Article

In-Field Performance of Biomass Balers

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Abstract: Herbaceous biomass will contribute significantly to meeting renewable energy goals. Harvesting equipment for hay is generally suitable for mowing, raking, and baling grasses such as switchgrass; however, there is a need for field data to better understand machine performance in energy crops. The purpose of this study was to collect field data to estimate baler field capacity, throughput, and speed. Data gathered with a Differential Global Positioning System (DGPS) unit during baling provided time-motion studies of baler productivity. Six fields were used to compare field capacity, speed, and throughput results from four round balers and one large-square baler. The results show that in-field performance of round balers is significantly affected by yield, but that the relationship can be represented with machinery management concepts, knowledge of maximum throughput, and wrap-eject time. Baler performance will be overestimated if the yield, maximum throughput, and wrap-eject time are not correctly accounted for.

Keywords: balers; energy crop; geo-referenced data; harvest; herbaceous biomass; machinery management

1. Introduction

Herbaceous biomass can contribute to the renewable energy supply, and the Southeast USA has unique biomass potential [1] because of: high annual rainfall, considerable land that can be diverted to biomass production without significant competition with food and feed production, and an established woody biomass industry. Grasses, such as switchgrass (*Panicum virgatum* L.), are one of the most significant potential sources of biomass. An advantage of using switchgrass and other native grasses as bioenergy crops is that it can be harvested much like hay, and hay harvest is a well-known operation amongst farmers in the region.

The two most commonly employed methods of hay harvesting are round and large-square baling. Although large-square balers can achieve a higher field capacity (ha/h), round bales offer several attractive features for the Southeast [2,3]. In a humid environment, round bales can typically be stored under ambient conditions in the field, whereas large-square bales require covered storage. Round balers are less expensive to purchase and operate and they require smaller tractors than large-square balers, an advantage for the smaller farms in the Southeastern USA [2].

Due to high variability of the machine capacity within a field, a consistent relationship has not yet been developed for measuring in-field performance of round balers. Such data are needed to define baler capacity and then simulate harvest of biomass. Typically, two major issues are poorly represented in machinery management models: available working time during the time window when the operation is required to be completed (often called probability of workdays) and the capacity of forage harvesting equipment as yield changes. Machinery performance assumptions have a direct effect on estimates of the number of pieces of equipment needed, and thus the total equipment investment

cost to fulfill biorefinery demand during the harvest window. Grisso et al. [4] developed a set of equations that matched the relationships as yield increased.

Grisso et al. [5] used geo-referenced data (from a Differential Global Positioning System (DGPS)) gathered during field operations (planting and harvesting) to determine productivity factors such as field efficiency. They demonstrated a strategy that compared field efficiency for machinery operations between flat, straight-rows and contoured traffic patterns. The methodology described by [4] has several potential applications. First, the ASABE Standards [3,6] could provide state-of-art information about specific field operating conditions. Results of the analysis are similar to other time-motion studies used in industrial applications, where the inefficiencies of a given process can be identified and quantified, and economic impacts can then be assessed.

Management strategies and enhanced design can be implemented to minimize inefficiencies [7–9]. Subsequent analysis could then be used to compare various machinery operation techniques and practices. Assessment of machinery and operator costs could be estimated for each field, or subsection, instead of using some type of aggregated average. Applying conventional machinery management models with DGPS data for round baling operations provides the basis for analysis and simulation of the harvest of high-yielding bioenergy crops [10–12].

Several researches have used time-motion studies and geo-referenced data to study impacts of field operations. Harrigan [13] used time-motion analysis of a corn silage harvest on seven Michigan dairy farms to identify representative forage harvester throughput and cycle times, transport vehicle travel speeds, and time in maneuvering transport vehicles in the field and near storage. They found when trucks and/or tractor-trailers were drawn alongside the harvester for filling, about 85% of the harvester's cycle time was available for harvesting and processing corn silage. Fifteen percent of the harvester cycle time was spent in turning on the headlands and switching transport vehicles. Similar studies using GPS technology [14–17] concluded that the geo-referenced information can be used by researchers and farm managers to appropriately size machinery and change management practices to minimize forage harvesting costs. Amiama et al. [14], concluded that 'crop yield' was the dominant variable in determining the effective field capacity of the forage harvester.

Palmer et al. [18] used georeferenced positioning to determine sprayer paths to improve coverage of field areas and determine the amount of overlapped and missed areas. From their study it was found that significant improvement could be made in field efficiency. It was suggested that precise tracking of predetermined efficient courses could reduce both overlapping and misses. By using such predetermined maps to control a sprayer, the distance travelled to cover a field could be reduced by 16% and the amount of inputs could be reduced by 10%.

Adamchuk et al. [19] parameterized the spatially variable characteristics of traffic patterns and defined field areas with significant reduction in field efficiency. Geographic positions recorded during harvesting of a field with complex shape were used to illustrate the method. The information obtained can be used either to optimize the traffic patterns, if possible, or to reevaluate the potential profitability of field areas with different degrees of machinery maneuvering complexity.

