plants to dry faster. The crop either falls directly to the ground, or is put into narrower strips called windrows. Second, the hay is raked after the hay dries to the desired moisture range on top of the already cut windrow. This process flips the hay over so that the wet hay underneath can dry to the ideal moisture content of 13 to 17%. Finally, when the hay is cured to the desired moisture content, it is typically baled into square or round bales.

When a hay bale is formed in variable chamber round baler, it goes through the pickup into the bale chamber as shown in Figure 2.1. The belts have a set pressure on them to compact the hay, and allow the bale to form until the desired bale size is achieved. The bale is then tied with either twine or net wrap, and then is ejected.

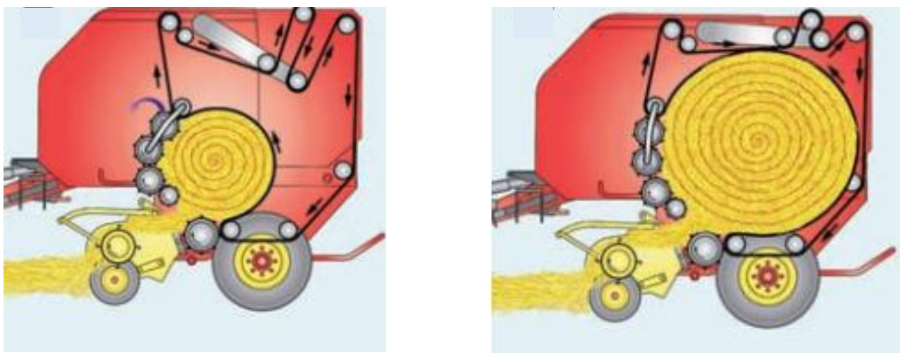


Figure 2.1: Typical formation of a Hay Bale in a Variable Chamber Round Baler (Philip Shaw, 2010)

As seen in Figure 2.1 the bale grows in size from the center of the baler to the back, and taller in size. Because of this, and with limitations of mechanical components on the sides of round balers, there is limited space to mount a moisture sensor on a round baler. Two optimum locations to mount moisture sensor as shown in Figure 2.2, since the sensors will sense the new hay as the bale forms at the different diameters. Most moisture sensing technologies give instantaneous moisture readings as the bale is forming. Some of these sensors also output an average bale moisture for each bale at the end of baling.

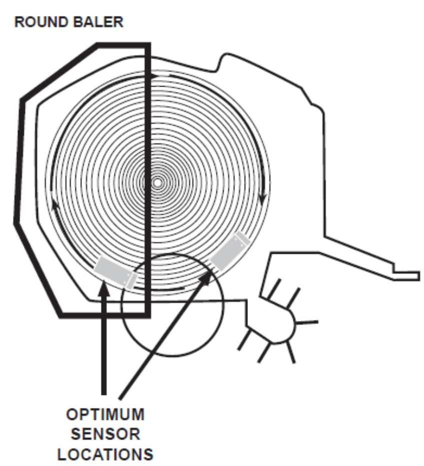


Figure 2.2: Optimal Location for Moisture Sensors on Round Balers (Agratronix)

Current Methodology

To be able to compare various moisture sensing technologies, there needs to be an accurate method to compare moisture sensor readings with actual hay moisture. The hay moisture samples are collected through a process called coring. A corer is a round tube that is either hand-pushed or drilled into bales to gather hay samples from within the bale. Currently, there is no standard methodology for coring a bale to determine the bale moisture content, or for comparing hay moisture sensor reading with actual samples. Various coring practices have been used in previous research projects to determine the average moisture of a round bale correlate sensor readings to the whole bale moisture rather than at looking at the hay moistures at different diameters of the hay bale. Coblentz (2009) tested the effects of bale moisture and bale diameter on spontaneous heating for round alfalfa bales. For each bale, they took nine 0.025m diameter, 0.049 meter long cores from the round face of the bale with a Uni-Forage Star Sampler (Star Quality Samplers, Edmonton, Alberta, Canada). Hay samples were mixed together (~400g), and dried to a constant weight at 50°C so the samples could be further analyzed. Lötjönen (2013) also followed a similar procedure as Coblentz (2009), but only used five cores instead of nine cores to determine the average bale moisture. Anderson (1981) also obtained core samples along the round face of 1.4m and 1.7m diameter bales by drilling to the center of the bale on a radius parallel to the ground. It wasn’t listed though how many cores were pulled from each bale for this research aimed at dry matter losses in bale storage. Just (2017) took at least four samples from different points along the bale’s radius on one of the flat sides of each cotton bale as shown in Figure 2.3. The cotton bales were tested with a custom-built dielectric impedance moisture meter, which took readings along the face of each cotton bale as it was formed.

Figure 2.3 Sample coring points from Just (2017) on round cotton bale.

Previous moisture sensor research with square bales correlated sensor readings based upon using whole bale averages. (Just, 2017) took cores of 0.1m (4 inches) diameter and 0.61m (2ft) deep from the ends of large square bales with a tractor three point mounted coring device. Samples were dried in a forced-air oven per ASABE S358.3. Behringer (2004) used several different coring sample sizes for determining square bale moisture. This included single large core in the center of ends of bales with a three-point tractor mounted coring device, the entire bale (collected and dried in fractions), and the side of the bale that the moisture sensors were tested with. This is shown in Figure 2.4. Samples were dried in a forced-air oven per ASABE S358.3.

Figure 2.4: Hydraulic Boring Device used to collect core samples by Behringer (2004)

The previous methodology used coring techniques that resulted in samples that were representative of the entire hay bale rather than individual positions within a bale. Producers would want moisture sensors to output accurate moisture readings at the corresponding diameters. If the hay is too wet, the producer can stop baling, and if it is too dry so they can separate the drier, lower quality, hay from the better quality hay. To be able to test and develop accurate moisture sensors, researchers and end users would need a more robust understanding of actual moisture distributions within flat and round faces of the bales. The knowledge of hay moisture within a bale would help users to confidently implement coring of hay samples to compare it to sensor readings at the locations. Therefore, the proposed study was designed with two main objectives.

1) Establish a protocol for coring methodology to assess the moisture variability within a round bale of hay.
2) To compare the developed methodology of coring along the bale diameter with the previous methodology of using radial cores.

Methodology

Preparing the Hay for Testing

The alfalfa variety used for this research was WL Alfalfas WL 372HQ.RR and was planted in the fall of 2012. The alfalfa was first cut into 1.52 m (5ft) wide windrows using a CIH 8312 Disk mower conditioner. Alfalfa was then raked into 0.91 m (3ft) windrows with a 10-wheel V-Rake for curing when the alfalfa was at the approximate target moisture on top of the windrow. An Agratronix 07140 Windrow Moisture Tester (Agratronix, LLC, Streetsboro, Ohio) was used to check approximate windrow moisture with samples from the top of the windrow and checked again before baling. Cutting on average occurred a couple of days before raking the alfalfa hay. Then, the alfalfa hay was dried to achieve the desired moisture content targets of 10%, 15%, and 20%. The windrow moisture content was monitored with the Agratronix Windrow Moisture Tester. Once the alfalfa reached each of the three desired moisture contents, it was immediately baled and moved to the testing site. Baling was conducted with a New Holland RB560 Specialty Crop Round Baler which made a 1.52m (5ft) wide and 1.83m (6ft) bale diameter bale (Figure 2.5). Each of the bales were weighed using a custom built electronic scale platform with Longacre Computer Scales AccuSet II Wireless scales (Model #725934, Booneville, Indiana) having four pads. Each pad had a rate capacity of 680kg (Figure 2.6). The diameters of each bale were recorded for density calculations. Finally, the alfalfa bale was marked up (Figure 2.7) to extract core samples.

Figure 2.5: New Holland T6.180 baling alfalfa hay with New Holland RB560 Round Baler

Figure 2.6: Custom Built Scale Platform with Longacre Wireless Scales

Three bales were produced for each of the moisture targets (10%, 15%, and 20%). The testing was duplicated across three alfalfa plant growth stages – Late Vegetative State, Mid to Late Budding Stage, and Mid-Blooming Stage, across three separate cuttings (1^{st}, 2^{nd}, and 3^{rd} Cuttings) for 2017 and 2018 growing seasons. This resulted in 61 bales for 2017, and 52 for 2018. 2018 had some abnormally dry weather which cut down that amount of material that was available to test. An additional test was conducted in the 2017 season looking at varying baler density settings of 1.72, 2.76, and 5.52MPa (250, 400, and 800psi) by varying the baler belt downward pressure. Typical bale weights at 2.76 MPa of pressure resulted in an average of 540kg for the 10% MC target bales, 660kg for 15% MC target bales, and 750kg for 20% MC target bales.

Developed Procedure for Coring Round Alfalfa Hay Bale

To see if coring along the flat face along the diameter of the bale provides the same moisture average as coring along the radial side, four positions were selected (A, B, C, and D) for each of the two flat sides of the bale (Figure 2.7). The selected locations provided a total of eight different coring locations. At each location, there were two cores taken, one 0.30 m (1 foot) deep, and the other 0.30 m to 0.6 m (1 foot) deep from the face of the bale. For example, at coring position A shown in Figure 2.7, two coring samples were taken at location 1, and two at location 8. Three additional coring locations, 9, 10, and 11 were selected on the radial face of the bale. The coring locations for radial face were on the same half of the bales as positions A, B, C, and D, and were taken at the same height as positions A, B, C, and D were taken. Cores 9, 10, and 11 provided additional bale moisture for averaging purposes, but also gave data from the radial positions to compare with moisture samples from the flat surface.

Each bale was cored at all 11 positions shown in Figure 2.7. A Uni-Forage Star Sampler (Star Quality Samplers, Edmonton, Alberta, Canada) was used to gather core samples (Figure 2.8). The corer was 2.2 cm (7/8 inch) in diameter, and was 0.6m (2ft) long. The cores were immediately weighed in the field with an OHAUS Scout II scale with 600g capacity and 0.1g resolution, before being bagged for oven drying (Figure 2.9). ASAE S358.3 (R2017) was used as the guide for oven-dry core method for this project. The samples were dried at 55°C for 72 hours. (ASABE, 2017)

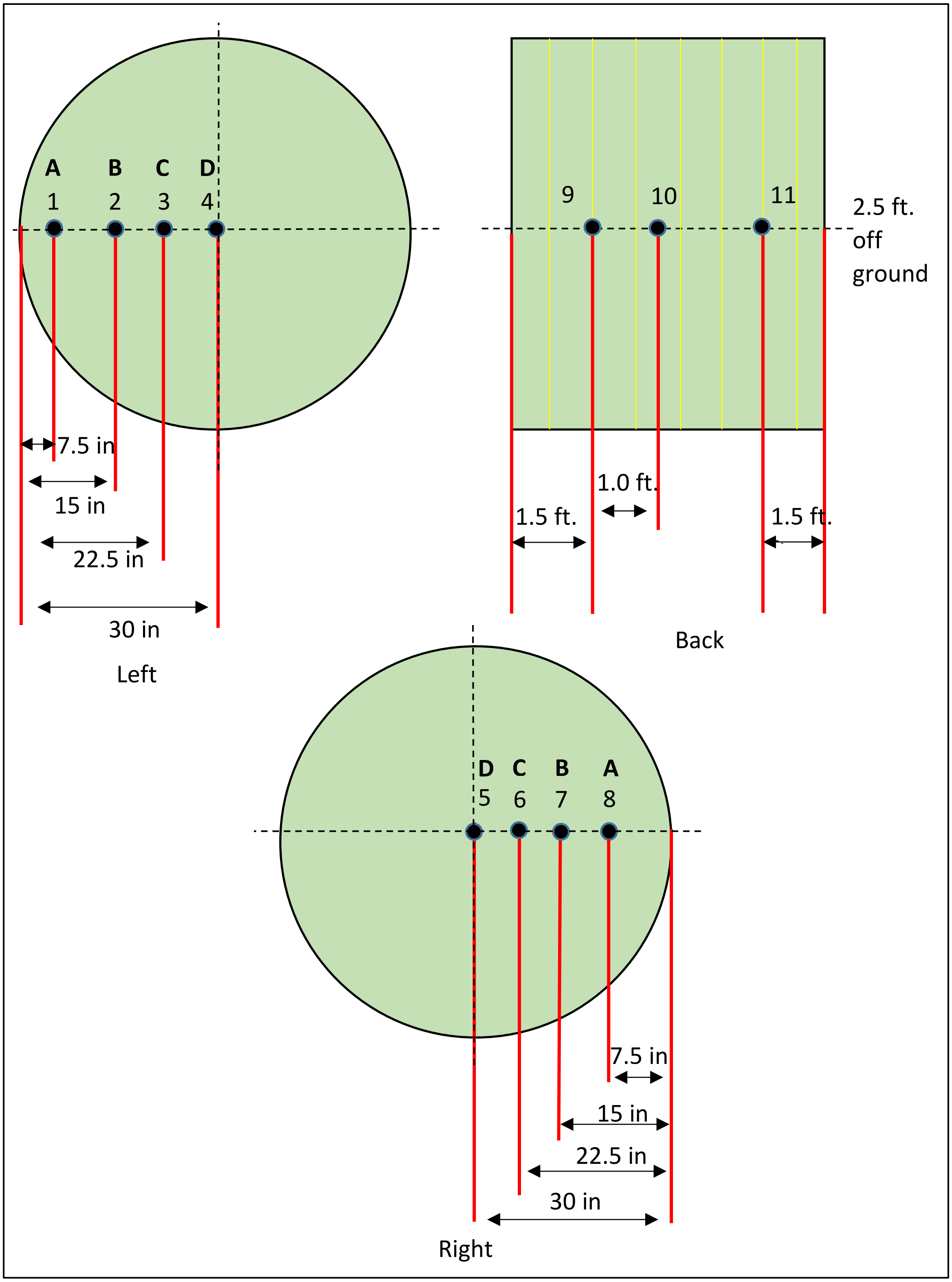


Figure 2.7: Core sample locations tested upon on a 1.52m by 1.52m (5 foot by 5-foot) alfalfa hay bale

Figure 2.8: Coring on a sample round alfalfa bale

Figure 2.9: Weighing core samples on scale after collecting each core

Data Analysis

All calculations for the average sample and bale moisture contents, along with the bale moisture content standard deviations, were performed in Microsoft Excel. Each individual core moisture content was calculated according to Equation 2.1 below:

$$Percent\ Moisture\ Content = \frac{Total\ Loss\ in\ Sample\ Weight}{Initial\ Wet\ Sample\ Weight} * 100 \quad (2.1)$$

The average bale moisture contents without the radial cores was the average of the cores from the first eight coring positions, as shown in Figure 2.7. The average bale moisture contents with the radials used the additional cores from locations 9 to 11 for the average bale moisture content for both of those data tables. The core moisture contents for each of the bales were plotted using a code written in MATLAB to visualize the moistures in a round bale (Figure 2.10 and Figure 2.11).

The results will be shown for 2017 first, followed by 2018 data. For each year, a sample cutting is shown, along with the generalized data for each of the testing years across all moisture targets (10%, 15%, and 20%). The average bale moistures are also presented for the Density test conducted in 2017.

Results and Discussion

An example of overall moisuture variablity within the cores and within a whole round hay bale is shown in Figure 2.10. The radial cores in this figure are not shown in the actual cored location so each of the cores moistures could be displayed in the figure. The actual radial coring locations are shown in Figure 2.7. The average moisture for the example bale shown in Figure 2.10 varied between 16% and 23%. The average moisture content of this bale was 18.4%. The cores within each bale tested had an overall moisture variance of 4% to 8%. The moisture range was similar for a bale with a relatively lower average moisture (11.7%) content (Figure 2.11). Figure 2.10 and Figure 2.11 show that there is wide moisture variations within a single bale. The moisture variability within the bale also indicated that using a single average moisture value to quantify the average moisture of a single round bale of alfalfa would not accurately exhibit the true moisture spread of the bale. This further provides support to why moisture measurements for comparison with moisture sensors should be done by position rather than using a whole bale average for comparison.

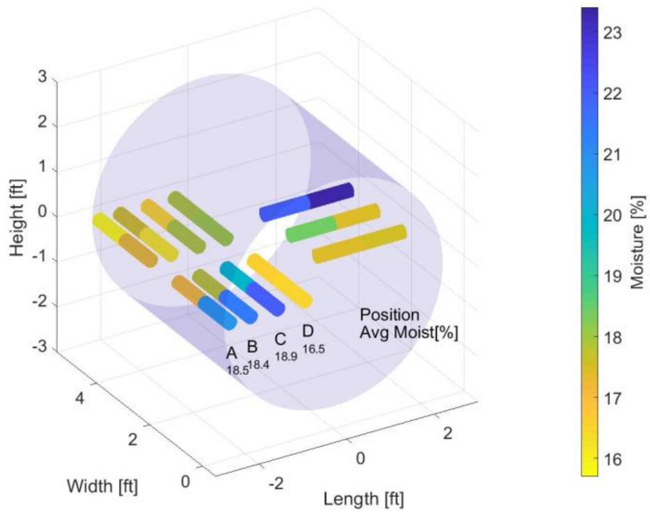


Figure 2.10: An example of moisture variation within an alfalfa hay baled during cut in the 2nd Mid-Budding Cut of 2018, and target moisture content of 20%.

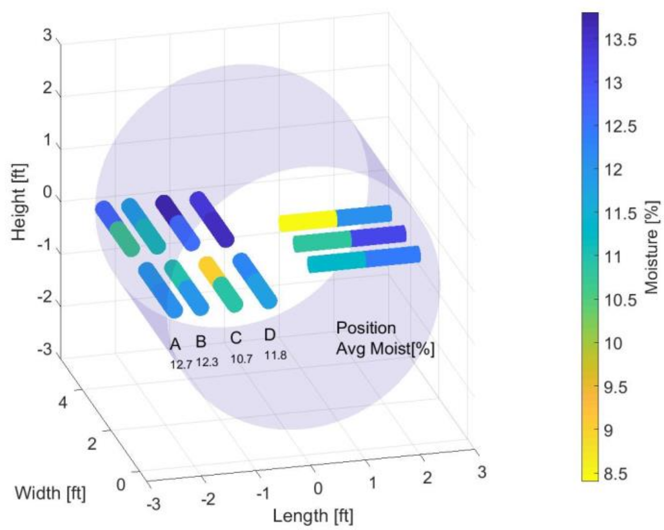


Figure 2.11: An example of moisture variation within an alfalfa hay baled during cut in the 3rd Mid-Blooming Cut of 2018, and target moisture content of 10%.

Bale Coring Data and Analysis

The average bale moistures with and without the radial cores were compared across all cuts. Some selected cuts have been depicted in An example of bale average moistures from the 1st Budding cut from the 2017 testing year is shown in Table 2.1. The averages with and without the the radial cores were almost the same. The standard deviation of these cores within a single bale varied between 1 and 5% actual moisture. In 95% of the cases, the moisture averages were within 1% of each other across all cuts. The rest of the averages with and without the radial cores were within 3% of each other. This means that coring along the diameter of the bale and coring along the radial face of the bale for the average bale moisture yielded smilar results.

