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Research Report

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Work Element Time Study of a Prototype for Baling Forest Residual Biomass into Large Rectangular Bales

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ABSTRACT.

The productivity of forest biomass collection equipment is highly dependent on site conditions, spatial distribution of biomass, operator skill, and functional design of the equipment used. A prototype woody biomass baler was used to produce large rectangular bales of woody biomass. Rectangular bales enable high payloads during transport and efficient storage at centralized processing facilities. A series of empirical time studies were conducted using experienced operators to assess the baler-specific productivity of making bales of urban, forest thinning, and forest harvest residuals. This paper reports on the results of a forest harvest residuals baling study conducted during 2015. As with prior studies evaluating bundlers, bulk containers, and forwarders, grappling and arranging biomass with a boom-type loader consumed approximately 25% of the total time to make bales. Biomass gathering can only be improved by better arrangement during harvest operations. Platen cycling was a significant production rate factor and is directly related to chosen engine power and available hydraulic flow. Simulations of baler specific production rates (time to make a bale) were informed by field study data. Sensitivity analyses enable choice and specification of functional design attributes for commercial models of woody biomass balers.

Keywords.

Biomass, forest residues, densification, harvest, logging, slash, bioenergy, biofuels, baler

Introduction

Harvesting of public and private forests is motivated to remove and sell roundwood logs that have positive net commercial value. Various amounts of biomass consisting of tops, small diameter and off-quality poles, broken log sections, branches, and brush are left behind as forest residuals. The amount of residual biomass available for removal from harvest units depends upon current market values for roundwood and chips, harvest methods, landowner requirements, sustainability goals, and regulatory requirements. Some of the residual material is lightly distributed across the harvest unit, and other material is piled, windrowed, or aggregated at landings and at the roadside. Concentrated materials often need to be removed to enable replanting, reduce fire danger, and/or supply bioenergy markets. Methods for removal include burning in-place, scattering across the landscape, chipping-and-scattering, or transportation away from the site. Although burning has been the historic method of choice, it is being phased out in many locales due to air quality regulations, risks for escaped fires, escalating costs, and landowner policies.

Markets for forest residuals include biopower, composite wood panel products, densified solid fuels, bioproducts, and liquid biofuels. Distributed small-scale producers of bio-based industrial and energy feedstocks are likely to become more common in the future (Hess et al. 2006; Hess et al. 2009; Lamers et al. 2016). Woody biomass processing depots are likely to be located near to forests, thus reducing the hauling distance for raw biomass.

Woody biomass slated for physical removal can be chipped or ground on-site and transported in specialized trucks (Dukes et al. 2013; Marrs et al. 2016), loaded into hook-lift containers (Rummer and Klepac 2003; Han et al. 2010) or dump trucks (Bisson et al. 2013; Bisson et al. 2016) for grinding at centralized sites, or densified into bundles (Timperi 2002) or bales (Pottie and Guimier 1986) for truck transport. Major components of biomass cost include capital, mobilization, in-woods relocation, biomass gathering, processing, hauling, and storage. Each of the alternative in-woods processing and handling alternatives has been successfully deployed at operational scale.

The problem of forest residual collection and transport as bundles or bales has been a subject of study across North America and Europe. Various schemes for compacting and/or unitizing forest slash and other woody biomass were explored, usually as alternatives to on-site chipping and chopping, but with very limited market acceptance.

The Royal College of Forestry in Sweden was among the first to conduct a disciplined study of baling (Danielsson et al. 1977). Their laboratory baler with a high pressure system (1000 kPa, 150 psi) was able to compress unprocessed logging slash to bulk densities of 250 – 400 kg/m^3 (15.5 – 25.0 lb/ft^3). By 1980, baling research moved to North America at several institutions. Baling woody biomass to achieve high bulk density is currently being pursued along three technical approaches, with each approach being preferred for particular situations. The approaches are bundling, round bales, and large rectangular bales. The objective of this study is to better understand the baling alternative.

Bundles

A biomass bundling system was developed and commercialized by Timberjack in Finland to enable forest materials to be handled similar to logs (Timperi 2002). The concept was to arrange residual tops and branches into parallel-stem bunches, compact the bunch, and wrap completed bundles with netting or baler twine to facilitate handling of units in a way similar to logs (Rummer et al. 2004). John Deere acquired Timberjack from Metso Corporation in 2000 and the bundler mounted on an articulated forwarder-type prime mover was then sold internationally as the Deere 1490D slash bundler. Early evaluations of the bundling system were conducted by the U.S. Forest Service (Rummer et al. 2004). Rummer found that productivity was limited by the time needed to move the machine between places within a harvest unit. The machine moves frequently to gather slash, or for operator use of the grapple to arrange slash into full grapple-loads. A U.S. study of forest residues bundling, followed by in-woods grinding, was conducted in California (Harrill et al. 2009). High capital and operating costs combined with low production rates under the tested conditions caused higher than desired costs of collection. Improved biomass handling and densification of forest residuals could help to reduce these costs of collection. Meadows et al. (2011) found that slash movement and gate delimbing consumed 18 percent of skidder total productive time and that bundling operations at the landing may increase skidder productivity compared to operations where slash is moved away from landings. Meadows et al. (2011) also concluded that set-out trailers directly loaded with finished bundles could benefit production and limit handling.