McDonald and Fulton [20] used time studies methods to compare productivity of forest harvesting systems across varying conditions. To achieve the twin goals of safety and cost reduction, they found it preferable to have a means of performing autonomous time study that did not involve fieldwork and that produced detailed summaries of machine or system performance over long periods of time. They used a data acquisition system to convert movement and positional data collected using a GPS receiver mounted in the harvesting equipment to observe time study information. The stream of events was evaluated using a pattern-matching algorithm that translated events into machine functions. Field trials showed the autonomous time study was capable of reproducing measurements obtained from field crews. The automated time study algorithm missed identifying fewer than 10% of the cycles. Other techniques such as tracking with a Smartphone [21] and the output from the ISOBUS on machinery [22] have been used to monitor machinery performance as well as operator behavior.

Capacity measurements [23] can be on the basis of area covered per unit time (in ha/h) or of material processed per unit time (in Mg/h, also called throughput) but they are related because the equipment cannot exceed their design material handling capacity limitation. The area that can be covered in unit time is called theoretical field capacity (ha/h) and is a product of the processing width and speed of the machine. Effective field capacity (ha/h) is a measure of actual productivity that accounts for field efficiency, the ratio of effective field capacity and theoretical field capacity. Since width and speed are easily measured, theoretical field capacity measurements are not complex. For machines such as mowers, rakes, mower-conditioners, or windrowers, where field efficiency is not significantly affected by yield since the forage receives minimum processing by the machine, theoretical field capacity is simple to calculate.

Conversely, the material handling capacity is very important in determining the performance of forage harvesters or balers. Material handling capacity is the maximum feed rate (maximum throughput) that can be accommodated on a sustained basis. This typically is a design limitation of the machine. For example, the mechanism that feeds material into a baler, or the cutting process in a chopper, must be adjusted based on forward speed to ensure that the design throughput is not exceeded. In round balers, the field efficiency can be significantly impacted by yield as it reaches its maximum design throughput and the machine must stop more frequently to wrap or tie bales.

With increasing production of higher-yielding grasses, such as switchgrass for bioenergy, improved relationships for quantifying the impact of yield on harvest machinery is needed for planning harvest operations and for estimating equipment needs and costs. The objectives of this paper are to measure field performance of balers during grass harvest operations and to compare these observations with agricultural machinery management models that were recently refined to account for impacts of yield on baler speed, field capacity, and throughput [4]. Differential Global Positioning System (DGPS) data collected during hay harvest operations were used to better understand the effect of yield on round baler performance and to derive relationships that can be used in modeling harvest performance.

2. Materials and Methods

A handheld DGPS receiver monitored the traffic patterns of balers as they traveled through the field. Each DGPS entry included a time stamp, latitude, longitude, elevation, instantaneous speed, distance traveled, time, and directional heading data. The DGPS units were placed in the tractor cab. In two fields, an external DGPS signal antenna/radiator (Holux AR-10) was used to improve signal reception.

A stopwatch recorded the time to form the bale, and the time the baler stopped to wrap and eject a bale. Then a handheld DGPS unit was used to manually record latitude and longitude data at the location where the bale rested on the ground.

The generated log from the DGPS units was downloaded into Excel for analysis (see Section 2.1). The coordinate locations for the starting and ending position for each bale were overlaid with the positional track of the baler. The timestamp generated by the GPS was checked against the time recorded by the stopwatch. Additionally, the manual record of bale and eject times provided a backup of the time differences in case satellite reception was lost. From the spatial data, the distance traveled along a windrow was calculated to determine total length of windrow for a particular bale.

Each bale was weighed by cradling it with a sling connected to a crane scale. The sling was made from two 183 cm pieces of 5×10 cm lumber connected by two lengths of chain spaced 76 cm apart. Two cables connected the hardware at the ends of the sling to the crane scale (Cardinal CA 5000). The cable harness attached to a crane that was suspended by a clevis attached to the front-end loader of a tractor. The combined weight of the harness and sling was subtracted from the scale reading to determine the bale weight. Bale weights were adjusted for moisture content. Samples of grass were randomly collected and moisture content was determined following a standard oven-drying procedure [24].

2.1. Analysis

The baler throughput was calculated as shown in Equation (1). Note that the time to roll a bale, t_r, does not include the wrap and eject time.

$$C_b = \frac{M_b}{t_r} \tag{1}$$

where: C_b—baler throughput (Mg/h), M_b—mass of bale (Mg), and t_r—time to roll bale, (h).

Yield, windrow density, and field capacity could also be calculated from the baler DGPS data and bale weights. The yield (Equation (2)) was calculated by the bale weight divided by the traveled area (length of travel multiplied by the average width of the swath from which the windrow was formed).

$$Y = \frac{M_b \cdot 10,000}{L_b \cdot W_s} \tag{2}$$

where: Y—yield (Mg/ha), M_b—mass of bale (Mg), L_b—length traveled in order to create bale (m), and W_s—width of swath (m).