Table 2.1: 1st Budding cut average core moistures by bale for 2017

	Averages WITHOUT Radial Cores				Averages with Radial Cores			
10 % Bale #	1	2	3	ALL	1	2	3	ALL
Bale AVG	7.9%	8.8%	8.4%	8.4%	7.6%	8.0%	8.0%	7.9%
ST.DEV	2.8	2.0	1.6	0.4	2.6	1.7	1.7	0.3
15% Bale #	1	2	3	ALL	1	2	3	ALL
Bale AVG	14.0%	15.5%	14.7%	14.7%	14.8%	15.2%	14.6%	14.8%
ST.DEV	1.4	3.9	1.6	0.7	1.5	3.4	1.5	0.3
20% Bale #	1	2	3	ALL	1	2	3	ALL
Bale AVG	28.5%	24.5%	29.7%	27.6%	29.0%	26.1%	27.4%	27.5%
ST.DEV	3.6	2.3	3.6	2.7	3.4	2.8	3.3	1.5

The observations were similar for all the bales within each moisture target across all cuts, shown in Table 2.2, and across the different baler density, as depicted in Table 2.3. Testing in 2018 also yielded overall similar results as 2017, as shown in Table 2.4 for the 3rd Budding cut of the 2018 Year, and overall results for the 2018 testing year shown in Table 2.5.

Table 2.2: Average all bale moistures by target moisture for 2017

All 10% Moisture Cuts Combined	Without Radials	With Radials
Whole AVG	12.2%	11.8%
Whole St. Dev.	4.5	4.5
All 15% Moisture Cuts Combined	Without Radials	With Radials
Whole AVG	14.2%	14.2%
Whole St. Dev.	3.6	3.5
All 20% Moisture Cuts Combined	Without Radials	With Radials
Whole AVG	18.1%	18.0%
Whole St. Dev.	6.8	6.9

Table 2.3: Density test core comparison for 2018

Averages By Cut Without Radials

Baler Pressure (psi)	250	400	800	ALL
Bale by Bale Cut AVG	15.4%	18.7%	18.9%	17.6%
Cut ST.DEV	0.3	5.1	4.1	1.9

Averages By Cut With Radials

Baler Pressure	200	400	800	ALL
Bale by Bale Cut AVG	15.3%	17.8%	19.0%	17.4%
Cut ST.DEV	0.3	4.1	3.9	1.9

Table 2.4: Average bale moisture and standard deviation among bales during 3rd budding cut within 10%, 15% and 20% moisture target during 2018

	Averages WITHOUT Radial Cores				Averages with Radial Cores			
10% Bale #	1	2	3	ALL	1	2	3	ALL
Bale AVG	9.7%	11.1%	11.2%	10.7%	9.7%	11.4%	11.0%	10.7%
ST.DEV	0.9	1.6	1.8	0.9	1.0	1.6	1.6	0.9
15% Bale #	1	2	3	ALL	1	2	3	ALL
Bale AVG	29.1%	16.3%	15.2%	20.2%	29.0%	15.9%	15.5%	20.1%
ST.DEV	2.5	6.1	1.8	7.7	3.8	5.9	1.7	7.7
20% Bale #	1	2	3	ALL	1	2	3	ALL
Bale AVG	18.8%	31.9%	33.6%	28.1%	19.6%	32.0%	34.0%	28.5%
ST.DEV	5.1	2.2	3.1	8.1	5.3	2.0	2.8	7.8

Table 2.5: Average All Bale Moistures by Target Moisture for 2018

All 10% Cuts Combined	Without Radials	With Radials
Whole AVG	11.4%	11.5%
Whole St. Dev.	1.6	1.8
All 15% Cuts Combined	Without Radials	With Radials
Whole AVG	14.6%	14.7%
Whole St. Dev.	3.3	3.3
All 20% Cuts Combined	Without Radials	With Radials
Whole AVG	19.1%	18.7%
Whole St. Dev.	4.5	4.7

Table 2.6 shows the difference of least squares means analysis for radial cores moisture average vs. core moisture average along the outside diameter of the bale for all bales tested in both years. Data was analyzed as a completely randomized design using PROC GLIMMIX of SAS (SAS Institute Inc., 2018, SAS University Edition, Cary, NC). Individual bales constituted as the experimental unit. The treatments were the radial core whole bale moisture average and, and the non-radial core whole bale moisture average. Significance was at p≤ 0.05. For 2017 and 2018, the actual difference between the average moisture between the radial cores and the cores along the diameter was around 0.06% actual moisture content. The null hypothesis for this analysis is that both moisture averages are the same (as the difference equals zero). The alternative hypothesis is that both moisture averages are different. With both p-values above 0.05, this shows that the null hypothesis can't be rejected and that both the radial and non-radial bale moistures are the same. This means that both of these average moisture determined by coring along the diameter of the bale yields the same results as using the radial cores to determine the average bale moisture.

Table 2.6: Difference of least squares means analysis for radial cores moisture average vs. core moisture average along the outside diameter of the bale.

Differences of Least Squares Means			
Year	**Actual Difference (%)**	**P-Value**	**Standard Error**
2017	-0.063%	0.952	0.0103
2018	0.062%	0.951	0.0101

Conclusion

A coring methodology was developed to assess the variation of moisture within a round bale of hay for coring along the flat face of the hay bale. The results showed that the moisture variation within single bales could vary from 4% to 8%, with examples shown in Figure 2.10 and Figure 2.11. Large moisture variations at different locations within a bale indicated that it may be inappropriate to use whole bale average moistures for comparing sensor readings. Bales could have relatively wetter and drier regions which could cause the part of the bale to spoil and make the bale be considered lower quality. Inconsistent hay moisture measurements by producers and user could result in revenue lost by the producer when selling hay.

Coring methodology developed in this study was compared to the previous methodology of using radial cores for bale moisture determination. The results showed that the whole bale average moistures using the cores along the flat face of the bale were all almost identical to the average moisture of the radial cores. The observed results have several overall implications. First, it shows that coring along the flat face of the bale would be an effective method, which could be used to correlate to actual sensor readings along the diameter at certain positions for comparing different moisture sensors and while testing of newly developed sensors. Second, this study showed that future research studies involving hay moisture assessment (i.e. forage quality studies, forage storage studies, etc.) can use either method for determining the average bale moisture. The added flexibility in moisture method determination for round bales may make it easier for other research studies to more accurately assess sensor response.

References

Agratronix, L. *Operators Manual BHT-2™ Advanced Baler-Mounted Hay Moisture Tester*. Streetsboro, OH: Retrieved from http://www.agratronix.com/wp-content/uploads/2015/11/07160-manual.pdf

Anderson, P.M. (1981). Harvesting practices and round bale losses. *Transactions of the ASAE, 24*(4), 841-842. doi:10.13031/2013.34349

ASABE. (2017). ANSI/ASAE S358.3 MAY2012 (R2017) moisture measurement- forages. Retrieved from https://elibrary.asabe.org/abstract.asp?aid=41661&t=2&redir=&redirType=

Behringer, C. B. (2004). Performance comparison of moisture sensor technologies for forage crops. University of Madison-Wisconsin.

Coblentz, W. K., & Hoffman, P. C. (2009). Effects of bale moisture and bale diameter on spontaneous heating, dry matter recovery, in vitro true digestibility, and in situ disappearance kinetics of alfalfa-orchardgrass hays. *Journal of Dairy Science, 92*(6), 2853-2874. doi:10.3168/jds.2008-1920

Just, J. (2017). *Moisture sensing in baled crops* Available from ProQuest. Retrieved from https://search.proquest.com/docview/1918070531

Lötjönen, T., & Paappanen, T. (2013). Bale density of reed canary grass spring harvest. *Biomass and Bioenergy, 51*, 53-59. doi:10.1016/j.biombioe.2012.12.041

Philip Shaw. (2010). New Holland BR7000 Series Roll-Belt Round Balers. *Country Guide Ontario*, *129*(7), 5. Retrieved from https://search.proquest.com/docview/743851101

Rich, D. (2017). Manage moisture for high quality alfalfa hay. Retrieved from http://www.hpj.com/alfalfau/manage-moisture-for-high-quality-alfalfa-hay/article_19bfd09a-08e8-11e7-a000-077ffbaa034c.html

USDA, National Agricultural Statistics Service. (2018). *Crop production 2017 summary*. (). Retrieved from http://usda.mannlib.cornell.edu/usda/current/CropProdSu/CropProdSu-01-12-2018.pdf

Chapter 3 - Comparison of Moisture Sensing Technologies

Abstract

Moisture measurement is critical when baling alfalfa into round bales for feed. If alfalfa is too wet or too dry, it can greatly diminish the alfalfa crop's feed quality and cause economic loss to producers. Therefore, monitoring of alfalfa moisture content while baling is critical for producers to maintain hay quality and maximize profits. Currently, there are several different types of moisture sensing technologies available for round balers. These sensors are typically mounted on the hay baler where they can be in direct contact with new hay in the round bale chamber as the bale is growing in size or clearly see formed bale beyond the baling chamber. But, concerns exist regarding their accuracy and repeatability during hay production. The objectives of this project are to 1) Compare and contrast sensing accuracy and repeatability of different hay moisture sensing technologies, and 2) Identify gaps in existing crop moisture sensing technologies and suggest future needs. A sensor testing stand was developed to perform comparative testing between the sensors on the same alfalfa hay bale immediately after it was formed. Five commercially available hay moisture sensors were selected to measure moisture at four pre-determined locations on hay bales. After the sensor measurements, core samples were extracted from the same locations to determine moisture using oven-drying method. The moisture measurements were conducted during three growth stages and bales were formed with three approximate moisture contents of 10%, 15% and 20%. Six different cuts of alfalfa of the same variety were used to capture all the measurements during 2017 and 2018 growing season. Another cut was also performed in 2017 for moisture measurements with the alfalfa baled at 15% and the same growth stage, but different baler compression cylinder pressures (250, 400, and 800psi). After sensor testing, core samples were extracted from pre-determined locations along different diameters of a round bale to determine actual moisture using oven-drying method. Sensor and oven-dried measurements were compared to determine accuracy and repeatability of sensing technologies. Results showed that sensors and oven-dried measurement varied for all the sensors for every growth stage and baling moisture levels, with one sensor exhibiting lowest variability in its readings. This identified the most accurate and reliable sensor. Future research needs to be conducted to identify correlation between the testing stand readings and actual hay baler moisture sensor readings.

Introduction

Alfalfa (Medicago sativa) is one of the most common forages used to feed cattle and other livestock. In 2017, 55.1 million tons (with an average value of $140/ton is $7.71 billion value) of alfalfa was produced in the United States (USDA, National Agricultural Statistics Service, 2018). Every year, millions of tons of alfalfa are sold within the United States or exported to other countries. Moisture measurement is critical when baling alfalfa into hay bales for feed. If alfalfa hay is too wet (>22%), it can heat up the inside of the bale and spoil the alfalfa and cause instantaneous combustion of the hay when stored. But if the alfalfa is too dry (<12%), the leaves can fall off which lowers the feed quality of the alfalfa. Therefore, monitoring of alfalfa moisture content while baling is critical for producers to bale the hay within the desired moisture range of 13% to 17% moisture content to minimize feed value losses and get top dollar for their alfalfa. (Rich, 2017).

The hay forming process consists of swathing which cuts the hay down, and typically has conditioner rollers on it that crush the stems of the crop to allow the plants to dry faster. The crop either falls directly to the ground, or is put into narrower strips called windrows. Second, the hay is raked after the hay dries to the desired moisture range on top of the windrow. This process flips the hay over so that the wet hay underneath can dry to the ideal moisture content of 13 to 17%. Finally, when the hay is cured to the desired moisture content, it is typically baled into square or round bales. When hay is formed in variable chamber round baler, it goes through the pickup into the bale chamber as shown in Figure 3.1. The belts have a set pressure on them to compact the hay and allow the bale to form until the desired bale size is achieved. The bale is then tied with either twine or net wrap, and then is ejected. The whole process of preparing hay for baling could leave hay with significant variability on the moisture, based on location, soil moisture, air temperature, wind speed and density of the hay in the field.

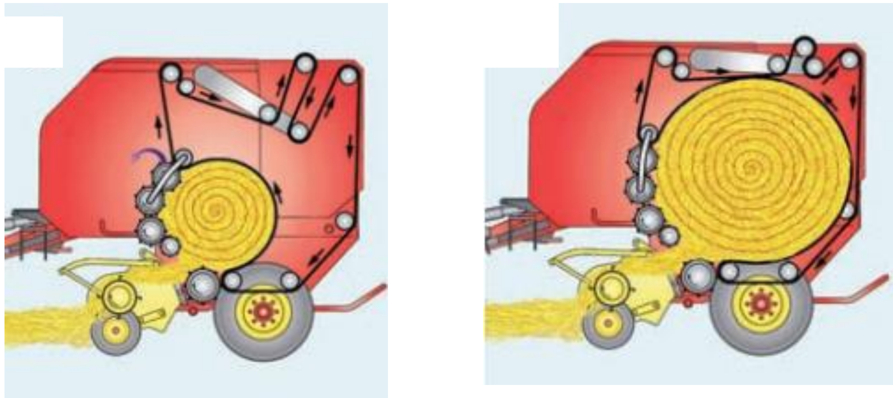


Figure 3.1: Typical formation of a hay bale in a variable chamber round baler (Philip Shaw, 2010)

The hay sensors are typically mounted on the baler where they can either be in direct contact with new hay in the round bale chamber as the bale is growing in size or clearly see formed bale beyond the baling chamber. As seen in Figure 3.1, the bale grows from the front of the baler to the back, and taller in size in the round balers. Because of this, and with limitations of mechanical components on the sides of round balers, there is limited spacing to mount a moisture sensor on a round baler. Two optimum locations to mount moisture sensor is shown in, since the sensors will see the new hay as the bale forms at the different diameters. Some of these sensors are mounted outside the bale chamber where formed bale is in front of the sensor. Most moisture sensing technologies give instantaneous moisture readings as the bale is forming and an average bale moisture at the end of the bale.

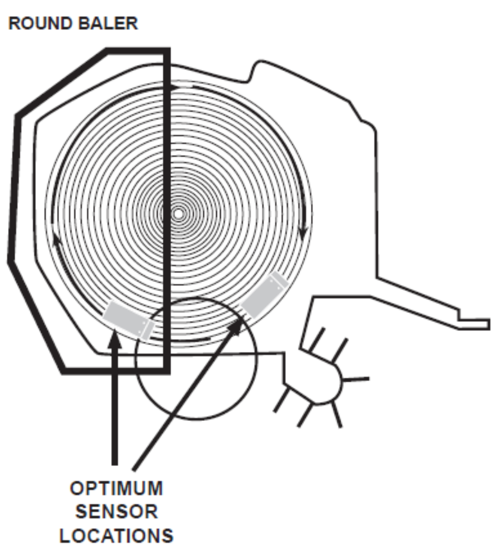


Figure 3.2: Optimum Location for Moisture Sensors on Round Balers (Agratronix)

Moisture Measurement Methods

According to (Kormann, 2000), there are multiple methods to measure the moisture content of a given material, which fall into four general categories. Absolute Methods are the standard methods to determine the actual moisture content directly and can be used as reference methods. The wet chemical methods uses reagents to directly determine the moisture content. Electrical methods use electrical energy to indirectly correlate with the moisture. Finally, Spectrometric Methods use light energy to indirectly correlate with actual moisture content. The stars in the last column in Table 3.1 indicate methods that are practical methods to determine the actual moisture content. The moisture methods with a * in will be discussed.

Table 3.1: Methods for moisture measurement.

Direct Methods	Absolute Methods	1	Dryer Oven	*
		2	Distillation	
		3	Separation by Absorption	
	Wet Chemical Methods	4	Calcium Carbide	
		5	Karl-Fischer	
Indirect Methods	Electrical Methods	6	Conductance	*
		7	Capacitance	*
		8	Microwave	*
	Spectrometric Methods	9	Infrared	*
		10	Nuclear Magnetic Resonance	
		11	Optical Refraction Method	

Oven-Drying

Oven drying is the benchmark method for estimating the moisture content of materials using a dryer oven. According to ASAE S358.3, the moisture content is estimated as shown in Equation 3.1. (ASABE, 2017)

*Moisture Content (%) = (Total Loss in Mass/ Wet Sample Mass)*100* (3.1)

The recommended drying temperature for alfalfa is 103°C for 24 hours. It is also recommended to dry the sample at 55°C for 72 hours if the sample contains volatile components. Alfalfa has volatile components that can be destroyed when dried at too high of a temperature. The drying temperature recommendation is to avoid the degradation of additional proteins, which is not considered part of a plant's moisture content. (Deinum & Maassen, 1994).

Conductance

The electrical conductance of a given material is the ease of which electrical current passes through a material. A conductance sensor sends a signal through a given material, which typically a constant current signal. The signal is emitted from the electrode into the testing medium, with the voltage drop across the medium is correlated to a specific moisture content. The higher the moisture content, the lower the overall resistance of the material, and the higher conductance (Behringer, 2004). In any type of hay bale, this path can be highly variable due to the variability in hay moisture within the given bale. Factors that can influence bale conductance include bale density, temperature, and the use of preservative or other additive chemicals which can affect the performance of conductance-based sensors. Conductance sensors tends to cost lower than other sensor types. It can be used after baling, or in chamber of the baler, depending on the specific sensor. The electrical signal transmission can be accomplished using several different contact types, including pins, probes, and electrodes.

Previous research with conductance-based sensors has shown that conductance-type sensors are not very accurate when tested with a square baler (Behringer, 2004). Behringer discovered from testing with several conductance-based moistures on a square baler that they lacked sensitivity to moisture range for hay due to the samples not being homogenous. Figure 3.3 shows this with the results from their testing with the Farmex BHT-1 sensor. It was recommended to use this sensor as more of a guideline or reference for comparing hay within the same crop instead of absolute measurement.

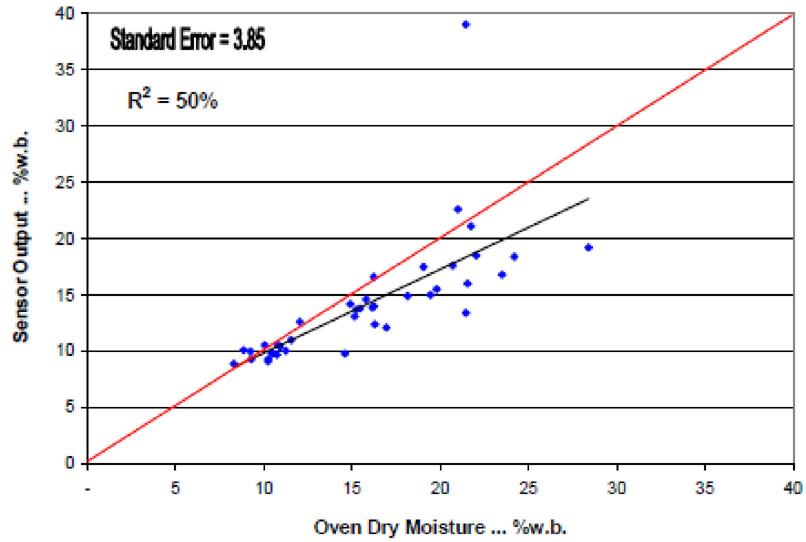


Figure 3.3: Behringer (2004)- Farmex BHT-1 conductance type sensor oven dry-(actual) moisture versus the sensor output moisture content. %w.b. means the wet basis moisture content. For the x axis, it is the same as equation 1.