Engineering research teams in Europe continue to pursue improvements to the bundling machinery and to take a systems optimization approach to reducing operating costs (Nuutinen and Björheden 2016). A team in Spain evaluated replacement of the bundle-cutting chainsaw with a shear, among other technical improvements (Sanchez-Garcia et al. 2015). They reported modest productivity improvements due to the shear. A study in Sweden (Bergström et al. 2016) explored the effects of forest structure and operational planning as systems improvements that could improve bundler productivity. They used a Logman 811FC harwarder (Logman Oy) with a modern Fixteri FX15a bundler unit. Work elements and time studies were used to quantify performance under various conditions and stand types, as well as to study the benefits or consequences of converting from sawing to shearing the bundles.

Another European effort to improve bundling systems was led by Spinelli in Italy. In an effort to improve mobility and reduce capital costs, the bundler was mounted on a highway-legal truck to improve mobility between small, scattered landings, where frequent relocation was necessary (Spinelli et al. 2012). Spinelli found that productivity was approximately 10 bundles (4.5 green metric tons) per on-site hour. Operator skill resulted in up to 30% productivity differences among multiple operators.

A frequent question about bundling is the long-term stability of densified forest residuals during storage. A study of “brash baling” using the 1490D bundler in the U.K. (Forbes et al. 2014) concluded that bundling followed by long-term storage and centralized chipping was practical. In their study, bundles were stored for up to three years.

Round bales

Collection and densification of woody biomass into round bales was initially explored by Fridley and Burkhardt (Fridley & Burkhardt, 1984) by modifying conventional agricultural hay balers. They concluded that only flexible, small diameter material could be successfully wrapped into round bales. They also evaluated the risk of bale heating during storage and found that the risk was low.

More recently, the round-baler concept was pursued in Canada. Savoie’s team in Canada advanced the round baling approach for woody biomass crops such as willow (Savoie et al. 2006; do Canto et al. 2011; Morissette and Savoie 2014). Their prototype baler was built from scratch and included a rotary flail chopper/shredder to coarsely process cut stems, so they could be readily formed into round bales. Their work led to the commercialization of the Anderson Biobaler (Savoie et al. 2012). The baler has been evaluated in the southeastern United States for forest understory removal and collection (do Canto et al. 2008; Klepac and Rummer 2009; do Canto et al. 2011). While the round baler has been successful in the United States and Europe for forest vegetation management, fuels reduction thinning, and harvest of short-rotation woody crops, it has not found success with harvest residuals and cannot bale material from piles.

Rectangular Bales

Baling into rectangular bales began in the 1970s with work in Virginia and Washington (Stuart and Walbridge 1978; Walbridge and Stuart 1981; Schiess and Stuart 1983). Dr. William Stuart at Virginia Polytechnic Institute and State University was among the early U.S. developers of forest biomass balers (Jolley 1977; Schiess and Yonaka 1982). His baler was brought to the University of Washington in 1982 for testing by Dr. Peter Schiess (Schiess and Stuart 1983). Unfortunately, the Stuart baler was never advanced to commercial units.

More recent development of rectangular bales began in 2005 with an objective to reduce the cost for aggregation and transport of urban woody biomass and wildland/urban interface fuel reduction prunings (Dooley et al. 2006). Development of a road-legal woody biomass baler over the next five years was documented by a series of conference papers (Dooley et al. 2008; Dooley et al. 2009; Dooley J.H. et al. 2011; Dooley J.H et al. 2011).

Figure1. a) Forest Concepts prototype forest residuals baler; b) completed bale; and c) stack of baled woody biomass

A time study was conducted for the baling of urban woody biomass to assess potential design improvements for commercial versions of the road-legal baler (Dooley et al. 2009). The study used the moment-method where an observer watched the baling operation and recorded which work element was being done at 10 second intervals. This resulted in approximately 270 observations per completed bale. Approximately 50% of the time was spent grappling, re-bunching, and biomass gathering/loading activities. Platen cycling accounted for approximately 30% of the time, in part due to an intentional very low power limitation on the hydraulic power system. The primary conclusion was that baler productivity could only marginally be increased through mechanical improvements to the baler; while gains from better prepared and arranged biomass could be large.

Work Element Time Study

Many studies have been conducted of gross productivity for forest residue collection using bundlers, forwarders, bins, and new technology developments, but few considered the contribution of individual work elements. Most were system-related rather than machine-related. Forest residue collection system optimization has also received significant recent attention in the United States (Zamora-Cristales et al. 2015). A study in northern Europe (Kärhä and Vartiamäki 2006) found that opportunities to reduce cost and improve productivity included: adding shifts, increasing bundle or container size, increasing operating hours, and concentrating residuals in larger piles or nearer to roads. As noted earlier Sanchez-Garcia et al. (2015) studied the benefits of shearing versus sawing bundles to length.