The windrow density (D_w) is the bale mass (t) divided by the distance traveled to form the bale (L_b) as:

$$D_w = \frac{M_b}{L_b} \tag{3}$$

where: D_w—windrow density (Mg/m),

The field capacity (ha/h) was calculated as the traveled area divided by the time to form a bale. The field capacity of the round baler did not include the time for the bale ejection process (addressed in later discussion).

$$C_F = \frac{L_b \cdot W_s}{t_r \cdot 10,000} \tag{4}$$

where: C_F—baler field capacity (ha/h), L_b—length traveled in order to create bale (m).

2.2. Field and Baler Specifications

Six different fields (Table 1) of varying size, shape, and contour were baled with 5 balers (Table 2). The field shape, traffic patterns and final bale location is shown in Figure 1. Field 1 was a moderately rolling field baled with Baler C. The field was a mix of cool season grasses and was raked into windrows from swaths averaging 6.6 m wide. Field 2 was composed of two adjacent fields totaling 4.5 ha and was baled with Baler D. A small portion of one field had a steep slope, and the rest of the area was relatively flat. The field was a mix of alfalfa and cool season grasses. The average width of the swath in these fields was 6.7 m. However, several areas of the field had denser windrows (it is believed that the rake operator combined multiple windrows) and these denser windrows "simulated" higher yield. Field 3 was a level field of 1.1 ha and was baled with a large-square baler (Baler E). In this field, grass was raked into windrows from swaths averaging 3.7 m in width. Field 4 was a moderately rolling field of 6.8 ha and was baled with Baler A. The field was a mix of cool season grasses and was raked into windrows from swaths averaging 5.8 m in width. Field 5 was a heavily rolling field of 3.6 ha and was baled with Baler A. The field was a mix of cool season grasses. The average width of the swath for each windrow was 6.6 m, but during the first pass around the field the rake formed heavier windrows from swaths with an average width of 11.6 m. Field 6, a gently rolling field of 1.7 ha, was baled with Baler B. Switchgrass (1.2 to 1.8-m tall) was the primary species in the field and it had the highest yield observed. It was raked into windrows from swaths averaging 4.6 m.

Table 1. Field characteristics, baler used, number of bales and number of Differential Global Positioning System (DGPS) points for the field.

Field	Field Size (ha)	Field Terrain	Baler [1]	Moisture Content (% w.b.) [3]	Yield (Mg/ha)	Number of Bales	Number of DGPS Data Points
1	5.6	moderately rolling	C	-	2.3 (1.3 to 3.8)	29	902
2	4.5	hilly	D	-	3.2 (1.7 to 9.4)	37	903
3	1.1	flat	E	-	5.1 (3.3 to 6.8)	11	230
4	6.8	hilly	A	17.9 (14.3 to 25.5)	4.7 (3.1 to 5.6)	19/88 [2]	349 [2]
5	3.6	hilly	A	15.7 (14.6 to 16.4)	2.7 (1.8 to 5.2)	36	618
6	1.7	flat	B	24.6 (24 to 25.5)	9.2 (5.0 to 17.3)	26	333

[1] See Table 2, [2] Due to GPS malfunctioned only 19 bales/tracks had sufficient data, [3] w.b. is wet basis.

Table 2. Baler specifications.

| Baler	Tractor Rated Power (kW)	Baler Model	Bale Wrap Specifications
A	-	Case IH BR740 Round Baler (1.5 m)	3 Wraps polyurethane net
B	63.4	John Deere 467 Round Baler (1.5 m)	3 Wraps polyurethane net
C	67.5	Case IH RBX462 Round Baler (1.8 m)	3.5 Wraps polyurethane net
D	67.5	Case IH RBX462 Round Baler (1.8 m)	10 Wraps baling twine
E	-	Case New Holland BB940A Large Square Baler 91 × 91 × 183 cm	4 Wraps baling twine
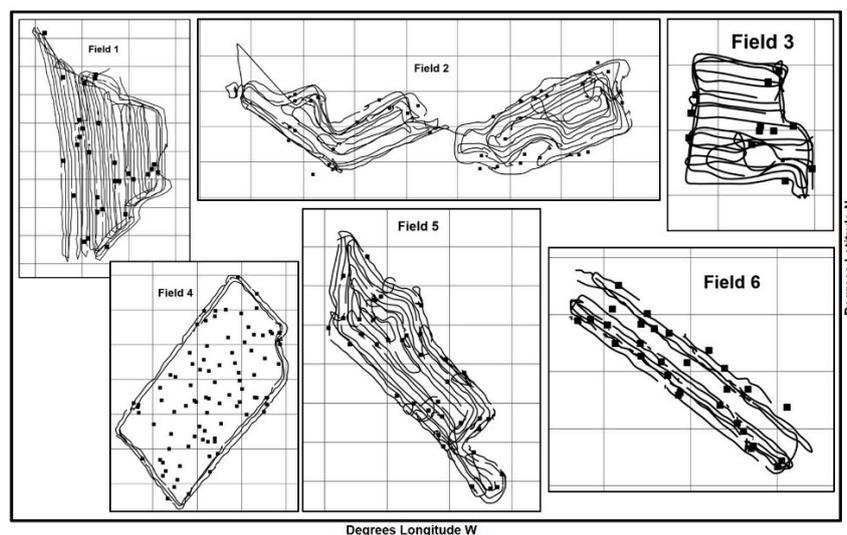
Figure 1. Traffic patterns of Fields 1–6 baled with conventional baling equipment. (Lines are the traffic pattern and square symbol represents where the bale was dropped. Figures are not to scale. Traffic pattern missing for Field 4 due to DGPS malfunction).