Capacitance

When a dielectric material is placed in between two plates of a capacitor, the capacitance changes by a numerical value called the dielectric constant. Water has a dielectric constant of 80, and most normal materials have a constant between 3 and 13. If the composition of the material is known, and there are no other foreign components present, it is possible to make a correlation between the moisture content and the capacitance. This technology has been used on grains, wood chips, sand, and other materials (AgriChem, 2016). (Osman, 2003) tested a parallel plate capacitance moisture sensor in both hay and corn-silage. Results showed that the sensor could not directly estimate moisture without a known density of the material. The study also indicated that both 1) by adding more moisture, and 2) increasing the density of the testing material increases the dielectric constant, which correlates to higher moisture. The change in the dielectric constant due to the increase in density had a greater impact at higher moistures because water content has more influence on the dielectric constant. Just (2017) developed a capacitive dielectric sensor that worked by emitting a low frequency electric field from a source plate, and with receiver plates to read the signal. This allows for an impedance measurement, which can be treated as the dielectric constant. The paper is highly redacted but mentioned that overall this sensor is “on par” in terms of accuracy of other expensive (microwave) sensor technology after a Kalman filter has been applied to the sensor’s output for alfalfa. The same dielectric sensor was also tested in the chamber of a cotton module that produced round cotton bales. Just (2017) claimed that when comparing on per-module basis, the performance of the sensor presented was comparable to moisture measurement systems used in gin process control. Gin process control operates under more stable conditions, consistent material composition, and half the moisture content range compared to cotton field applications. They were able to maintain a less than 1% moisture content mean absolute error for moisture levels less than 12%.

Microwave

A microwave is electromagnetic radiation with a wavelength of 0.3 to 30 centimeters, and a frequency in the range of 1 to 100 gigahertz. Moisture measurements in the microwave region of the electromagnetic spectrum can occur in two ways: transmission/absorption, and reflectance. The reflectance sensor resonates at a particular frequency. Depending upon the moisture and density of the bale, the reflection time of the signal is changed. (Behringer, 2004) tested the TEWS MW- 1000 sensor that utilizes microwave reflectance method. The results seemed promising with alfalfa square bales, but it was concluded that there was not enough data to verify the accuracy of the MW-1000.

The other type of microwave moisture measurement is with microwave transmission and absorption. A transmitting antenna sends out a microwave signal, while the receiver antenna measures how much microwave signal energy is transmitted. The absorption can be calculated and related back to the moisture content of a given material. Factors that affect this sensor are the bulk density, and the length of the material the signal is transmitted through. The Gazeeka 870 is an example of a microwave transmission sensor. It has been shown to be very accurate on a large square baler with corn stover up to 28.9% moisture content (Webster, July 2013). An R^2 value of 86.7% was determined when comparing measured moisture vs. actual with the Gazeeka 870 on all of the corn stover bales. (Behringer, 2004) built a microwave transmission system consisting of an Agilent model 8720ES vector network analyzer, coaxial cables, two antennas, and a special bale test fixture for square bales. While there was limited success, it was discovered that their design was not accurate or precise for alfalfa. There was one test where the sensor transmitted a microwave signal showed no sensitivity to moisture with samples actual moisture ranging between 11% and 22% moisture.

Near-Infrared Reflectance (NIR)

Near-infrared reflectance (NIR) sensors utilize an infrared light source on a material to estimate material moisture, along with other physical properties. Some of the light is absorbed or transmitted, while the rest will be reflected. Higher absorption will occur with a decrease in the amount of reflected light at higher moisture content in a given sample. The amount of reflected light at specific wavelengths, ranging from 200nm to 2200nm can be used to determine the moisture content. . The amount of light that is transmitted through a material is minimal. One limiting factor is that NIR light only penetrates the outer surface of the material tested and does not reflect the physical properties of the material underneath a sample surface. (Behringer, 2004)

Behringer (2004) conducted tests with the Zeiss Corona 45 NIR sensor in a laboratory environment, as well as the MESA MM710 NIR sensor in a laboratory and field environment. The MESA sensor did not adequately estimate alfalfa silage or wet corn silage moisture contents in both the lab (static test stand) and field environments (mounted on a silage chopper). The Zeiss Corona 45 lab results showed the sensor to be accurate, with 94% of the data for wet corn silage within ±2% of the actual moisture content for static laboratory testing. Field testing with a silage chopper showed that the accuracy within ±2% decreased to 81% of all samples collected. No testing was conducted on these sensors with alfalfa hay bales.

Summary of Current Moisture Measurement methods

Hay moisture sensing systems are continuously evolving and newer systems are being developed for hay production. However, little research have quantified comparative accuracy of currently available hay moisture sensors. To be able to compare various moisture sensing technologies, there also needs to be an accurate method to compare moisture sensor readings with actual hay moisture. The previous methodology used moisture testing techniques that resulted in samples that were representative of the entire hay bale rather than individual positions within a bale. The moisture sensors are expected to output accurate moisture readings at the corresponding diameters to provide reliable information. To be able to test and develop accurate moisture sensors, researchers and end users need a more robust mechanism to compare moisture sensors accuracy and repeatability to bale moisture contents relative to selected locations on a round baler. This methodology would allow users to confidently and accurately observe acceptable sensor behavior. Therefore, the proposed study was designed with two main objectives.

3) Compare and contrast sensing accuracy and repeatability of different hay moisture sensing technologies, and
4) Identify gaps in existing crop moisture sensing technologies and suggest future needs.

Developed Methodology

Development of the Testing Stand

A sensor testing stand (Figure 3.4 and Figure 3.5) was developed to perform comparative sensor testing between the sensors on the same alfalfa hay bale as sample material immediately after it was formed. Several factors were considered critical when formulating design for the testing stand. Based on the considerations, the main objectives were 1) For the test stand to be portable for easy movement during testing field, 2) Practical installation of different sensors to easily take moisture measurements at the selected locations to allow direct comparison, and 3) Allow for contact and non-contact moisture sensor technologies to be used. The developed testing stand allowed for the sensors to test for moistures along the center diameter of a round hay bale, as the sensor would typically perform when taking measurements on the baler.

Figure 3.4: Testing Stand (Left Side) mounted on the back of a tractor with moisture sensors installed for hay moisture recording

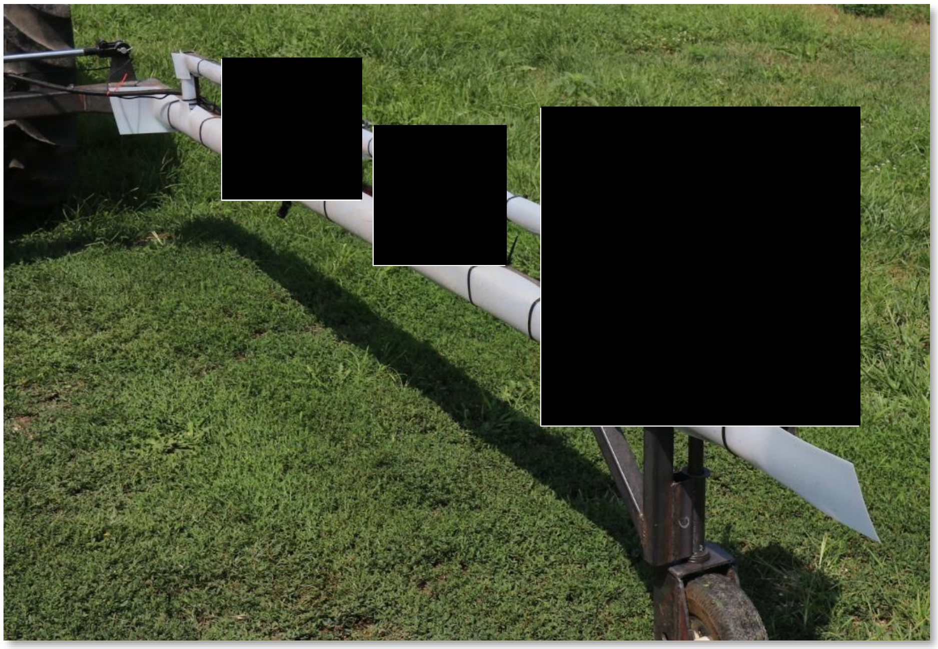


Figure 3.5: Testing Stand (Right Side) mounted on the back of a tractor with different sensors installed for comparison

Five hay moisture sensors were selected and mounted on the testing stand for the first year (2017), as seen in Figure 3.5. [redacted] Each arm of the testing stand can compress Sensors 1 to 4 flush against the flat face of the bale to replicate the baler pressure conditions with dual hydraulic cylinders. The pressure within the hydraulic sensors was recorded during testing. The applied testing stand pressure caused the sensors to indent the side of the bale between 10-15 mm during testing. Sensor displays and data acquisition systems were positioned inside the tractor cab for in-field testing. The testing stand was designed to be used with five-foot-wide bales. [redacted] Plastic strips were added along the frame of the testing stand, along with covers for each of the sensors, to prevent the sensor electrical interference across the testing stand and with each other. The sensors were spaced 7.5 inches apart, based upon the selected locations on the hay bale to increase the speed of switching between sensors.

In 2018, three modifications were made to the testing stand (Figure 3.6) including 1) sensor 5 was not tested again; 2) flat pieces of metal were used to help align the sensors more evenly to avoid one sensor digging in the side of the bale while testing; and 3) Sensor 6 was added. Plastic strips were again added to prevent the testing stand from electrical interference out the sensor readings. [redacted]

Figure 3.6: Testing Stand 2018 Modifications

Figure 3.7: Left Hand Side of Testing Stand

Figure 3.8: Right Hand Side of Testing Stand

Preparing the Hay for Testing

The alfalfa variety used for this research was WL Alfalfas WL 372HQ.RR and was planted in the fall of 2012. The alfalfa was first cut into 1.52 m (5ft) wide windrows using a CIH 8312 Disk mower conditioner (CIH Industrial, Racine, Wisconsin). Alfalfa was then raked into 0.91 m (3ft) windrows with a H&S 2110 10-wheel V-Rake for curing when the alfalfa was of the approximate target moisture on top of the windrow (H&S Manufacturing Co. Inc, Marshfield, Wisconsin). An Agratronix 07140 Windrow Moisture Tester (Agratronix, LLC, Streetsboro, Ohio) was used to check approximate windrow moisture with samples from the top of the windrow and checked again before baling. Cutting on average occurred two to three days before raking the alfalfa hay. Then, the alfalfa hay was dried to achieve the three target moisture contents of 10%, 15%, and 20%. The windrow moisture content was monitored with the Agratronix Windrow Moisture Tester. Once the alfalfa reached each of the three desired moisture contents, it was immediately baled to form three bales at each moisture content and moved to the testing site. Baling was conducted with a New Holland RB560 Specialty Crop Round Baler (CNH Industrial, New Holland, Pennsylvania) which made a 1.52m (5ft) wide and 1.83m (6ft) bale diameter bale (Figure 2.5). Each of the bales were weighed using a custom built electronic scale platform with Longacre Computer Scales AccuSet II Wireless scales (Model #725934, Booneville, Indiana) having four pads. Each pad had a rate capacity of 680kg (Figure 3.10). The diameters of each bale were recorded at five locations using a tape measure. The diameter and weight was used to calculate for bale density. Finally, the alfalfa bale was marked at four locations along each flat face of the bale (Figure 2.7) to record sensor response and also to extract core samples for moisture quantification used oven drying method.

Figure 3.9: New Holland T6.180 baling alfalfa hay with New Holland RB560 Round Baler

Figure 3.10: Custom Built Scale Platform with Longacre Wireless Scales

The testing was duplicated across three alfalfa plant growth stages – Late Vegetative State, Mid to Late Budding Stage, and Mid-Blooming Stage, across three separate cuttings (1st, 2nd, and 3rd Cuttings) for 2017 and 2018 growing seasons. An additional test was conducted in the 2017 season looking at varying baler density settings of 1.72, 2.76, and 5.52MPa (250, 400, and 800psi) by varying the baler belt downward pressure. Typical bale weights at 2.76 MPa of pressure resulted in an average of 540kg for the 10% MC target bales, 660kg for 15% MC target bales, and 750kg for 20% MC target bales. In 2017, there were 61 bales tested across three cuttings, as shown in Table 3.2. In 2018, there were 52 bales tested, as shown in Table 3.3. In 2018, a cross-contamination between left over chemical from previous spray and one intended for spraying on alfalfa killed most of the alfalfa in 2018 before the first cutting. Therefore, it was required to relocate to different alfalfa fields of the same variety as used in 2017, but without the Round-Up ready gene in it. Also, due to limited availability of alfalfa during the first cut, hay from third cut was utilized to produce sufficient bales to conduct replicated tests for the three growth stages. For the 2018 testing year, there were enough bales in the 1st and 3rd Late Vegetative, and the 2nd and 3rd Late Budding and the 2nd and 3rd Mid-Blooming Stages for a full statistical analysis. The statistical analysis performed with this cut used growth stage and moisture target as treatments.

Table 3.2: 2017 Summary of Cuts

Cutting	Growth Stage	Moisture Target
1st	Late Vegetative	10
		15
		20
	Late Budding	10
		15
		20
	Mid-Blooming	10
		15
		20
2nd	Late Vegetative	10
		15
		20
	Late Budding	10
		15
		20
	Mid-Blooming	10
		15
		20
Density (1.72, 2.76, and 5.52MPa)	Late Budding	15
		15
		15

Table 3.3: 2018 Summary of Cuts

Cutting	Growth Stage	Moisture Target
1st	Late Vegetative	10
		15
		20
	Late Budding	10
		15
		20
	Mid-Blooming	10
		15
		20
2nd	Late Vegetative	10
		15
		20
	Late Budding	10
		15
		20
	Mid-Blooming	10
		15
		20
3rd	Late Vegetative	10
		15
		20
	Late Budding	10
		15
		20
	Mid-Blooming	10
		15
		20

Coring Samples from Round Alfalfa Hay Bale

Core samples were extracted from selected locations from the flat face along the diameter of the bale and along the radial side. Four locations were selected (A, B, C, and D) for each of the two flat sides of the bale as depicted in Figure 3.11. The selected locations provided a total of eight different coring locations on the flat faces along the diameter. At each coring location, there were two cores taken, one 0.30 m (1 foot) deep, and the other 0.30 m to 0.6 m (1 foot) deep from the face of the bale. For example, at coring position A shown in Figure 3.11, two coring samples were taken at location 1, and two at location 8. Three additional coring locations, 9, 10, and 11 were selected on the radial face of the bale. The coring locations for radial face were on the same half of the bales as positions A, B, C, and D, and were taken at the same height as positions A, B, C, and D were taken. Cores 9, 10, and 11 provided additional bale moisture for averaging purposes, but also gave data from the radial positions to compare with moisture samples from the flat surface. Each bale was cored at all 11 positions shown in Figure 3.11. A Uni-Forage Star Sampler (Star Quality Samplers, Edmonton, Alberta, Canada) was used to gather core samples (Figure 3.12). The corer was 2.2 cm (7/8 inch) in diameter, and was 0.6m (2ft) long. The cores were immediately weighed in the field with an OHAUS Scout II scale with 600g capacity and 0.1g resolution, before being bagged for oven drying (Figure 3.13). ASAE S358.3 (R2017) was used as the guide for oven-dry core method for this project. The samples were dried at 55°C for 72 hours. (ASABE, 2017). The procedure for core sampling and moisture estimation procedure as established in Chapter 2, was used to quantify actual moisture distribution within round alfalfa bales.

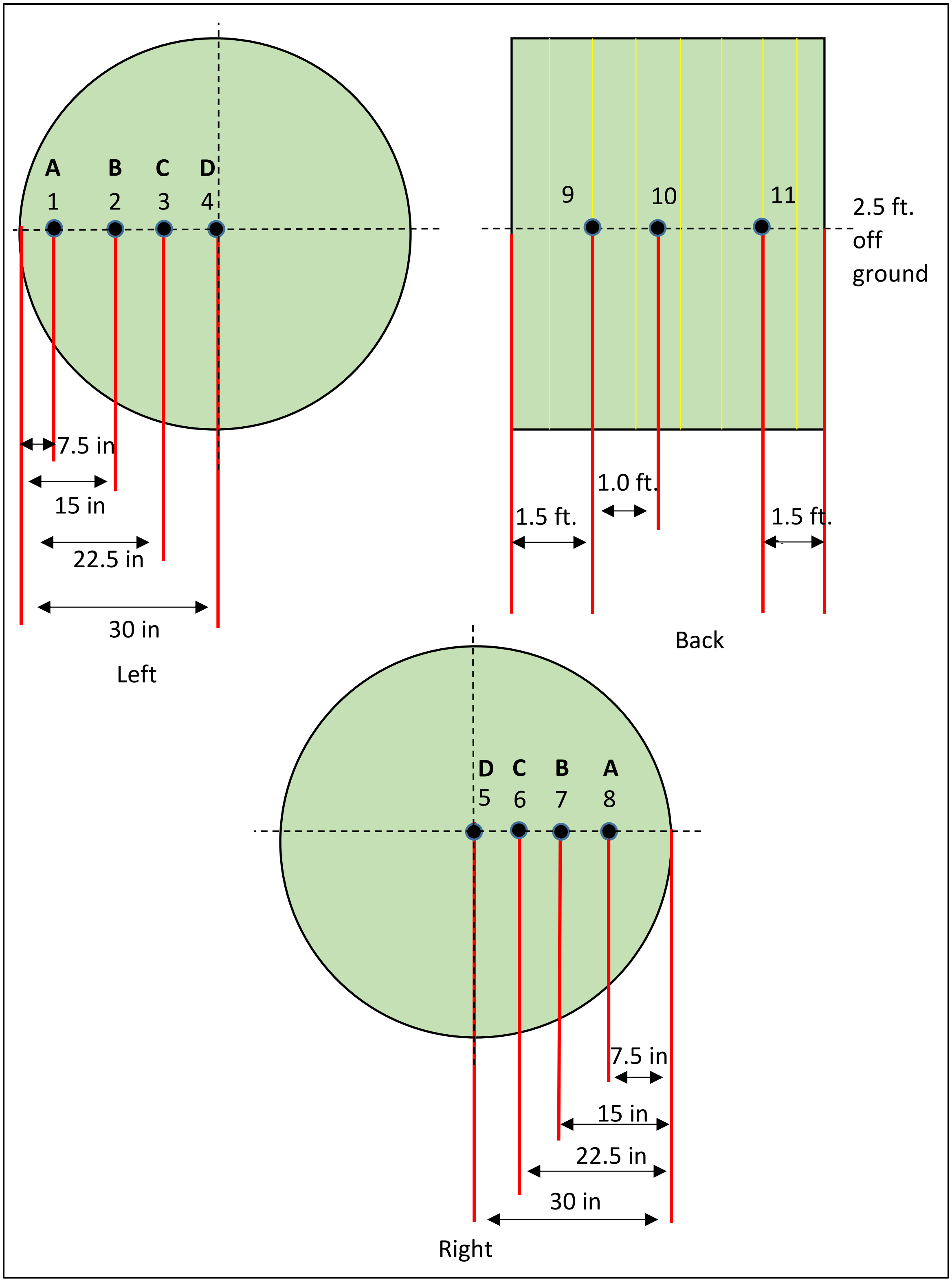


Figure 3.11. Core sample from selected locations tested upon on a 1.52m by 1.52m (5 foot by 5-foot) alfalfa hay bale

Figure 3.12: Coring on a sample round alfalfa bale

Figure 3.13: Weighing Core Samples on Scale after collecting each core

Testing Procedure with the Testing Stand

All the moisture sensors tested used the followed the same testing procedure on the testing stand for each of the desired moisture target bales (10%, 15% and 20%) at each of the three growth stages (the late vegetative, mid to late budding stage, and the blooming stages). Each sensor was tested independent of each other to avoid the effect from them interfering with each other, in the order listed in the beginning of this section. For each sensor testing, the operator would back the testing stand extended to its full width and get the tractor and stand properly horizontally aligned with the bale, as shown in Figure 3.14. Once the stand was aligned, it was moved to where the Sensor 1 was in line with Position A as shown in Figure 3.11. Then, the operator would compress the stand, and take the sensor and cylinder pressure readings with the sensor for 30 seconds. Next, the operator would extend the testing stand, and move on to the next position, position B. The operator repeated the same data recording process for the first position and proceeded to record for the third and fourth positions, Positions C and D, respectively as shown in Figure 3.11. Finally, the operator would move onto the next sensor and repeat the process for Sensors 2, 3, and 4 in 2017 and 3, 4 and 6 in 2018. To make sure accurate readings occurred while testing, the operator checked the sensors for correct location and appropriate contact with the bale at each selected location.