3. Results and Discussion

Baler performance data are summarized in Table 3. Average wrap-eject time for the 1.8 m diameter bales was 36 s, while the 1.5 m diameter bales were ejected in 27 s. In previous studies [25,26], the time to wrap a bale with net wrap was shorter than for wrapping a bale with twine. Only one round baler

used in this study, Baler D, used baling twine. The wrap-eject time for Baler D was 41 s compared to 31 s for the same size bale covered with net wrap (Baler C). Figure 2 shows the "Box-Whisker" graph of the ejection time for the round balers. This figure does not show the wide difference in average ejection times between the balers. Since Field 3 was baled with a large-square baler, no ejection time is needed since the baler continues to bale while the previous bale is being tied.
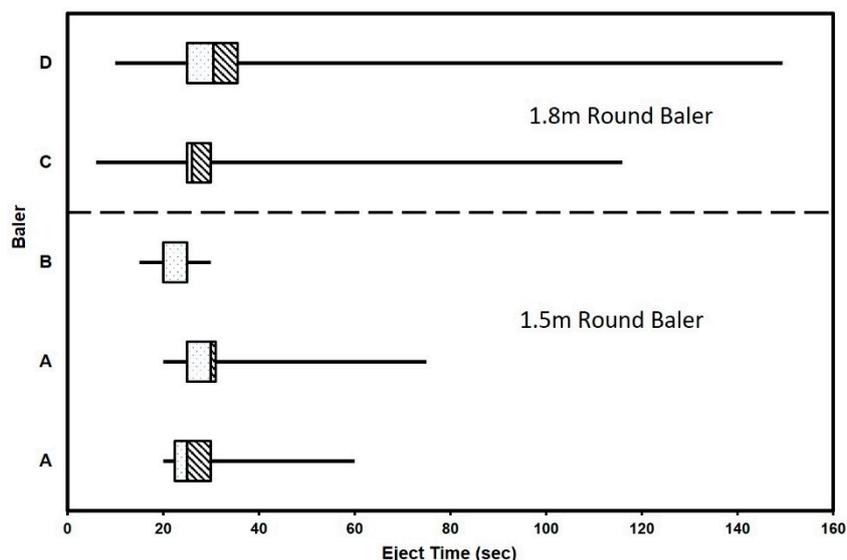

Figure 2. The box–whiskers graph of the wrap-eject time from round balers. Tails represent the highest and lowest extremes and the box ends are the 25th and 75th percentiles and the solid line in the box is the median.

Table 3. Measured performance data for round and large-square balers (note, the capacity of a square baler does not include a bale wrap-eject time).

Baler	Field	Average and Ranges						
		Speed (km/h)	Windrow Density (kg/m)	Mass per Bale (Mg)	Field Capacity (ha/h)	Throughput (Mg/h)	Time to Form Bale (sec)	Time to Wrap-Eject (sec)
A	4	5.7 (4.8 to 6.8)	2.7 (1.8 to 3.2)	0.38 (0.33 to 0.44)	3.3 (2.8 to 4.0)	15.1 (11.0 to 18.8)	92	28
A	5	7.0 (4.2 to 8.7)	2.3 (1.13 to 6.0)	0.32 (0.28 to 0.35)	5.47 (4.1 to 8.0)	15.0 (8.5 to 28.3)	84	32
B	6	5.9 (4.2 to 6.9)	4.2 (2.3 to 7.9)	0.43 (0.15 to 0.48)	2.7 (1.9 to 3.2)	25.1 (14.8 to 42.7)	65	23
C	1	8.9 (6.3 to 9.9)	1.5 (0.8 to 2.5)	0.56 (0.28 to 0.66)	5.8 (4.1 to 6.5)	13.1 (8.0 to 24.2)	167	31
D	2	8.2 (3.1 to 12.3)	2.4 (1.1 to 9.7)	0.52 (0.46 to 0.61)	5.4 (3.2 to 8.2)	16.9 (8.2 to 32.3)	123	41
E [a]	3	9.6 (6.8 to 11.4)	1.9 (1.2 to 2.5)	0.42 (0.38 to 0.45)	3.52 (2.5 to 4.2)	17.9 (11.4 to 27.6)	91	-

[a] Large square baler.

Speeds for Fields 1, 2, 5, and 6 averaged 8.9, 8.2, 7.0, and 5.9 km/h, respectively (Figure 3). This shows that the larger round baler was faster than the smaller baler. There was less variability in Field 6 than other fields. Fields 1 and 2 had a bi-modal distribution (two peak speeds) this was probably due to the field shape (irregular) and small size which influenced the operator's traffic patterns.
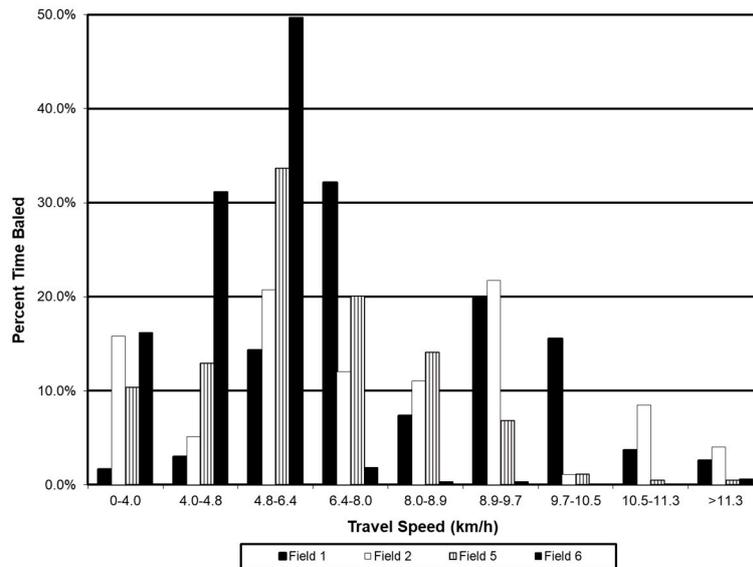
Figure 3. The frequency distribution of baler speed in Fields 1, 2, 5 and 6.

Field 1 had 29 round bales, formed in 1.87 h. The yield data indicated a relatively uniform density of biomass across the field. Field 2 had 37 round bales and the bales were formed in 2.06 h. Windrow density in this field was observed to be heavier than in other fields baled using the 1.8 m round baler. Deviations from the average occurred in locations where the baler was harvesting from a "double" windrow. In these locations, the rake formed one normal windrow, then switched direction and combined another windrow on top of the first.

Field 3 had 11 large-square bales, and the bales were formed in 0.33 h. Field 4 had 88 round bales, and the bales were formed in 2.7 h. The manual record of time interval between bales allowed for calculation of baler capacity, but this record increased variability in readings. Variability in capacity is due not only to windrow density and baler speed, but extra maneuvering required during baling. Field 5 had 36 round bales, and they were formed in 1.4 h. Field 6 had 26 round bales, and they were formed in a 1.7 ha field in 0.77 h. In this field, the clutch on the baler pickup slipped in high throughput conditions and, in one instance, the pickup stalled and the operator had to back up to clear the baler. The average yield in Field 6 was 9.2 Mg/ha.

The performance of each of the observed balers has characteristics that are best explained in Figure 4. The field data is compared to the machinery management relationships as outline by [4]. Figure 4 shows a round baler's productivity during bale formation and does not include the bale wrap-eject time. The purpose of considering the baler performance during rolling only was to compare with existing models for agricultural equipment performance. It will be clear when the wrap-eject time is reintroduced that the complexity of the relationships is more difficult to discern when the time to wrap and eject is included in the calculations of baler performance. During bale formation, the baler throughput increased linearly for the range of yields encountered. Figure 4 also shows speed and achieved field capacity versus yield. The points are measured data and the solid lines (red, green and blue) are calculated by assuming an effective speed and swath width and using Equations (2) and (3). As shown in Figure 4, the assumed effective speed of 5.8 km/h (green line) was similar to the average of the observed values (6.0 km/h). Please note that the solid lines in Figure 4 are calculated and these lines are not regression relationships of the observed values of speed and field capacity.
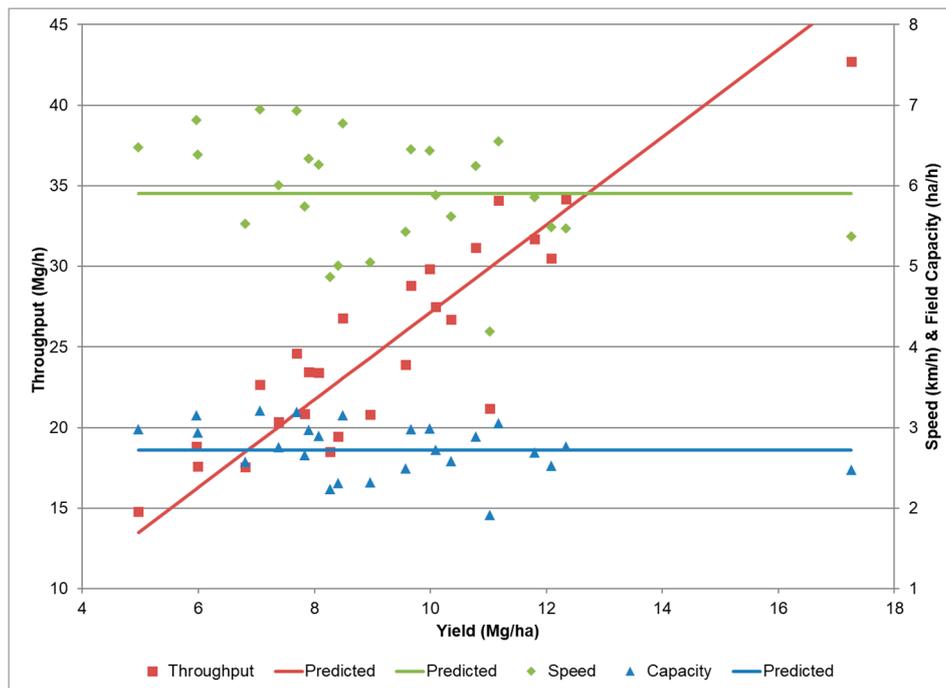
Figure 4. The relationship of the performance data to switchgrass yield from Field 6. Productivity data does not include time spent wrapping and ejecting the bale. The individual points are observations from field data. The solid lines (green—effective speed, red—throughput, blue—effective field capacity) are predicted [4] assuming values of v_e = 8.0 km/h, E_f = 0.74, and W_s = 4.6 m.