To test Sensor 5, the testing stand was left in the extended position. [redacted]

After all the sensor testing was completed, the bale was cored each of the 11 positions shown in Figure 3.11. The cores were weighed in the field before being bagged for oven drying. ASAE S358.3 (R2017) standard was used as the guide for oven-dry core method. All samples that were analyzed for plant properties were dried at 55 °C for 72 hours. The rest were dried at 70 °C, per the recommendation of Deinum (1994).

Figure 3.14: 2018 Testing Stand running on Alfalfa Hay sample

Density Testing procedure

The Density Test was the final test that was conducted with all sensors in the 2017 testing year. The main objective of this test was to see if the baler pressure density setting affected the sensing accuracy and repeatability. For this set of tests, the alfalfa was baled at a target moisture of 15%, and at the budding growth stage. The baler density pressure was set at three different settings 1.72, 2.76, and 5.52MPa (250, 400, and 800psi) The baler was set to 400 psi baling pressure for all the other tests for both testing years, except for the density test. The procedure was the same as described in the "Testing Procedure" earlier, except for that the baler density setting was change, and all the hay was baled around 15% moisture content.

Data Analysis

Data analysis to deduce the average sample and bale moisture contents, along with the bale moisture content standard deviations, was performed in Microsoft Excel. Each individual core moisture content was calculated according to Equation 3.2 below:

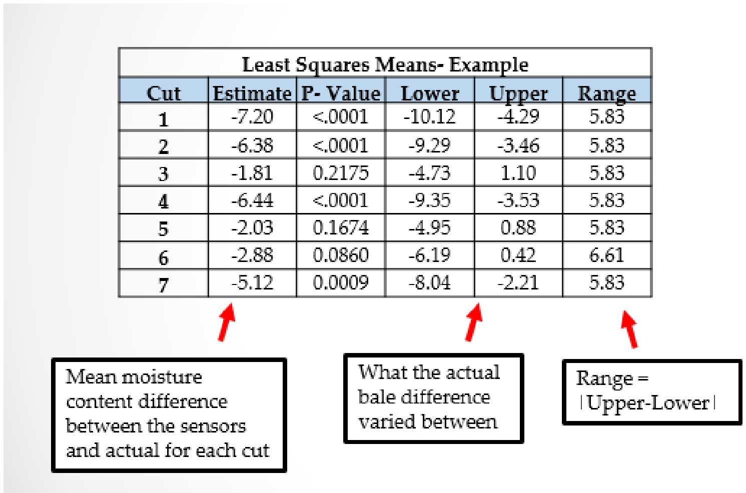
$$\text{Core Percent Moisture Content} = \frac{\text{Final Sample Weight} - \text{Initial Sample Weight}}{\text{Initial Sample Weight}} * 100 \qquad (3.2)$$

For each sensor, the actual moisture versus the sensor response moisture plots are shown for all bales tested for both testing years. The data is displayed by whole bale averages rather than by position, for both the sensor readings and actual bale moisture. The whole bale average moistures were determined by taking the average of the coring positions 1 through 8 at both depths. Cores from positions 9 to 11 weren't considered because (as stated in Chapter 2 and in the testing procedure development) the procedure was based upon being able to compare moisture readings by position rather than by using whole bale averages. From end user perspective, accurate whole bale moisture measurement is the most critical for assessment of sensor response. The average sensor moisture content for each bale is the average of the moisture contents at each of the four diameter positions (A, B, C, and D) tested. In each of the average versus sensor measured data charts for each of the sensors for both years, there is the an equation for the best line of fit, the R^2, Pearson's coefficient, and the p-value for Pearson's coefficient

The results are shown separately for 2017 and 2018 field testing. Comparisons are also drawn to exhibit percentage of bales within ±3% and and ±5% between the sensor response and actual moisure difference for each moisture sensor. This gave a direct comparison of each the sensors in terms of two accuracy ranges, with the ±3% being fairly accurate, and ±5% being less accurate. [redacted]

A statistical analysis was used to determine the difference between the sensor's reading and the actual moistue was statistically equal to zero, and how similar the cuts were to each other. To accomplish this, SAS software was used, with the least squares method and the difference of least squares method. A 95% confidence level was assumed in this analysis. There were two comparisons, 1) comparison by target moistures (10, 15, and 20%), and 2) cut by growth stages (late vegetative, mid to late budding, and mid blooming, as shown in Table 2 and 3. A T-Test was also performed to check for the data being normally distributed.

Figure 3.15 shows a sample data with the least squares means for different cuts with Sensor 2. Data was analyzed as a completely randomized design using PROC MIX method of SAS (SAS Institute Inc., 2018, SAS University Edition, Cary, NC). Individual bales constituted as the experimental unit. The treatments were the radial core whole bale moisture average and, and the non-radial core whole bale moisture average. Significance was at $\alpha = 0.05$. When the p-value for a specific cut or moisture target was less than 0.05 are considered statistically significant, and the mean moisture percentage was statistically not similar to zero for the least squares means. When the p-value was greater than 0.05, the data is not statistically significant and the mean moisture percentage is not statistically different from zero. Table 3.4 lists the cut numbers and the associated cuts for the statistical analysis for each sensor. A PROC CORR method was also used to determine the R^2 value and Pearson's correlation coefficient and the probability of it being a correlation (for $\alpha = 0.05$) for each sensor. If the -value is less than 0.05, then there is a definite correlation to the data. Note that some of the results are blacked out for proprietary purposes.



Least Squares Means- Example

Cut	Estimate	P- Value	Lower	Upper	Range
1	-7.20	<.0001	-10.12	-4.29	5.83
2	-6.38	<.0001	-9.29	-3.46	5.83
3	-1.81	0.2175	-4.73	1.10	5.83
4	-6.44	<.0001	-9.35	-3.53	5.83
5	-2.03	0.1674	-4.95	0.88	5.83
6	-2.88	0.0860	-6.19	0.42	6.61
7	-5.12	0.0009	-8.04	-2.21	5.83

Figure 3.15: Example of stat analysis for one cut

Table 3.4: Cutting numbers with cuts used in statistical analysis

Cutting Number	2017	2018
1	1st Late Vegetative	1st Late Vegetative
2	1st Late Budding	1st Late Budding
3	1st Mid-Blooming	1st Mid-Blooming
4	2nd Late Vegetative	2nd Late Budding
5	2nd Late Budding	2nd Mid-Blooming
6	2nd Mid-Blooming	3rd Late Vegetative
7	Density Test	3rd Late Budding
8	-	3rd Mid-Blooming

Results and Discussion

The results and statistical analysis for each sensor, for both 2017 and 2018 are listed in each sensor section.

Sensor 1

Figure 3.16 depicts the measured moisture for Sensor 1 mounted on the testing stand versus the oven dry moisture from the 2017 testing year. The solid line represents a one-to-one moisture line. Each point represents average moisture content measured from locations A through D of one alfalfa bale. The majority of the data points in Figure 3.16 lie to the right of the one to one line, which means that Sensor 1 readings were on an average higher than the actual bale moisture content. Pearson's coefficient was 0.666. This showed that there is moderate correlation of the data, and was confirmed by the p-value (<.0001) being less than 0.05. The data from a wide range target moisture contents showed that Sensor 1 response deviated from the actual moisture content for each bale tested by an average of 4.3%. Among all the 61 bales tested in 2017, only 51% of the bales tested with sensor were within ±3% and 67% of the total bales were within ±5% of the actual moisture content. For hay moisture sensing, a 5% moisture error can mean the difference between having good hay and bad hay, which could potentially result in a loss of revenue for producers. For this sensor, it would equate to 1/3 of the total crop being considered bad hay. A summarized table of data for Sensor 1 across all cuts and moisture targets for 2017 testing year is shown in Appendix A.

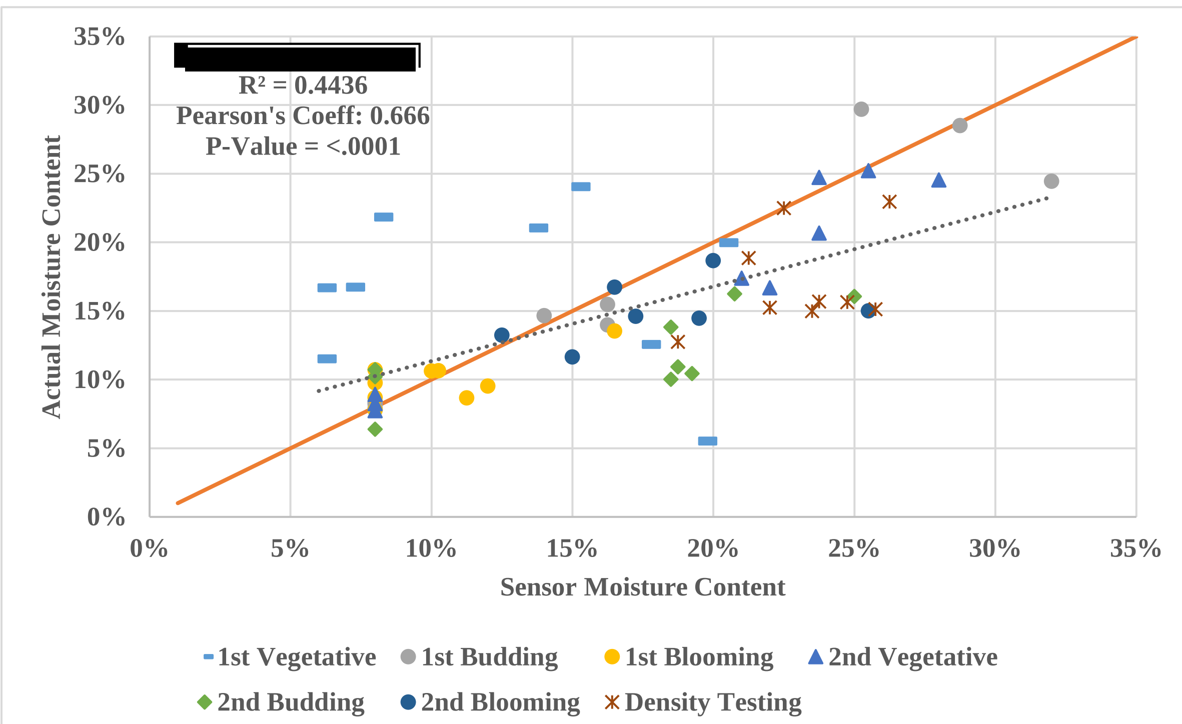


Figure 3.16. Sensor 1 measured moisture (on testing stand) versus oven dry moisture during 2017 testing.

Table 3.5 and Table 3.6 show the least squares mean analysis when using the moisture targets and cuts by growth stages for comparison. For Sensor 1, the differences from actual moisture content for each of the target moistures (10, 15, and 20%) are non-significant (statistically similar to zero). Similar results for Sensor 1 were observed for the cut by growth stages comparison. Table 3.6 shows that most of the cuts are non-significant, except for cuts 1 and 7. The estimates had a range of 12% (-6% to 6%), which would not provide confidence in hay moisture sensing accuracy and repeatability.

Table 3.5: Least squares mean analysis for Sensor 1 by target moisture for 2017 data

Least Squares Mean- Sensor 1					
Target	**Estimate**	**P-Value**	**Lower**	**Upper**	**Range**
10	0.91	0.70	-3.85	5.66	9.51
15	2.96	0.07	-0.33	6.27	6.60
20	2.56	0.14	-0.93	6.06	7.00

Table 3.6: Least squares mean analysis for Sensor 1 by cut for 2017 data

Least Squares Means by Cut – Sensor 1					
Cut	**Estimate**	**P- Value**	**Lower**	**Upper**	**Range**
1	-5.95	0.0019	-9.60	-2.31	7.29
2	-0.68	0.7113	-4.32	2.97	7.29
3	-2.76	0.1351	-6.40	0.89	7.29
4	0.52	0.7750	-3.12	4.17	7.29
5	3.43	0.0648	-0.22	7.07	7.29
6	3.11	0.1369	-1.02	7.24	8.26
7	6.07	0.0015	2.43	9.72	7.29

Sensor 1 was tested again on the testing stand for a second year (2018) and results are shown in Figure 3.17. Sensor 1's moisture distribution for 2018 appeared to be more evenly distributed across the one to one moisture line compared to 2017. The spread of the data was more than that from 2017 testing, as seen by the lower R^2value of 0.1602. Pearson's Coefficient (0.401) showed that there is still moderate correlation. But similar to as in 2017, the possible actual moisture range at each sensor reading indicated moisture was large. Sensor 1 had an average error of 4.3% from the actual moisture content for each bale tested. A summarized table of data for Sensor 1 across all cuts and moisture targets for 2018 testing year can be seen in Appendix C. There were 52 bales tested in 2018. Only 46% of the bales tested with sensor were within ±3% actual moisture content of the actual average moisture. 69% of the total bales were within ±5% of the actual moisture content. These numbers are almost identical to the numbers from 2017 (51% for ±3%, 67% for ±5%).

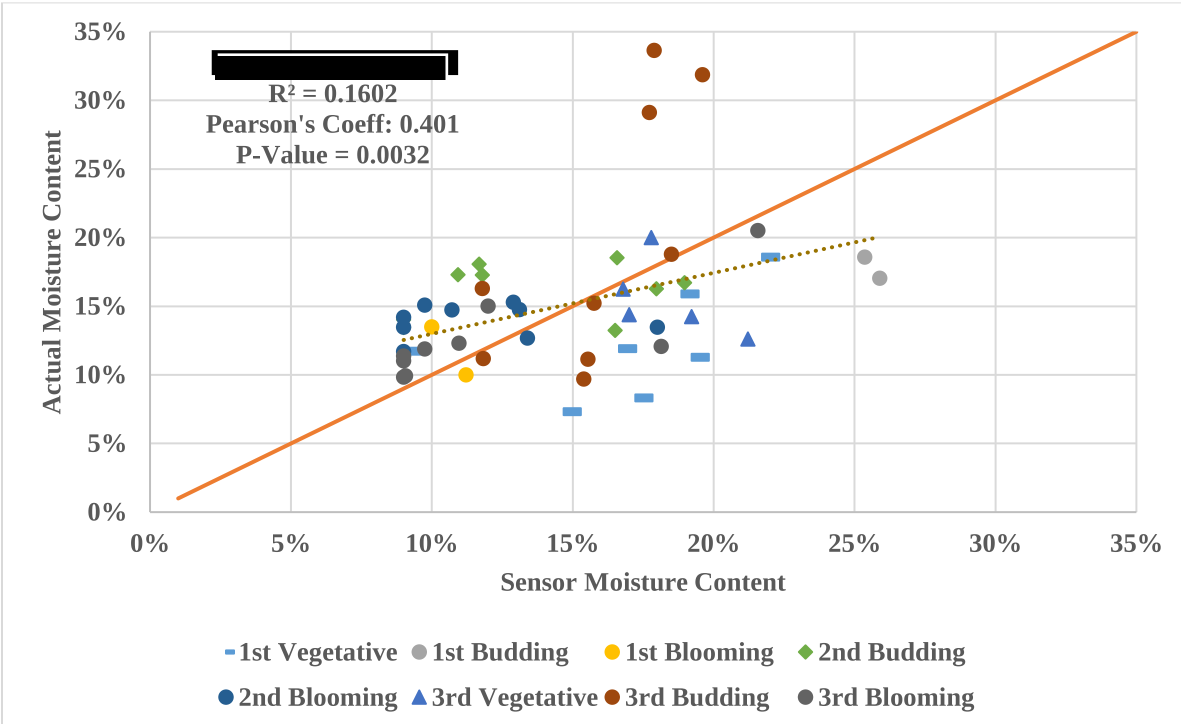


Figure 3.17. Sensor 1 measured moisture (on testing stand) versus oven dry moisture during 2018 testing

Least squares mean analysis performed for the 2018 data (Table 3.7 and Table 3.8) showed that the differences for each of the target moistures (10, 15, and 20%) were statistically nonsignificant (similar to zero), indicating the differences between sensor and actual moisture measurements were different among different moisture levels. Table 3.8 showed that most of the cuts were significant (not statistically equal to zero), except for cut 3. This is different from the the 2017 testing year data (Table 3.6). The randomness of the estimates of the actual differences for both target moisture and by cut for two years of data showed that cut and target moisture have no effect of the performance of Sensor 1. The estimates had a range of 5.6% (2.2% to 7.8% actual estimates). For two years of results indicated that Sensor 1 deviated from actual bale moisture by an average of 4.3% on the testing stand across all moisture contents. Overall, Sensor 1 typically provided higher than actual moisture values, and showed greater variation in the recorded moisture values compared to actual bale moisture. But, it showed that there was a moderate correlation in being able to different moisture contents as seen by Pearson's coeffient and the R^2value across both testing years.