Some models assume that forage equipment operate at a constant speed and field capacity regardless of yield. So far, this has been shown to be true. Field capacity and speed were constant with increasing yields and the throughput was shown to have a positive linear relationship to yield. However, there will be limits at which this can occur. When forage equipment encounters a high-yield situation it is possible to exceed the maximum throughput of the machine. In a study by Shinners et al. [25], ground speed was limited due to high yields. They suggest that modifications to the baler pickup and throat may be needed to improve performance in high-yielding energy crops.

In this study, only one field/baler (Field 2, Baler D) had yield conditions at which a change in baler field performance was observed. These data are shown in Figure 5. At a yield of 9.4 Mg/ha, the throughput was essentially the same as was observed at 5.6 Mg/ha. Based on this, it was concluded that the maximum throughput for this particular baler was approximately 31 Mg/h. The observed values of speed and field capacity were also reduced at this higher yield, as expected. The development of the performance relationships in this situation is somewhat more difficult because the linear relationship and the maximum throughput must be correctly divided. Unfortunately, maximum throughput is not included in manufacturer specifications or in machinery management standards [3,6]. If this information was provided by manufacturers of forage equipment, performance in higher yields, as will be encountered for many energy crops, could be more accurately modeled. Development of the linear portion model is the same as above and at the transition (yield) the maximum throughput becomes constant and the speed and field capacity decrease proportionally with yield.
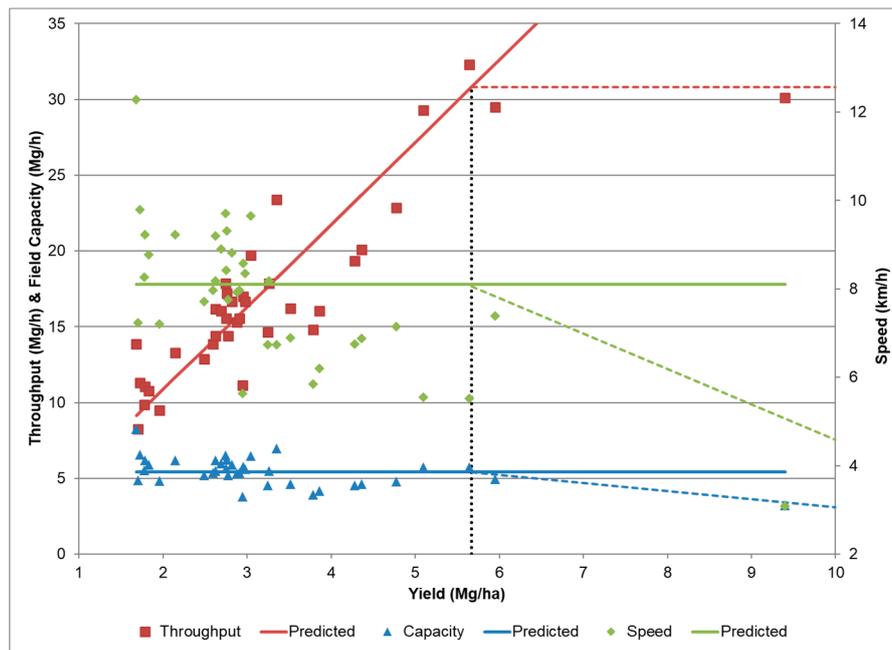
Figure 5. Throughput reached a maximum capacity. The relationship of the performance data to yield from Field 2 is shown here. Productivity data does not include time spent wrapping and ejecting the bale. The individual points are observations from field data. The solid and dash lines (green—effective speed, red—throughput, blue—achieved field capacity) are predicted [4] assuming v_e = 11.0 km/h, E_f = 0.74, and W_s = 6.7 m.

For round balers, the time to wrap and eject a bale must also be considered. In the previous discussion, the relationships between yield and throughput, field capacity, and speed were developed considering only the time to form the bale, not the wrap-eject time. Since stopping to wrap and eject a bale is a unique event for round balers, the performance was modeled first with the same equations as for other forage equipment with the time to wrap-eject the bales introduced later (Figure 6). When the observed wrap-eject times are included with the field observations, the relationship becomes somewhat more variable but the trends are intact. Figure 6 shows the performance of the balers with the wrap-eject time included from Field 6. Again, a predicted relationship of the throughput data is shown (red line) along with both observed values and predicted values for speed and field capacity. Speed and effective field capacity decrease with the increase in yield.