Table 3.7: Least squares mean analysis for Sensor 1 on test stand by target moisture for 2018 data

Least Squares Mean- Sensor 1					
Target	**Estimate**	**P-Value**	**Lower**	**Upper**	**Range**
10	1.42	0.27	-1.14	3.99	5.13
15	-0.23	0.86	-2.80	2.33	5.13
20	-2.00	0.11	-4.49	0.50	4.99

Table 3.8: Least squares mean analysis for Sensor 1 on test stand by cut for 2018 data

Least Squares Means by Cut – Sensor 1					
Cut	**Estimate**	**P- Value**	**Lower**	**Upper**	**Range**
1	5.3881	<.0001	3.05	7.73	4.68
2	7.8125	0.0008	3.44	12.19	8.75
3	2.3590	0.2832	-2.02	6.74	8.75
4	4.0947	0.0002	2.03	6.16	4.13
5	3.4422	0.0016	1.38	5.51	4.13
6	3.7882	0.0084	1.02	6.56	5.54
7	6.1607	<.0001	4.10	8.22	4.13
8	2.1882	0.0381	0.13	4.25	4.13

An additional unit of Sensor 1 mounted on the New Holland RB560 Baler for the second year of testing provided a comparison of sensor performance on the testing stand compared to the baler. Figure 3.18 shows the actual moisture content versus the sensor read moisture content for mounted in the round bale chamber. Except for eight of the bales, the sensor read moisture content was higher than the actual moisture content of the bale (Figure 3.19). On average, Sensor 1 on the baler was off by 5.6% from the average actual bale moisture content, which was higher than the sensor from the testing stand. Sensor 1 on the baler had a similar Pearson's coefficient as both years of testing of Sensor 1 on the stand, and a R^2value that is in line with the testing stand results. A change in the calibration would help slightly improve the accuracy of the sensor in the baler chamber. A summarized table of data for Sensor 1 on the baler across all cuts and moisture targets for 2018 testing year can be seen in Appendix C.

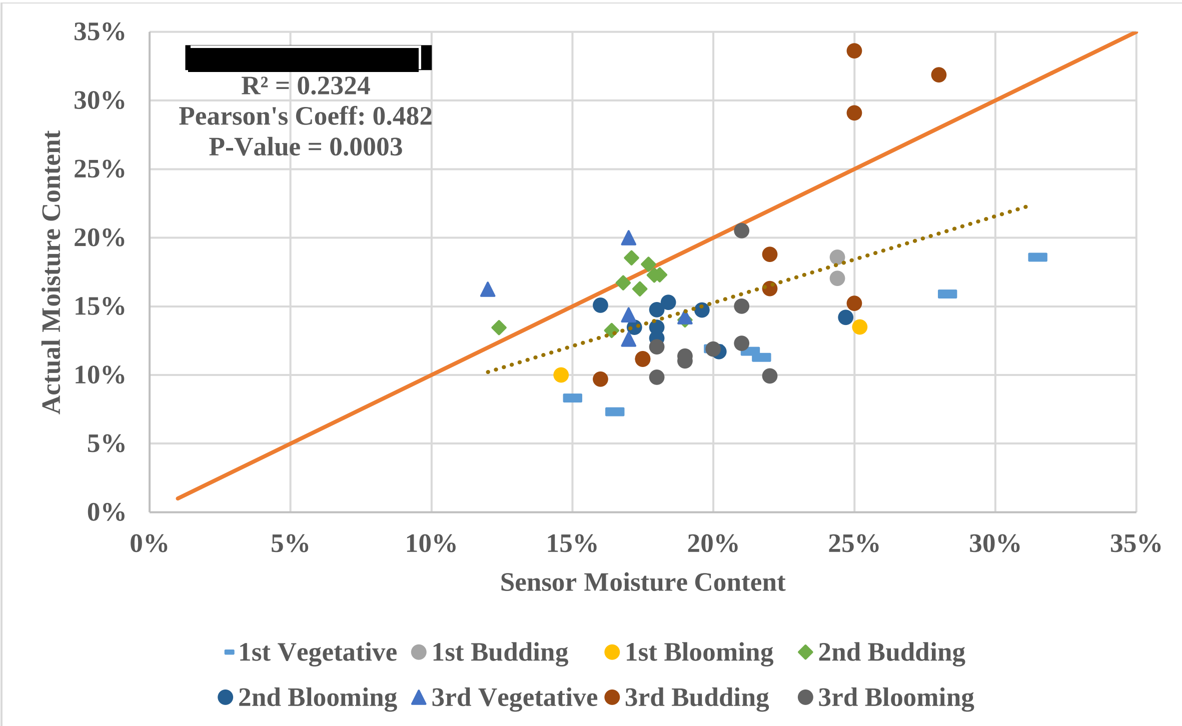


Figure 3.18: Sensor 1 measured moisture (On Baler) versus Oven Dry Moisture during 2018 testing

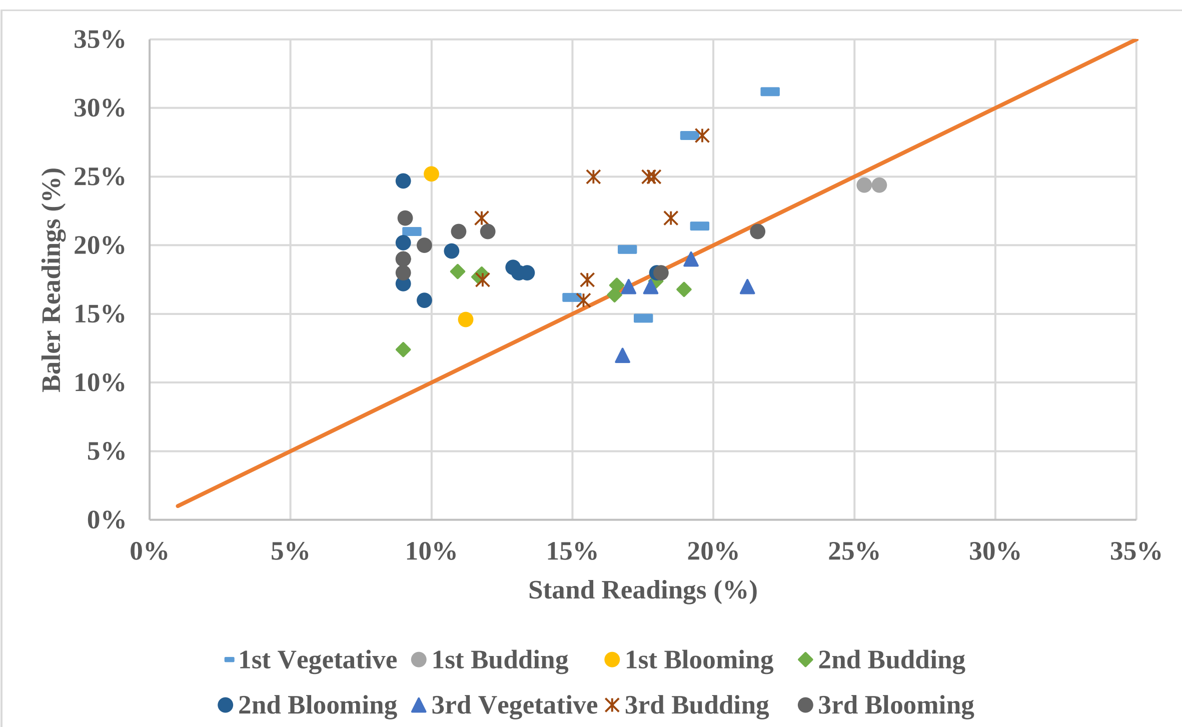


Figure 3.19: Sensor 1 Baler vs. stand readings during 2018 testing

Least squares mean analysis performed for Sensor 1's data mounted on the baler using the moisture targets (Table 3.9) were statistically significant (statistically different from zero). Table 3.10 also showed that most of the cuts by growth stages were not statistically significiant (statistically similar to zero), except for cuts 4 and 6. The estimates had a range of 8.7% (0.9% to 9.6% actual estimates). The results emphasized that Sensor 1 when mounted on testing stand and in the baler tend to read moisture value higher than actual, and that cut and moisture target have no effect on sensor performance.

Table 3.9: Least squares mean analysis for Sensor 1 on the baler by target moisture for 2018 data

Least Squares Mean- Sensor 1 on Baler					
Target	**Estimate**	**P-Value**	**Lower**	**Upper**	**Range**
10	5.89	<.0001	3.62	8.16	4.53
15	4.90	<.0001	2.63	7.16	4.53
20	3.19	0.01	0.99	5.39	4.40

Table 3.10: Least squares mean analysis for Sensor 1 on the baler by cut for 2018 data

Least Squares Means by Cut – Sensor 1 on the Baler					
Cut	**Estimate**	**P- Value**	**Lower**	**Upper**	**Range**
1	9.59	<.0001	6.73	12.45	5.72
2	6.59	0.0170	1.24	11.94	10.70
3	8.15	0.0037	2.80	13.50	10.70
4	0.97	0.44	-1.56	3.49	5.05
5	4.97	0.0003	2.45	7.50	5.05
6	0.90	0.60	-2.49	4.28	6.77
7	2.34	0.07	-0.18	4.87	5.05
8	7.23	<.0001	4.71	9.75	5.05

[redacted]

[redacted] Overall, Sensor 1 can detect differences in moistures in different hay samples, but lacks precision and isn't accuracy, as seen with the data from both years with the sensor, the R^2 values, Pearson's coefficient with P-Values, and the overall accuracy of Sensor 1 within ±3% and ±5%. The observed deviations in moisture measurements might not be enough to accurately monitor hay bale moisture by end users for precision agriculture. These results agree with what Behringer (2004) found with square hay bales.

Sensor 2

Sensor 2 didn't have an initial calibration curve for alfalfa hay. A calibration curve was developed based upon the raw output sensor value with the actual moisture content of the hay sampled. All data analysis was performed with this developed calibration curve. Figure 3.20 depicts the measured moisture for Sensor 2 versus the oven dry moisture for 2017. The solid line represents a one-to-one moisture line. Each point represents average moisture content measured from locations A through D of one alfalfa bale. The data is evenly and tightly distributed on both sides of the one-to one line. Pearson's coefficient was 0.639. This showed that there is strong correlation of the data, and was confirmed by the p-value (<.0001) being less than 0.05. When the six bales farthest away from the one-to-one are factored out of data, the data has a high correlation. The R^2 value becomes 0.713, and Pearson's correlation coefficient was 0.844, which indicates a really strong relationship and correlation. This is confirmed by that Sensor 2 was off by an average 3.4% moisture content for each bale tested across all the sensor moisture range. Among all the 61 bales tested in 2017, 61% of the bales tested with sensor were within ±3% actual moisture content of the actual average moisture. 84% of the total bales were within ±5% of the actual moisture content. Even though Sensor 2 had a low percentage of the total bales within ±3% actual moisture content compared to what producers would like to have, Sensor 2 was the most accurate compared to the other sensors for 2017. A summarized table of data for Sensor 2 across all cuts and moisture targets for 2017 testing year can be seen in Appendix A. [redacted]

[redacted]

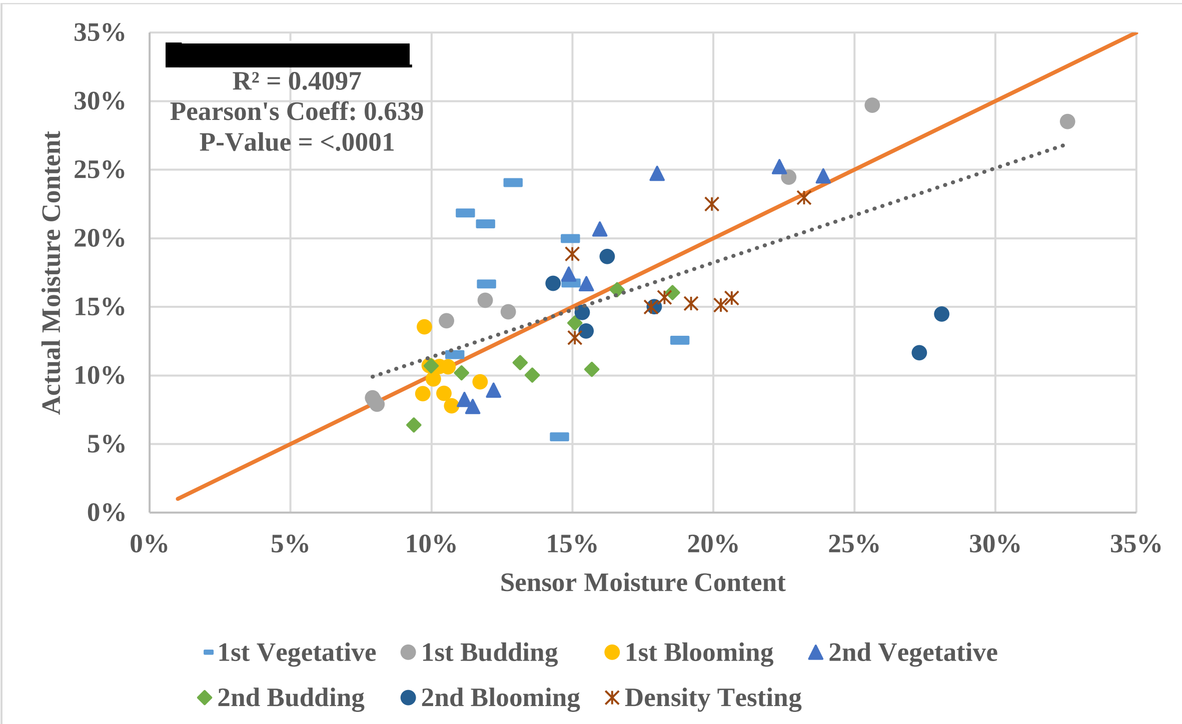


Figure 3.20: Sensor 2 measured moisture versus oven dry moisture during 2017 testing

Table 3.11 and

Table *3.12* show the least squares mean analysis when using the moisture targets and cuts by growth stages for comparison. For Sensor 1, the differences for each of the target moistures (10, 15, and 20%) are statistically significant (not statistically similar to zero). Similar results for Sensor 2 were observed for the cut by growth stages comparison.

Table 3.12 shows that most of the cuts are not statistically non-significant (different from zero), except for cuts 3 and 5. The estimates had a range of 5.4% (-7.2% to -1.8%). The all negative estimates on both the cuts and moisture targets suggests that the calibration curve needed to be modified to improve the accuracy of the sensor. A constant of +3% moisture constant to the calibration equation was necessary, and was implemented in the 2018 testing year.

Table 3.11: Least squares mean analysis for Sensor 2 by target moisture

Least Squares Mean- Sensor 2					
Target	**Estimate**	**P-Value**	**Lower**	**Upper**	**Range**
10	-2.34	0.08	-5.02	0.34	5.36
15	-4.81	0.00	-7.23	-2.40	4.83

20	6.18	<0.0001	-8.76	-3.60	5.16

Table 3.12: Least squares mean analysis for Sensor 2 by cut

Least Squares Means- Sensor 2					
Cut	**Estimate**	**P- Value**	**Lower**	**Upper**	**Range**
1	-7.20	<.0001	-10.12	-4.29	5.83
2	-6.38	<.0001	-9.29	-3.46	5.83
3	-1.81	0.2175	-4.73	1.10	5.83
4	-6.44	<.0001	-9.35	-3.53	5.83
5	-2.03	0.1674	-4.95	0.88	5.83
6	-2.88	0.0860	-6.19	0.42	6.61
7	-5.12	0.0009	-8.04	-2.21	5.83

Sensor 2 was tested again on the testing stand for a second year (2018) and results are shown in Figure 3.21. Sensor 2's moisture distribution for 2018 shifted above the one to one moisture line as compared to in 2017 using the unmodified 2017 calibration curve. Sensor 2 was off by an average of 4.9% from the actual moisture content for each bale tested, compared to 3.4 % for 2017. 52 bales were tested in 2018. Of those, only 40% of the bales tested were within ±3% moisture units of the actual average moisture. 60% of the total bales were within ±5% of the actual moisture content.

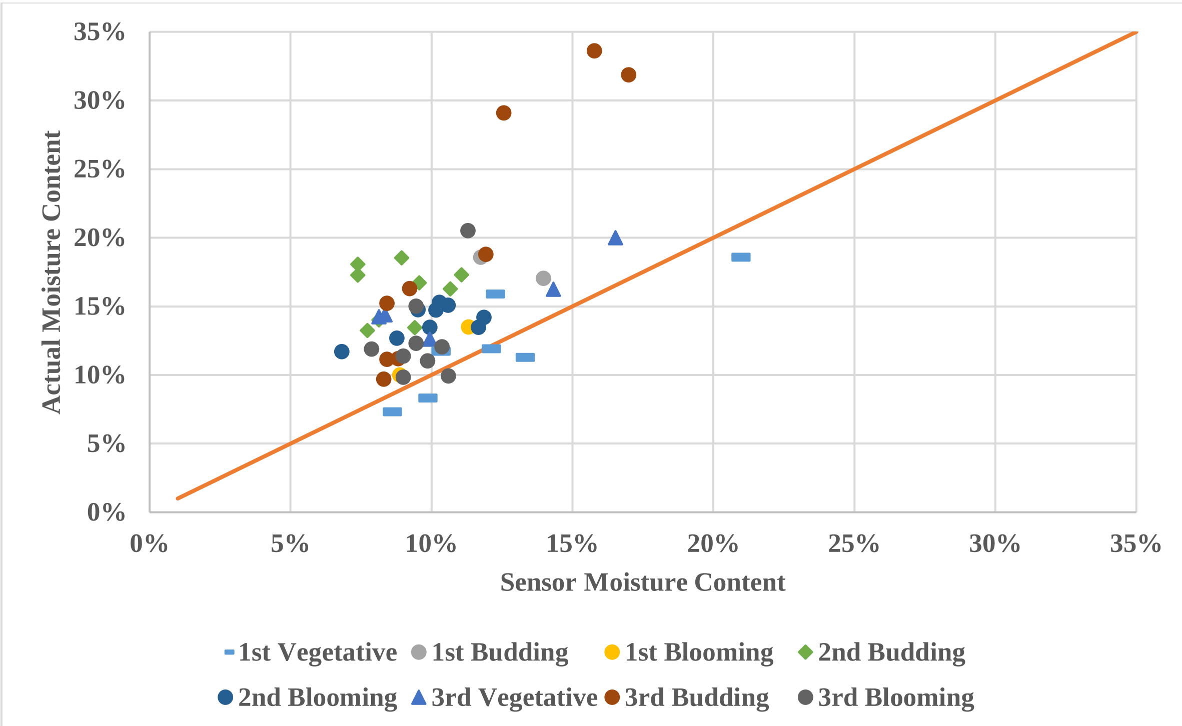


Figure 3.21: Sensor 2 measured moisture versus oven dry moisture during 2018 testing