The total time to produce a round bale is a function of the productivity time (forming bale) and the time to wrap-eject the bale. Performance of the round baler was best modeled using separate functions for these two operations. The productivity efficiency (not including the time for wrap/eject a bale) will be similar to the field efficiencies reported in the [3]. The efficiency due to wrapping and ejecting the bale is a function of yield and field capacity. As yield increases, so do the number of bales produced, and the total time spent wrapping and ejecting the bales, per unit area harvested, increases.
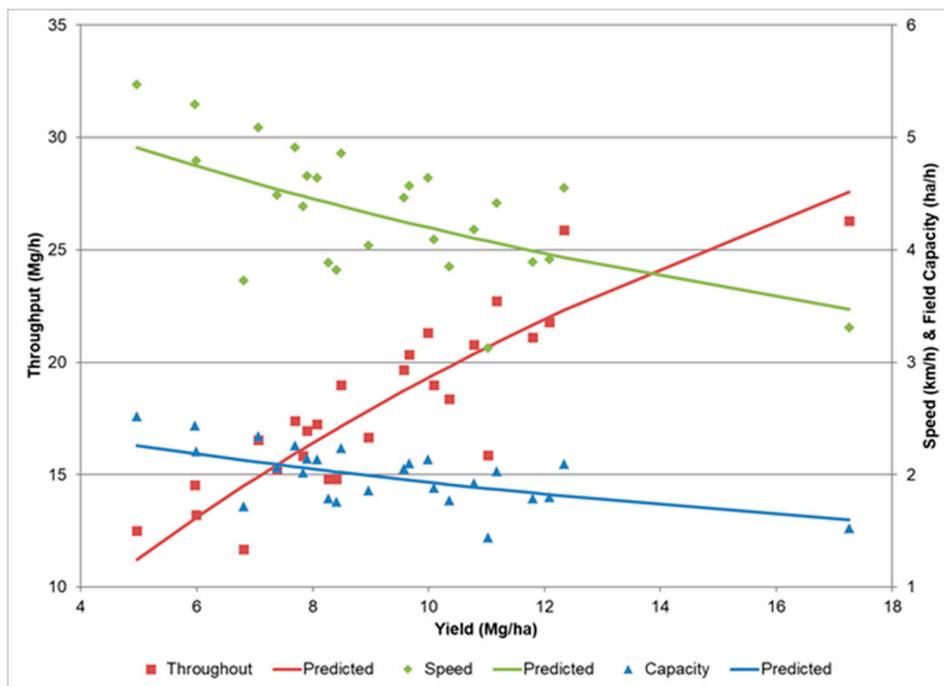
Figure 6. Effect of wrap-eject time on baler performance. This graph shows productivity, including time spent wrapping and ejecting the bale, for field 6. The individual points are observations from field data. The solid lines (green—effective speed, red—throughput, blue—achieved field capacity) are predicted [4] assuming v_e = 8.0 km/h, E_f = 0.74, W_s = 4.6 m, t_e = 23 s, and M_b = 0.43 Mg.

The round baler is not the only agricultural machine for which this additional efficiency should be considered in modeling field productivity. Over time, the cotton industry has moved from a cotton picker dumping cotton into in-field hauling conveyances to forming a round bale of cotton that can be wrapped while the next bale is formed. Data from Willcutt et al. [27] demonstrates how a machine function affects productivity. When yield is relatively low, the time to wrap-eject does not have much impact on the system capacity; however, as the yields increase, speed and field capacity are no longer constant.

An example of all predicted factors impacting round baler capacity is shown in Figure 7. The only field with indication of exceeding the maximum throughput was Field 2. The impact of the wrap-eject time on productivity is included as well as the impact of exceeding the maximum throughput. Based on visual observation of the data, the maximum throughput was estimated to be 20.4 Mg/h at yields of 5.6 Mg/ha and higher. For yields less than this, throughput can be modeled using a linear relationship. For higher yields, the throughput is constant. Unlike Figure 4, where speed and field capacity are constant and the wrap-eject times are not considered, these values decline with increasing yield as the baler must stop to wrap and eject a bale more frequently. The effect of wrap-eject is also seen in observed throughput. The solid red line shows estimated throughput when wrap-eject is not accounted for.
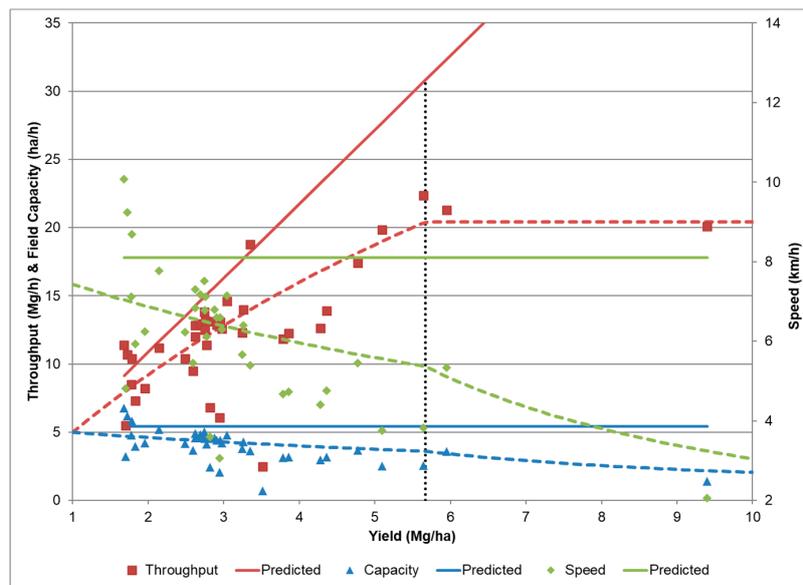
Figure 7. Effect of maximum throughput and wrap-eject time on baler performance. Productivity in Field 2, including time spent wrapping and ejecting the bale, is shown. The individual points are observations from the field data. The solid and dashed lines (green—effective speed, red—throughput, blue—achieved field capacity) are predicted [4] assuming v_e = 11.0 km/h, E_f = 0.74, W_s = 6.7 m, t_e = 32 s, and M_b = 0.52 Mg.