With the apparent bias in the 2018 Sensor 2 data using the 2017 calibration curve, a 3% constant was added to the data to improve the accuracy of Sensor 2. The adjusted Sensor 2 results for Sensor 2 are shown in Figure 3.22. This constant improved Sensor 2's accuracy. Pearson's coefficient was 0.581. This showed that there is strong correlation of the data, and was confirmed by the p-value (<.0001) being less than 0.05. But, the data was spread out more than last year as seen with the R^2 value (0.4257). Sensor 2 was off by an average of 3.2% from the actual moisture content for each bale tested, compared to 4.9% without the additional 3% constant added. Of the 52 bales tested, 60% of the bales tested were within ±3% moisture units of the actual average moisture. 81% of the total bales were within ±5% of the actual moisture content. This additional bias improved the overall accuracy of Sensor 2's calibration curve. A summarized table of data for Sensor 2 (with the calibration adjustment) across all cuts and moisture targets for 2018 testing year can be seen in Appendix C. [redacted]

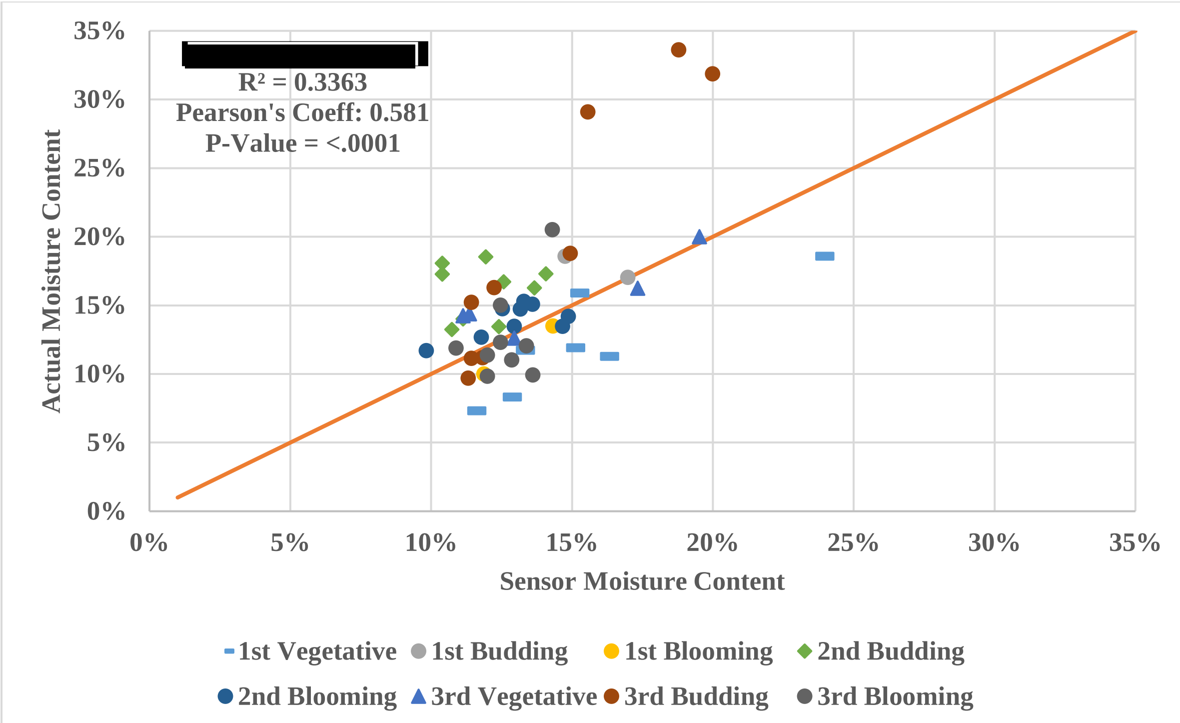


Figure 3.22: Sensor 2 measured moisture with additional 3% constant versus oven dry moisture during 2018 testing

Least squares mean analysis performed for the 2018 data including the additional 3% constant (Table 3.13 and Table 3.14) showed that the differences for the target moistures of 10% and 15% bales were statistically significant (similar to zero), and statistically non-significant for 20% bales. Table 3.14 shows that most of the cuts are non-significant, except for cuts 1, 4, and 7. As with Sensor 1, the randomness in the estimate of the average difference between the sensor outputted moisture and the actual moisture shows that the cut and target moisture have no effect on the performance of the sensor. The estimates had a range of 8.5% (-5.5% to 3.0% actual estimates). For two years of results indicated that Sensor 2 deviated from actual bale mousture by an average of 3.3% on the testing stand Overall, Sensor 2 typically provided evenly distributed values across the one-to-one moisture line, and showed less variation in the recorded moisture values compared to actual bale moisture. The observed deviations in moisture measurements might be small enough to accurately monitor hay bale moisture by end users.

Table 3.13: Least squares mean analysis for Sensor 2 by target moisture for 2018 data

Least Squares Mean- Sensor 2					
Target	**Estimate**	**P-Value**	**Lower**	**Upper**	**Range**
10	0.48	0.62	-1.45	2.41	3.86
15	-1.78	0.07	-3.71	0.15	3.86
20	-3.25	0.001	-5.13	-1.38	3.75

Table 3.14: Least squares mean analysis for Sensor 2 by cut for 2018 data

Least Squares Means by Cut – Sensor 2					
Cut	**Estimate**	**P- Value**	**Lower**	**Upper**	**Range**
1	3.05	0.02	0.49	5.61	5.13
2	-1.95	0.42	-6.74	2.85	9.59
3	1.35	0.57	-3.44	6.15	9.59
4	-4.17	0.00	-6.43	-1.91	4.52
5	-0.97	0.39	-3.23	1.29	4.52
6	-1.04	0.49	-4.07	1.99	6.06
7	-5.49	<.0001	-7.75	-3.23	4.52
8	0.00	1.00	-2.26	2.26	4.52

Sensor 6

Sensor 6 was tested only during the 2018 testing year. [redacted] Figure 3.23 depicts the measured moisture versus the oven dry moisture compared to the measured moisture with the Sensor 6's calibration curve. The solid line represents a one-to-one moisture line. Again, each point represents average moisture content measured from locations A through D of one alfalfa bale. Sensor 6's moisture distribution for 2018 shifted above the one to one moisture line similarly as was for Sensor 2. The additional 3% constant was also added as was done for Sensor 2. For the 52 bales tested in 2018, only 37% of the bales tested with sensor were within ±3% actual moisture content of the actual average moisture, and 79% of the total bales were within ±5% of the actual moisture content. Sensor 6 was off by an average of 4.2% actual moisture content per bale without the additional 3% constant. This isn't acceptable for hay moisture sensing as this high moisture error that can cause a loss of revenue for producers. Therefore, the 3% constant was also added to this sensor's calibration curve to improve its accuracy. [redacted]

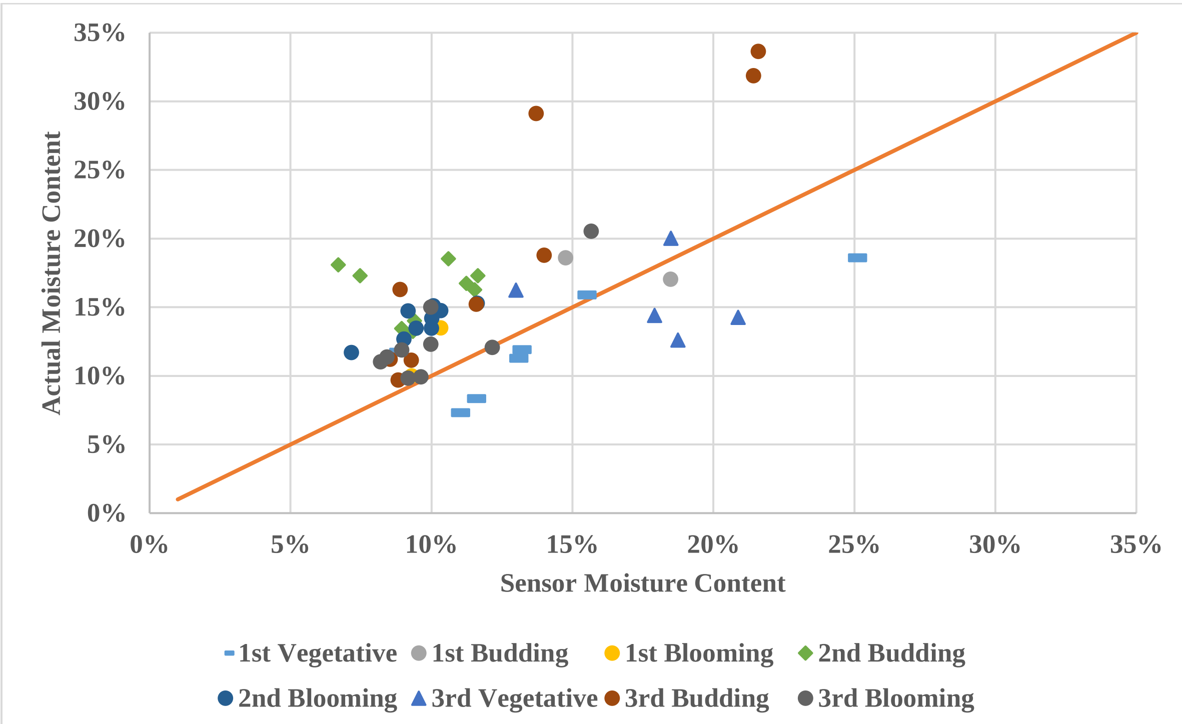


Figure 3.23: Sensor 6 measured moisture versus oven dry moisture during 2018 testing

Figure 3.24 depicts the measured moisture versus the oven dry moisture compared to the measured moisture with the adjusted calibration curve. Pearson's coefficient was 0.652. This showed that there is strong correlation of the data, and was confirmed by the p-value (<.0001) being less than 0.05. The R^2 value for Sensor 6 was 0.4258. [redacted] For the 52 bales tested in 2018 with the additional bias factored in, 71% of the bales tested with sensor were within ±3% actual moisture content of the actual average moisture. 85% of the total bales were within ±5% of the actual moisture content. This improved the accuracy of Sensor 6, which is shown by the fact that it was off by only 2.9% actual moisture content, rather than by 4.2% without the adjusted calibration curve. This is more acceptable for hay moisture monitoring. [redacted] A summarized table of data for Sensor 6 across all cuts and moisture targets for 2018 testing year can be seen in Appendix C.

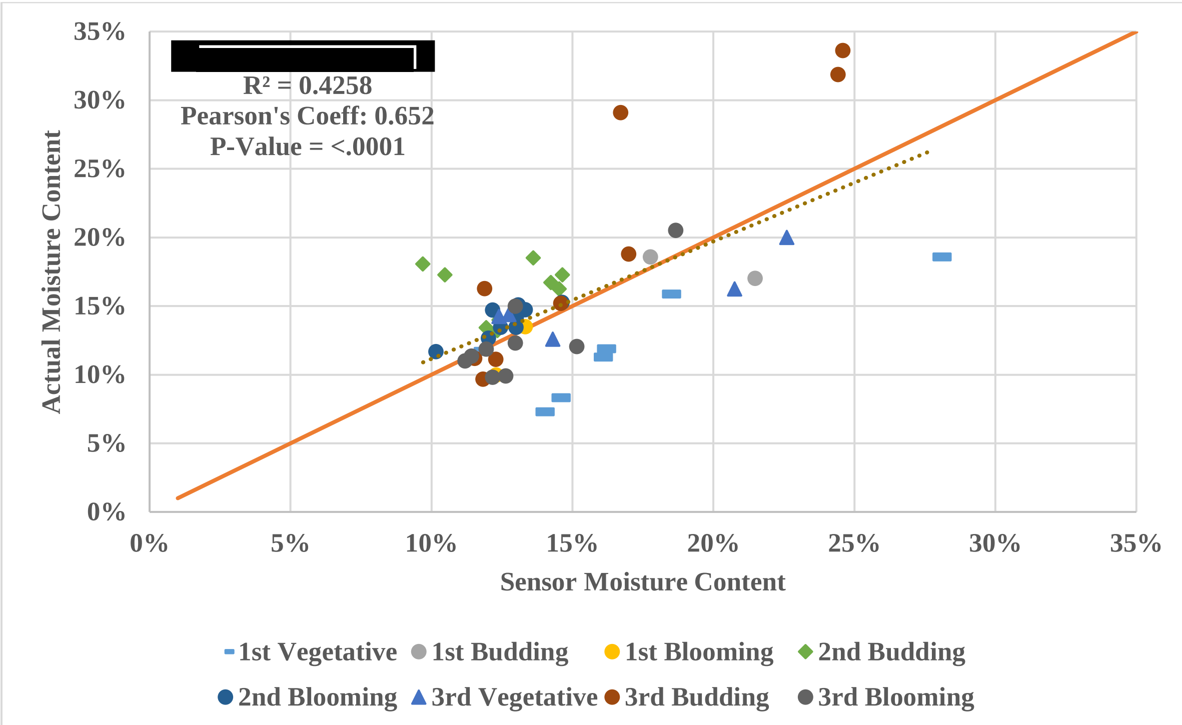


Figure 3.24: Sensor 6 measured moisture versus oven dry moisture during 2018 testing with the adjusted calibration curve

[redacted]

Figure 3.25: [redacted]

Least squares mean analysis performed for Sensor 6's data shows that the differences for each of the target moistures (10, 15, and 20%) were statistically nonsignificant (statistically equal to zero), indicating the differences between sensor and actual moisture measurements were uniquely different among different moisture levels as shown in

Table 3.15. Table 3.16 also showed that most of the cuts are statistically nonsignificant, except for cuts 1, 4, and 7. Just like for sensor 2, with the randomness of the estimates of the actual difference between the sensor actual moisture content showed that cut and moisture targets have no effect on sensor 6's performance. The estimates had a range of 8.1% (-3.5% to 4.6% actual estimates). The estimates of the actual difference between the Sensor 6 and the actual bale moisture for each cut and target moisture are variable. This shows that the cuts and moisture target ranges have no affect on the Sensor's output.

Overall, Sensor 6 typically provided an narrow and even spread of moisture values across the one to one moisture line, and showed smallest in the recorded moisture values compared to actual bale moisture. The observed deviations in moisture measurements might not be enough to accurately monitor hay bale moisture by end users, but was the most accurate of all the sensors tested during this project..

Table 3.15: Least squares mean analysis for Sensor 6 by target moisture for 2018 data

Least Squares Mean- Sensor 6					
Target	**Estimate**	**P-Value**	**Lower**	**Upper**	**Range**
10	0.77	0.42	-1.13	2.67	3.79
15	-1.10	0.25	-3.00	0.79	3.79
20	-1.13	0.23	-2.97	0.72	3.69

Table 3.16: Least squares mean analysis for Sensor 6 by cut for 2018 data

Least Squares Means by Cut – Sensor 6					
Cut	**Estimate**	**P- Value**	**Lower**	**Upper**	**Range**
1	4.61	0.0002	2.32	6.89	4.56
2	1.81	0.40	-2.46	6.08	8.54
3	1.07	0.62	-3.20	5.33	8.54
4	-3.44	0.0013	-5.45	-1.43	4.03
5	-1.27	0.21	-3.29	0.74	4.03
6	1.06	0.43	-1.64	3.76	5.40
7	-3.56	0.0009	-5.58	-1.55	4.03

8	0.58	0.56	-1.43	2.59	4.03

Sensor 3

Figure 3.26 depicts the measured moisture versus the oven dry moisture compared to the measured moisture for Sensor 3. The solid line represents a one-to-one moisture line and each point represents average moisture content measured from locations A through D of one alfalfa bale. Like Sensor 1, the data is very for Sensor 3 is scattered. It tended to read a lower whole bale moisture content than that of the actual oven dry moisture content. Pearson's coefficient was 0.589. This showed that there is strong correlation of the data, and was confirmed by the p-value (<.0001) being less than 0.05. The R^2 value for Sensor 3 in 2017 was 0.3228. 61 bales were tested in 2017. Only 52% of the bales tested were within ±3% moisture units of the actual average moisture, and 75% of the bales tested were within ±5% moisture units of the actual average moisture for 2017. Sensor 3 was off by an average 3.9% moisture content for each bale tested. A summarized table of data for Sensor 3 across all cuts and moisture targets for 2017 testing year can be seen in Appendix A.

After using this sensor for testing, there were concerns with the moisture content outputs of this sensor. While testing, Sensor 3's readings were occasionally unstable. During these brief unstable periods, the readings on Sensor 3 display would consistently change over 10% to 20% range while taking measurements on the same sample of hay. This would make it difficult for a producer to accurately acquire a correct moisture for round hay bales.

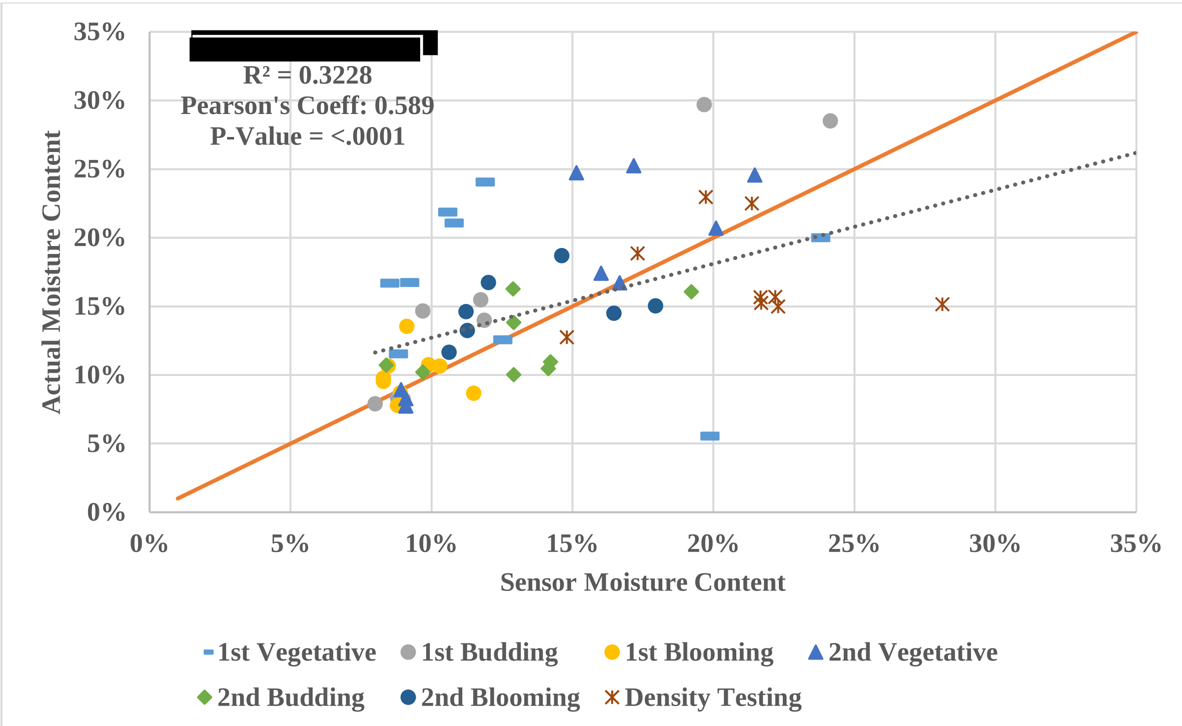


Figure 3.26. Sensor 3 measured moisture versus oven dry moisture during 2017 testing

Table 3.17 and Table 3.18 show the the target moisture and cut statistical analysis for the 2017 data. For Sensor 3, the differences for each of the target moistures (10, 15, and 20%) and for each cut are statistically nonsignificant (statistically similar to zero) based upon the p-values, except for cuts 1 and 7. Even though the mean estimates in Table 3.18 are close to zero, there is a wide range that the actual differences for the estimates of 8% (-4% to 4%), which is a huge variation for hay moisture just like for Sensor 1. This agrees with the data shown in Figure 3.26 for Sensor 3, as it tended to read a higher moisture value, and shows high variation in the moisture values.