As shown in Figure 8, there is good agreement between the predicted machinery management equations as presented by [4] and observed data for Field 1. The constant effective speed and calculated field capacity without the time of wrap/eject is clearly seen and the scatter for these parameters with the wrap-eject included may be closer if actual values of time were used instead of the average time.
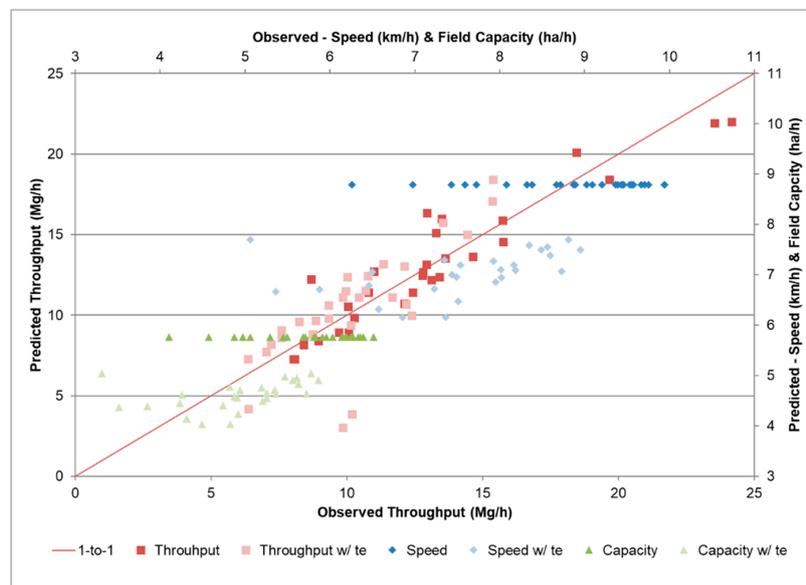
Figure 8. Comparison of the observed and calculated productivity factors for Field 1. The observed from the field data and calculated [4] (v_e = 12.0 km/h, E_f = 0.74, and W_s = 6.55 m, t_e = 39 s, and M_b = 0.56 Mg). The red line indicates a perfect correlation between calculated and observed values (1:1 line).

These results show that not including the impact of yield on round baler field efficiency risks overestimation of round baler throughput. At high yields, the measured values of throughput were up to 50% lower that the calculated throughput when the maximum throughput and the effect of

wrap-eject time were not considered. When capacity is overestimated, the estimated number of machines needed to complete the harvest is too low and the cost may not be appropriately allocated. Additionally, as round balers encounter higher yields, as expected for many dedicated energy crops, performance is impacted. Simulation models of biomass harvesting should correctly adjust for the impacts of yield on machine capacity.

The impact of the wrap-eject time is unique amongst forage equipment for the round baler. There are many advantages of round bales, particularly for the Southeast USA, including protection from precipitation and lower capital costs. However, the reduced field efficiency caused by stopping to wrap and eject bales at higher yields is a challenge. Multiple manufacturers have developed prototypes of continuous round balers. Assessing potential cost improvements of these more expensive continuous baler designs will require the more accurate assessment of conventional round baler field performance provided in this study. Such design improvements would combine the high efficiency of large-square balers with the advantages of round bale packages.

4. Conclusions

DGPS data collected during forage harvest operations showed to be effective for time-motion studies. In-field performance (ha/h) of round balers was significantly affected by yield. Machinery management concepts developed by [4], knowledge of maximum throughput, and wrap-eject time can represent the field data. Six fields were used to compare field capacity results from round and large-square balers. The results showed that predicted baler performance was overestimated when the yield, maximum throughput, and wrap-eject time were not correctly accounted for. In the highest-yielding situations, balers encountered a maximum throughput beyond which increases in yield did not provide increases in baler productivity. Assuming that baler productivity increases linearly with increasing yield, an assumption of many models, is only valid at yields below this maximum throughput of balers. For round balers, the effect of the wrap-eject time must be accounted for in simulation of harvest operations.

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