Table 3.17: Least squares mean analysis for Sensor 3 by target moisture

Least Squares Mean- Sensor 3					
Target	**Estimate**	**P-Value**	**Lower**	**Upper**	**Range**
10	-1.16	0.46	-4.28	1.96	6.24
15	0.43	0.72	-2.10	2.97	5.07
20	-2.34	0.10	-5.14	0.46	5.60

Table 3.18: Least squares mean analysis for Sensor 3 by cut

Least Squares Means-Sensor 3					
Cut	**Estimate**	**P- Value**	**Lower**	**Upper**	**Range**
1	-4.08	0.0208	-7.51	-0.65	6.87
2	-1.30	0.4498	-4.74	2.13	6.87
3	-1.02	0.5538	-4.45	2.41	6.87
4	-2.29	0.1876	-5.72	1.15	6.87
5	0.81	0.6363	-2.62	4.25	6.87
6	-1.47	0.4532	-5.36	2.43	7.79
7	3.93	0.0257	0.50	7.37	6.87

Figure 3.27 shows the measured moisture versus the oven dry moisture compared to the measured moisture with Sensor 3 moisture in 2018. Like in 2017, the data is very scatter across the one-to one line. Pearson's coefficient was 0.120. This showed that there is no correlation of the data, and was confirmed by the p-value 0.3961) being greater than 0.05. The R^2 value for Sensor 3 in 2018 was 0.3228. 52 bales were tested in 2018. Of those, only 29% of the bales tested were within ±3% moisture units of the actual average moisture. 52% of the total bales were within ±5% of the actual moisture content. Sensor 3 was off by an average 5.7% moisture content for each bale tested. A summarized table of data for Sensor 3 across all cuts and moisture targets for 2017 testing year can be seen in Appendix B. This showed that the sensor wasn't able to differentiate moisture differences across all moistures.

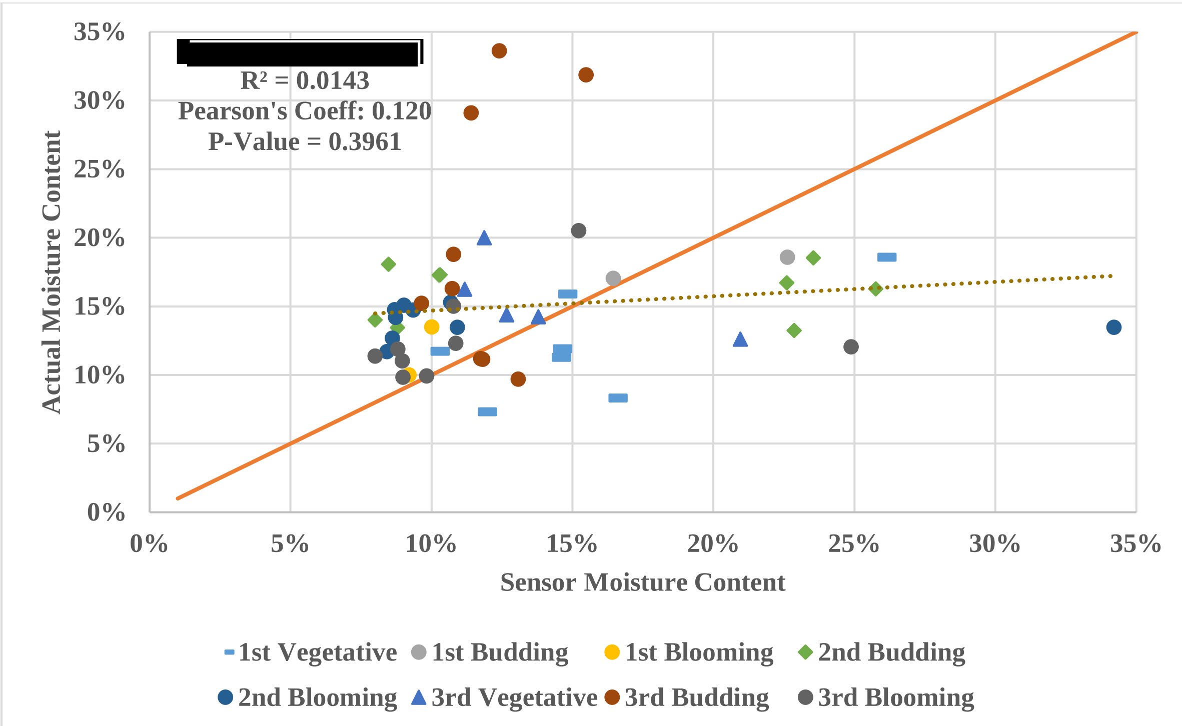


Figure 3.27. Sensor 3 Measured Moisture versus Oven Dry Moisture during 2018 testing

A least squares mean analysis was also performed for Sensor 3's data using the moisture targets and cuts for comparison for 2018. These are shown in Table 3.19 and Table 3.20. For Sensor 3, the estimate for the actual difference for the 20% target moisture is statistically significant (statistically different from zero), while the 10% and 15% moisture targets are statistically nonsignificant (statistically similar to zero). Table 3.20 shows that the acutal difference for all of the cuts are statistically nonsignificant (equal to zero), except for cut 7. Like for the other sensors tested, the randomness of the estimates between the actual moisture content and the sensor measured across all cuts and target moistures show that cut and moisture target have no effect on sensor performance. The estimates had a range of 11.8% (-7.8% to 4.0% actual estimates). This is a wide range, and is unacceptable for producers needing to estimate hay moisture.

Table 3.19: Least squares mean analysis for Sensor 3 by target moisture for 2018 data

Least Squares Mean- Sensor 3					
Target	**Estimate**	**P-Value**	**Lower**	**Upper**	**Range**
10	1.86	0.27	-2.08	7.31	9.39
15	-0.75	0.65	2.61	11.87	9.26
20	-5.38	0.00	0.00	9.26	9.26

Table 3.20: Least squares mean analysis for Sensor 3 by cut for 2018 data

Least Squares Means by Cut – Sensor 3					
Cut	**Estimate**	**P- Value**	**Lower**	**Upper**	**Range**
1	4.02	0.13	-1.30	9.34	10.64
2	1.73	0.73	-8.22	11.68	19.91
3	-2.14	0.67	-12.09	7.82	19.91
4	-0.47	0.84	-5.16	4.23	9.38
5	-1.85	0.43	-6.54	2.84	9.38
6	-1.40	0.66	-7.70	4.89	12.59
7	-7.75	0.002	-12.45	-3.06	9.38
8	-0.84	0.72	-5.53	3.85	9.38

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Overall, Sensor 3 didn't adequately estimate the moisture content of the alfalfa bales tested. With this sensor being off by an average of 5% throughout this testing, the lack of sensitivity as seen in the 2018 moisture data, and the variability in the readings as seen in Figure 3.26 and Figure 3.27, Sensor 3 isn't recommended for usage as a precise moisture meters for hay production. This inaccuracy could cause producers to loss income by baling lower quality hay, or not bale the hay at the proper time with the sensor giving high readings when the hay is at ideal baling moisture contents.

Sensor 4

Sensor 4 arrived in the middle of the summer halfway through the 2017 testing year. This resulted in this sensor getting tested on fewer cuts compared to the other four sensors for the first year. Figure 3.28 shows the measured moisture versus the oven dry moisture compared to the measured moisture with Sensor 4 moisture in 2017. The solid line represents a one-to-one moisture line. Each point represents average moisture content measured from locations A through D of one alfalfa bale. The majority of the data points in Figure 3.28 lie slightly to the right of the one to one line, which means that Sensor 1 readings were on an average higher than the actual bale moisture content. Like for Sensor 1 and Sensor 3, the data is very scattered. Pearson's coefficient was 0.461. This showed that there is strong correlation of the data, and was confirmed by the p-value (0.02) being less than 0.05. The R^2 value for Sensor 4 was 0.2122. The average actual difference from the actual moisture content of the bale for Sensor 4 was 4.7%. There were 27 bales tested with this sensor in 2017. Only 32% of the bales tested with sensor were within ±3% actual moisture content of the actual average moisture. 56% of the total bales were within ±5% of the actual moisture content. For hay moisture sensing, a 5% moisture error can mean the difference between having good hay and bad hay, which could potentially result in lost revenue for producers. For this sensor, it would equate to over half of the total crop being considered bad hay. This is unacceptable. A summarized table of data for Sensor 4 across all cuts and moisture targets for 2017 testing year can be seen in Appendix A.

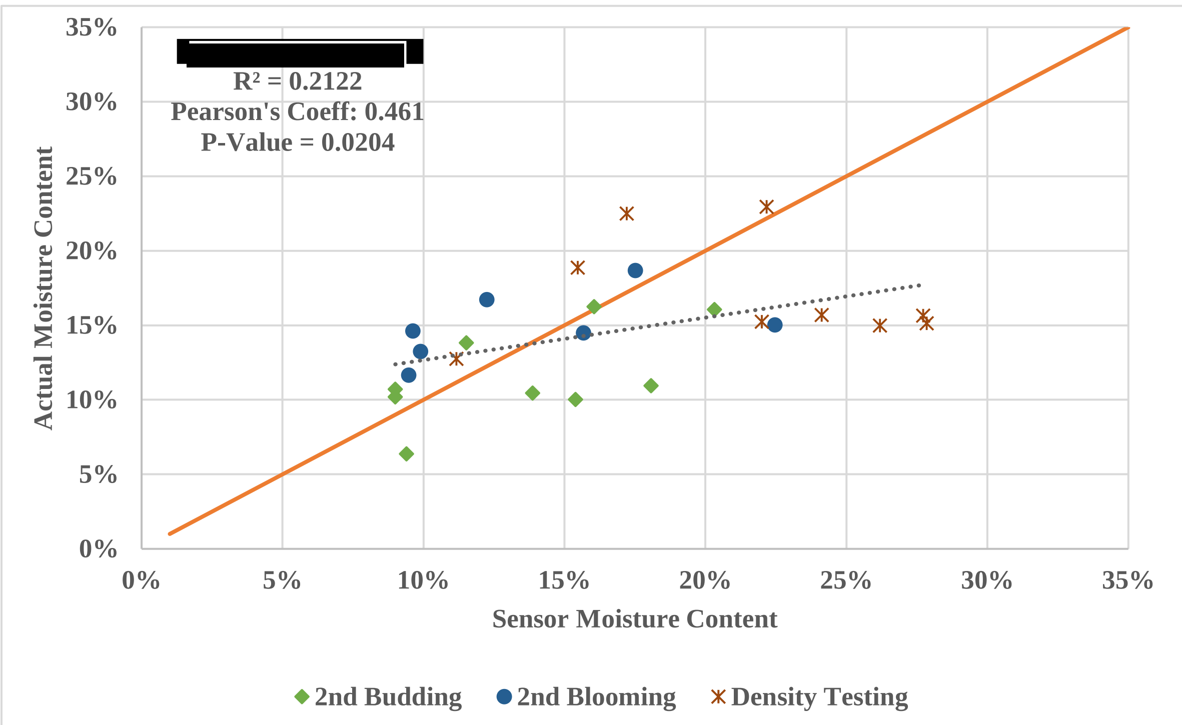

Figure 3.28. Sensor 4 measured moisture versus oven dry moisture during 2017 testing

Least squares mean analysis performed for the 2017 data (Table 3.21 and Table 3.22) shows that the differences for each of the target moistures (10, 15, and 20%) were statistically nonsignificant (statistically similar to zero), indicating the differences between sensor and actual moisture measurements were uniquely different among different moisture levels. Table 3.22 showed that most of the cuts were are statistically nonsignficant (statistically similar to zero). The estimates had a range of 5.5% (-1.0% to 4.5% actual estimates). The observed deviations in moisture measurements might not be enough to accurately monitor hay bale moisture by end users.

Table 3.21: Least squares mean analysis for Sensor 4 by target moisture

Least Squares Mean- Sensor 4					
Target	**Estimate**	**P-Value**	**Lower**	**Upper**	**Range**
10	0.50	0.90	-8.07	9.08	17.14
15	3.79	0.15	-2.88	10.45	13.33
20	-0.63	0.82	-6.57	5.31	11.88

Table 3.22: Least squares mean analysis for Sensor 4 by cut

Least Squares Means-Sensor 4					
Cut	**Estimate**	**P- Value**	**Lower**	**Upper**	**Range**
5	1.94	0.2844	-1.72	5.60	7.32
6	-1.08	0.5956	-5.23	3.07	8.30
7	4.46	0.0193	0.79	8.12	7.32

Figure 3.29 **Error! Reference source not found.**shows the measured moisture versus the oven dry moisture compared to the measured moisture with Sensor 4 moisture in 2018. Like in 2017, the data is scattered across the one-to one line. Pearson's coefficient was 0.214. This showed that there is no correlation of the data, and was confirmed by the p-value (0.1277) being greater than 0.05. The R^2 value for Sensor 4 in 2018 was 0.2123. This is similar behavior as seen with Sensor 3 in 2018. 52 bales were tested in 2018. Of those, only 40% of the bales tested were within ±3% moisture units of the actual average moisture. 62% of the total bales were within ±5% of the actual moisture content. Sensor 4 was off by an average 5.0% moisture content for each bale tested. A summarized table of data for Sensor 4 across all cuts and moisture targets for 2017 testing year can be seen in Appendix B.

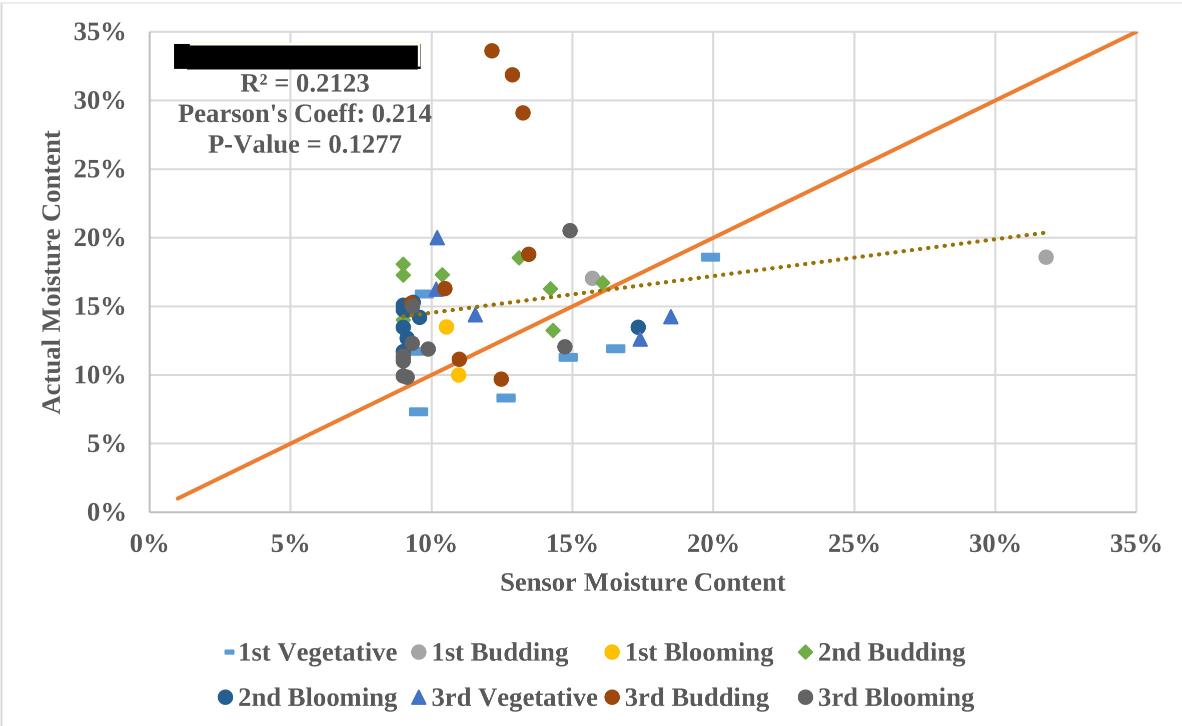

Figure 3.29: Sensor 4 Measured Moisture versus Oven Dry Moisture during 2018 testing

Least squares mean analysis performed for the 2018 data (Table 3.23 and Table 3.24) for Sensor 4. The estimate for the actual difference for the 15% target moisture is statistically significant, while the 10% and 20% moisture targets are not statistically significant. Table 3.24 shows that most of the cuts are not statistically significant, except for cuts 4, 5, and 7. The estimates had a range of 14.1% (-8.1% to 6.0% actual estimates). For two years of results indicated that Sensor 4 deviated from actual bale mousture by an average of 5% across all moisture contents. Overall, Sensor 4 typically provided lower than actual moisture values, and showed greater variation in the recorded moisture values compared to actual bale moisture. This sensor behaved similarly as Sensor 3, and yield similar results. The observed deviations and low coorelations as seen in 2018 moisture measurements might not be enough to accurately monitor hay bale moisture by end users, just like for Sensors 1 and 3. Therefore, Sensor 4 isn’t recommended for usage for monitoring moisture of alfalfa hay.

Table 3.23: Least squares mean analysis for Sensor 4 by target moisture for 2018 data

Least Squares Mean- Sensor 4					
Target	**Estimate**	**P-Value**	**Lower**	**Upper**	**Range**
10	-0.19	0.20	-1.43	6.48	7.91
15	-2.72	0.01	1.18	8.97	7.79
20	-5.26	0.20	-1.35	6.44	7.79

Table 3.24: Least squares mean analysis for Sensor 4 by cut for 2018 data

Least Squares Means by Cut – Sensor 4					
Cut	**Estimate**	**P- Value**	**Lower**	**Upper**	**Range**
1	3.37	0.08	-0.46	7.20	7.66
2	5.95	0.10	-1.22	13.11	14.33
3	-1.00	0.78	-8.16	6.17	14.33
4	-4.52	0.01	-7.90	-1.15	6.76
5	-3.86	0.03	-7.24	-0.49	6.76
6	-1.93	0.39	-6.47	2.60	9.06
7	-8.11	<.0001	-11.49	-4.73	6.76
8	-2.18	0.20	-5.55	1.20	6.76

Sensor 5

Sensor 5 didn’t work on the round alfalfa bales when tested. [redacted] Because of this, this sensor wasn’t tested in the second year of testing.

Statistical Analysis Conclusion

For each sensor tested, there were two statistical comparisons performed- by target moistures (10, 15, and 20%), and by each cut. The statistical analysis proved for Sensors 1, 2, 3, 4 and 6 across all the different moisture targets and cuts that the there is no effect of cut or moisture content on sensor performance. This means that the sensor performance across different cuts and moisture ranges is random in behavior. The sensors had varying average moisture differences across different cuts and moisture targets, with these values changing between both testing years.

Summary of Results

Table 3.25 and Table 3.26 show the percentage of bales within an actual difference of ±3% and ±5% from the actual bale moisture content for each of the sensors for 2017 and 2018. These moisture targets were presented with the results of each individual sensor. Looking at Table 3.25, Sensor 2 stands out above all the other sensors in terms of overall accuracy for 2017. The data for Sensors 1, 3, and 4 was scattered more across their working ranges when compared to Sensor 2.

Table 3.25: Percentage of Bales within an actual difference of ±3% and ±5% from the actual bale moisture content by sensor for 2017

Bale Moisture Target	Sensor 1	Sensor 2	Sensor 3	Sensor 4
< ±3%	51	61	52	32
> ±3%	49	39	48	68
≤ ±5%	67	84	75	56
> ±5%	33	16	25	44

Table 3.26 shows the performance of Sensor 2 worse than the other sensors tested in 2018. But, there appeared to be a bias in the data where it was above the one-to one moisture line (as shown in Figure 3.21). When a 3% constant was added to all of the moistures, the sensor had better performance values than Sensor's 1, 2, and 4. Sensor 2's new average actual difference from the average bale moisture value was 3.1%. This was also true for Sensor 6, which used Sensor 2's calibration curve, as seen in Table 3.26.

Table 3.26: Percentage of Bales within an actual difference of ±3% and ±5% from the actual bale moisture content by sensor for 2017

Bale Moisture Target	Sensor 1 (Stand)	Sensor 1 (Baler)	Sensor 2	Sensor 2 (New Curve)	Sensor 3	Sensor 4	Sensor 6	Sensor 6 (New Curve)
< ±3%	46	21	40	60	29	40	37	71
> ±3%	54	79	60	40	71	60	63	29
≤ ±5%	69	48	62	81	52	62	79	85
> ±5%	31	52	38	19	48	38	21	15

Sensor 6 seems to be the most accurate based upon the test procedure, environmental conditions, the overall correlation of the sensor output with the actual bale moisture, and the crop analyzed. The overall rankings are as follows for the sensors based upon Tables 25 and 26: Sensor 6, Sensor 2, Sensor 1, Sensor 3, and Sensor 4. Sensor 2 and Sensor 6 were the only two sensors that had an additional 3% constant added for several reasons. First, Sensor's 2 and Sensor 6 were the only sensors that had an apparent upward shift in the data from the initial developed calibration curve. All of the other sensors didn't have this apparent bias. [redacted]

Overall Conclusion

A sensor testing stand was developed to perform comparative testing between the sensors on the same alfalfa hay bale immediately after it was formed. Six commercially available hay moisture sensors were selected to measure moisture at four pre-determined locations on hay bales. After the sensor measurements, core samples were extracted from the same locations to determine moisture using oven-drying method. The moisture measurements were conducted during three growth stages and bales were formed with three approximate moisture contents of 10%, 15% and 20%. Six different cuts of alfalfa of the same variety were used to capture all the measurements during 2017 and 2018 growing season. Another cut was also performed in 2017 for moisture measurements with the alfalfa baled at 15% and the same growth stage, but different baler compression cylinder pressures (250, 400, and 800psi). After sensor testing, core samples were extracted from pre-determined locations along different diameters of a round bale to determine actual moisture using oven-drying method. Sensor and oven-dried measurements were compared to determine accuracy and repeatability of sensing technologies. Results showed that sensors and oven-dried measurement varied for all the sensors for every growth stage and baling moisture levels, with Sensor 6 exhibiting lowest variability in its readings (after the calibration curve was adjusted), and its readings were highly correlated with the actual bale moisture. This identified the most accurate and reliable sensor. It was also discovered that the alfalfa crop and moisture target had no effect on each of the senor's performance.

References

AgriChem, I. (2016). Grain moisture measurement with capacitance type devices. Retrieved from http://www.agricheminc.com/downloads/Feedgrain-297.pdf

ASABE. (2017). ANSI/ASAE S358.3 MAY2012 (R2017) moisture measurement- forages. Retrieved from https://elibrary.asabe.org/abstract.asp?aid=41661&t=2&redir=&redirType=

Behringer, C. B. (2004). *Performance comparison of moisture sensor technologies for forage crops*

Deinum, B., & Maassen, A. (1994). Effects of drying temperature on chemical composition and in-vitro digestibility of forages. *Animal Feed Science and Technology, 46,* 75-86.

Kormann, G. (2000). (2000). Moisture measurement on forage harvesting machines. Paper presented at the *EurAgEng,*

Osman, A. M. (2003). *Development of a parallel-plate capacitance moisture sensor for chopped forage* (M.Sc.). Available from ProQuest Dissertations & Theses Global. (305261959). Retrieved from http://search.proquest.com.er.lib.k-state.edu/docview/305261959?accountid=11789

Progressive Publishing. (2017). *2016 U.S. forage statistics*. Jerome, IA: Progressive Publishing. Retrieved from https://www.progressivepublish.com/downloads/2017/general/2016_fg_stats_lowres.pdf

Rich, D. (2017). Manage moisture for high quality alfalfa hay. Retrieved from http://www.hpj.com/alfalfau/manage-moisture-for-high-quality-alfalfa-hay/article_19bfd09a-08e8-11e7-a000-077ffbaa034c.html

Webster, K. E., Darr, D. M. J., Askey, J., & Sprangers, A. (July 2013). (July 2013). Production scale single-pass corn stover large square baling systems. Paper presented at the *2013 ASABE Annual International Meeting,* Retrieved from https://lib.dr.iastate.edu/cgi/viewcontent.cgi?referer=https://www.google.com/&httpsredir=1&article=1328&context=abe_eng_conf

Chapter 4 - General Summary

Summary of Findings

A coring methodology was developed to assess the variation of moisture within a round bale of hay for coring along the flat face of the hay bale. The results showed that the moisture variation within single bales could vary from 4% to 8%. Large moisture variations at different locations within a bale indicated that it may be inappropriate to use whole bale average moistures for comparing sensor readings. Bales could have relatively wetter and drier regions which could cause the part of the bale to spoil and make the bale be considered lower quality. Inconsistent hay moisture measurements by producers and user could result in revenue lost by the producer when selling hay.

Coring methodology developed in this study was compared to the previous methodology of using radial cores for bale moisture determination. The results showed that the whole bale average moistures using the cores along the flat face of the bale were all almost identical to the average moisture of the radial cores. The observed results have several overall implications. First, it shows that coring along the flat face of the bale would be an effective method, which could be used to correlate to actual sensor readings along the diameter at certain positions for comparing different moisture sensors and while testing of newly developed sensors. Second, this study showed that future research studies involving hay moisture assessment (i.e. forage quality studies, forage storage studies, etc.) can use either method for determining the average bale moisture. The added flexibility in moisture method determination for round bales may make it easier for other research studies to more accurately assess sensor response.

A sensor testing stand was also developed to perform comparative testing between the sensors on the same alfalfa hay bale immediately after it was formed using the developed coring methodology. Six commercially available hay moisture sensors were selected to measure moisture at four pre-determined locations on hay bales. After the sensor measurements, core samples were extracted from the same locations to determine moisture using oven-drying method. The moisture measurements were conducted during three growth stages and bales were formed with three approximate moisture contents of 10%, 15% and 20%. Six different cuts of alfalfa of the same variety were used to capture all the measurements during 2017 and 2018 growing season. Another cut was also performed in 2017 for moisture measurements with the alfalfa baled at 15% and the same growth stage, but different baler compression cylinder pressures (250, 400, and 800psi). After sensor testing, core samples were extracted from pre-determined locations along different diameters of a round bale to determine actual moisture using oven-drying method. Sensor and oven-dried measurements were compared to determine accuracy and repeatability of sensing technologies. Results showed that sensors and oven-dried measurement varied for all the sensors for every growth stage and baling moisture levels, with Sensor 6 exhibiting lowest variability in its readings (after the calibration curve was adjusted). This identified the most accurate and reliable sensor.

Future Work

Opportunities for further research exist in this area. First, more research needs to be conducted to see the moisture profile of a full round hay bale, rather than just at select. Research in Chapter 2 showed the variation at select locations. But extending this research into full bales could help establish a more detailed baseline for testing. Additional testing needs to occur with the other sensors (2, 3, 4, and 6) with them mounted in the baler to see how the sensor's performance compares with the data from the sensors on the testing stand. Another research project idea would be to see if it is possible to build a microwave transmission sensor that will work for large round bales. If a working prototype was developed, it could be an accurate and reliable sensing technology for moisture measurements in large round bales. Finally, Sensor 2 and Sensor 6 need to be tested more to see if any additional bias occurs in different fields and varieties of alfalfa hay. There was a 3% bias in the data shown in the 2018 data without the adjustment in the calibration curve. If there is a consistent bias between the different varieties of alfalfa hay, this may prove Sensor 2 and Sensor 6 not to be as accurate as shown in this project across all alfalfa. This also may lead to the conclusion that producers may need to conduct their own coring to adjust the calibration curves to their own crops to determine accurate alfalfa hay moistures. While these questions will take many more studies to answer, they are important and will lead to better understanding of moisture sensing for hay forages.

Appendix A – Summary of 2017 Testing Data- By Moisture Target and By Cut

Cut	Target Bale Moisture Content	Actual Moisture Content	Actual Moisture Std. Deviation	Sensor 1 Average Moisture Reading	Sensor 1 Average Difference from Actual	Sensor 2 Average Moisture Reading	Sensor 2 Average Difference from Actual	Sensor 3 Average Moisture Reading	Sensor 3 Average Difference from Actual	Sensor 4 Average Moisture Reading	Sensor 4 Average Difference from Actual
1-Veg	20%	21.7%	7.3	16.3%	-5.5%	12.9%	-8.8%	15.2%	-6.5%		
1-Veg	15%	18.4%	6.7	6.5%	-11.9%	12.4%	-6.0%	9.1%	-9.3%		
1-Veg	10%	9.9%	4.2	14.3%	4.5%	14.4%	4.5%	13.4%	3.6%		
1-Bud	20%	27.6%	3.2	28.7%	1.1%	27.0%	-0.6%	27.2%	-0.3%		
1-Bud	15%	14.7%	2.3	15.5%	0.8%	11.7%	-3.0%	11.1%	-3.6%		
1-Bud	10%	8.2%	2.1	8.0%	-0.2%	8.0%	-0.2%	8.9%	0.7%		
1-Bloom	20%	9.7%	1.8	11.3%	1.5%	9.9%	0.2%	9.9%	0.2%		
1-Bloom	15%	9.0%	1.9	10.3%	1.2%	10.5%	1.4%	9.3%	0.3%		
1-Bloom	10%	11.2%	2.6	12.8%	1.6%	10.7%	-0.6%	8.6%	-2.6%		
2-Veg	20%	24.8%	2.6	25.8%	0.9%	21.4%	-3.4%	17.9%	-6.9%		
2-Veg	15%	18.3%	2.8	22.3%	4.0%	15.4%	-2.8%	17.6%	-0.7%		
2-Veg	10%	8.3%	1.6	8.0%	-0.3%	11.6%	3.3%	9.0%	0.7%		
2-Bud	20%	15.4%	2.0	21.4%	6.0%	16.7%	1.4%	15.0%	-0.4%	16.0%	0.6%
2-Bud	15%	10.5%	1.7	18.8%	8.4%	14.1%	3.7%	13.8%	3.3%	15.8%	5.3%
2-Bud	10%	9.1%	1.9	8.0%	-1.1%	10.1%	1.0%	9.1%	-0.1%	9.4%	0.3%
2-Bloom	20%	17.7%	2.9	18.3%	0.5%	15.3%	-2.4%	13.3%	-4.4%	14.9%	-2.8%
2-Bloom	15%	14.8%	2.4	21.4%	6.6%	16.6%	1.8%	14.6%	-0.2%	16.1%	1.2%
2-Bloom	10%	12.5%	2.0	13.8%	1.3%	21.4%	8.9%	11.0%	-1.5%	9.7%	-2.8%
Density-250	15%	15.3%	7.7	24.7%	9.4%	19.6%	4.3%	24.0%	8.8%	27.3%	12.0%
Density-400	15%	17.8%	3.1	22.8%	4.9%	19.1%	1.3%	21.8%	3.9%	21.1%	3.3%
Density-800	15%	18.2%	2.2	22.1%	3.9%	17.8%	-0.4%	17.3%	-0.9%	16.3%	-1.9%

Appendix B – Summary of 2018 Testing Data- By Moisture Target and By Cut – Sensors 3 and 4

Cut	Target Bale Moisture Content	Actual Moisture Content	Actual Moisture Std. Deviation	Sensor 3 Average Moisture Reading	Sensor 3 Average Difference from Actual	Sensor 4 Average Moisture Reading	Sensor 4 Average Difference from Actual
1-Veg	20%	17.2%	4.0	20.2%	3.0%	14.5%	-2.7%
1-Veg	15%	11.6%	2.1	14.3%	2.7%	15.4%	3.8%
1-Veg	10%	9.1%	1.8	12.7%	3.6%	10.2%	1.1%
1-Bud	20%	18.6%	4.6	22.6%	4.0%	31.8%	13.2%
1-Bud	15%	13.5%	1.4	10.0%	-3.5%	10.5%	-3.0%
1-Bloom	20%	17.0%	3.6	16.5%	-0.5%	15.7%	-1.3%
1-Bloom	10%	10.0%	0.8	9.2%	-0.8%	11.0%	1.0%
2-Bud	20%	17.5%	1.5	9.7%	-7.8%	9.5%	-8.0%
2-Bud	15%	17.2%	3.0	24.0%	6.8%	14.5%	-2.7%
2-Bud	10%	13.6%	2.8	13.2%	-0.4%	10.8%	-2.8%
2-Bloom	20%	13.9%	2.2	8.7%	-5.2%	9.2%	-4.7%
2-Bloom	15%	15.0%	2.1	9.7%	-5.3%	9.2%	-5.8%
2-Bloom	10%	12.9%	1.8	17.9%	5.0%	11.8%	-1.1%
3-Veg	20%	18.1%	2.7	11.5%	-6.6%	10.2%	-7.9%
3-Veg	15%	14.3%	3.6	13.2%	-1.1%	15.0%	0.7%
3-Veg	10%	12.6%	2.5	21.0%	8.4%	17.4%	4.8%
3-Bud	20%	28.1%	3.5	12.9%	-15.2%	12.8%	-15.3%
3-Bud	15%	20.2%	3.5	10.6%	-9.6%	11.0%	-9.2%
3-Bud	10%	10.7%	1.5	12.2%	1.5%	10.8%	0.1%
2-Bloom	20%	15.9%	6.9	12.3%	-3.6%	11.2%	-4.7%
2-Bloom	15%	10.6%	1.2	14.6%	4.0%	11.0%	0.4%
2-Bloom	10%	11.4%	1.0	8.6%	-2.8%	9.3%	-2.1%

Appendix C – Summary of 2018 Testing Data- By Moisture Target and By Cut – Sensors 1, 2, and 6

Cut	Target Bale Moisture Content	Actual Moisture Content	Actual Moisture Std. Deviation	Sensor 1 (On Stand) Average Moisture Reading	Sensor 1 (On Stand) Average Difference from Actual	Sensor 1 (On Baler) Average Moisture Reading	Sensor 1 (On Baler) Average Difference from Actual	Sensor 2 Average Moisture Reading	Sensor 2 Average Difference from Actual	Sensor 6 Average Moisture Reading	Sensor 6 Average Difference from Actual
1-Veg	20%	17.2%	4.0	20.3%	3.1%	29.6%	12.4%	19.3%	2.1%	23.0%	5.8%
1-Veg	15%	11.6%	2.1	17.9%	6.3%	20.6%	9.0%	15.4%	3.8%	15.9%	4.3%
1-Veg	10%	9.1%	1.8	13.6%	4.5%	17.3%	8.2%	12.3%	3.2%	13.2%	4.1%
1-Bud	20%	18.6%	4.6	25.4%	6.8%	24.4%	5.8%	17.0%	-1.6%	21.5%	2.9%
1-Bud	15%	13.5%	1.4	10.0%	-3.5%	25.2%	11.7%	14.3%	0.8%	13.3%	-0.2%
1-Bloom	20%	17.0%	3.6	25.9%	8.9%	24.4%	7.4%	14.8%	-2.2%	17.8%	0.8%
1-Bloom	10%	10.0%	0.8	11.2%	1.2%	14.6%	4.6%	11.9%	1.9%	12.3%	2.3%
2-Bud	20%	17.5%	1.5	11.5%	-6.0%	17.9%	0.4%	11.6%	-5.9%	11.6%	-5.9%
2-Bud	15%	17.2%	3.0	17.8%	0.6%	17.1%	-0.1%	12.7%	-4.5%	14.1%	-3.1%
2-Bud	10%	13.6%	2.8	11.5%	-2.1%	15.9%	2.3%	11.4%	-2.2%	12.2%	-1.4%
2-Bloom	20%	13.9%	2.2	11.8%	-2.1%	20.2%	6.3%	13.1%	-0.8%	12.8%	-1.1%
2-Bloom	15%	15.0%	2.1	11.1%	-3.9%	18.0%	3.0%	13.3%	-1.7%	13.3%	-1.7%
2-Bloom	10%	12.9%	1.8	12.0%	-0.9%	18.5%	5.6%	12.5%	-0.4%	11.9%	-1.0%
3-Veg	20%	18.1%	2.7	17.3%	-0.8%	14.5%	-3.6%	18.4%	0.3%	21.7%	3.6%
3-Veg	15%	14.3%	3.6	18.1%	3.8%	18.0%	3.7%	11.2%	-3.1%	12.6%	-1.7%
3-Veg	10%	12.6%	2.5	21.2%	8.6%	17.0%	4.4%	12.9%	0.3%	14.3%	1.7%
3-Bud	20%	28.1%	3.5	18.7%	-9.4%	25.0%	-3.1%	17.9%	-10.2%	22.0%	-6.1%
3-Bud	15%	20.2%	3.5	15.1%	-5.1%	24.0%	3.8%	13.1%	-7.1%	14.4%	-5.8%
3-Bud	10%	10.7%	1.5	14.3%	3.6%	17.0%	6.3%	11.5%	0.8%	11.9%	1.2%
2-Bloom	20%	15.9%	6.9	14.8%	-1.1%	21.0%	5.1%	13.1%	-2.8%	14.9%	-1.0%
2-Bloom	15%	10.6%	1.2	12.1%	1.5%	19.3%	8.7%	13.0%	2.4%	13.3%	2.7%
2-Bloom	10%	11.4%	1.0	9.3%	-2.2%	19.3%	7.9%	11.9%	0.5%	11.5%	0.1%