Spinelli applied work methods analysis to document the time allocation to specific machine and operator work elements that may be modified through better machine design, improved training, or automation (Koŝir et al. 2015). Specific productivity of bundling forest residuals and thinnings using the Deere 1490D machine was studied by the forest operations unit of the U.S. Forest Service Southern Research Station using video tapes and elemental time studies (Rummer et al. 2004). Work elements included:

- Traveling – machine moving between bundling locations
- Arranging slash – machine time to arrange material and accumulate a full grapple load
- Feeding slash – moving grapple full of material from the ground and into the bundling infeed area
- Cutting – saw cutting of bundle into discrete unit for dropping onto the ground
- Rotating bundler – rotation of the boom and bundler unit while the machine is stationary and not traveling.

Rummer found that the time to arrange biomass into full grapples consumed from no time to 34% of the total specific bundling time. This, when combined with traveling between bundling sites, dominated the time per bundle compared to machine-specific operations.

Several studies of in-woods biomass collection via haul trucks and hook-lift containers and in-woods grinding also found that work elements related to bunching, re-bunching, and pile arranging accounted for 20-50% of the total work time (Kizha and Han 2016) (Harrill et al. 2009). A study of bundler productivity found that slash preparation, or lack of it, was the dominant factor affecting production rates (Moskalik et al. 2016).

A detailed work elements analysis of bundling forest thinnings was conducted in Sweden (Bergström et al. 2016). The machine was a self-propelled forwarder with a Fixteri FX15a advanced generation bundler attached to the bunk. Their work elements included:

- Moving – moving the prime mover between biomass locations
- Boom out, felling, and Boom in – operation of cutting and bunching stems
- Feed – feeding a grapple-full of whole small trees into the feeding chamber
- Bundling – making bundles, cutting to length, wrapping
- Scaling and dropping completed bundles
- Arrangement of felled trees
- Arrangement of produced bundles
- Delays

Context of this study

Work at Forest Concepts, LLC on urban woody biomass baling was expanded to the problem of forest harvest residuals as part of a Biomass Research and Development Initiative (BRDI) project sponsored by the U.S. Department of Energy. The forest operations part of the project significantly advanced the collection of forest residuals by separating roundwood poles from branches and other fine materials prior to processing and hauling (Bisson and Han 2016; Bisson et al. 2016); (Kizha and Han 2015, 2016). Presorting and separate pole collection greatly facilitates baling of the finer materials. Since very few stems larger than 100 mm (4-inches) diameter are left after sorting, the residuals to be baled are easier to grapple and handle with a loader.

Large rectangular bales are potentially a preferred format for forest residuals due to higher transport payloads, stability when stacked in storage yards, and high volumetric density compared to round bales or bundles. The Forest Concepts prototype woody biomass baler was used as a basis for specifying and designing a baler for use with forest residuals. The design process began with stakeholder analysis and use of The Appreciative Design Method to establish functional and engineering specifications (Dooley et al. 2015a, 2015b; Dooley et al. 2016). Critical analysis of hauling, bale storage, and bale grinding elements of the supply chain led to specification of optimal bale dimensions and density (Dooley 2015). The earlier urban biomass baler-prototype was subsequently modified to meet the forestry context. Major revisions included: 1) shortening the baling chamber to enable smaller, higher density bales; 2) increasing the horsepower from 25 kw to 40 kw; 3) adding a commercially-available chainsaw slashing saw to eliminate the ground crew that was preparing slash for baling, and 4) moving the baler to a more robust trailer to enable use on unpaved forestry roads.

The modified prototype was tested on active logging sites in California, Oregon, and Washington (Dooley 2015; Dooley et al. 2015a, 2015c, 2015b; Dooley et al. 2016). In cooperation with Arciero Logging company, a field trial site was identified on Snoqualmie Pass, east of Seattle, WA that had significant roadside commercial thinning and harvest residues that were, according to the methods of Bisson, Han, and Kisha (Bisson and Han 2016; Bisson et al. 2016); (Kizha and Han 2015, 2016), similar to what would be expected from sites sorted. A field trial was then conducted in August 2015. Earlier productivity and work element-based studies informed the determination of work elements to be included in a final assessment of the Forest Concepts prototype forest utility baler.

Materials and Methods

The field trial was conducted with a single experienced operator on a clear day, so operator skill and weather would not be confounding factors. The primary data collection method was to use digital video cameras to capture a complete record of the trial for subsequent manual analysis. One video camera was set on a tripod approximately 30 meters from the baler with a viewing angle that encompassed both the baler and the extent of reach for the grapple boom. Two additional cameras were set to focus on the baler and the operator. Recording was started after the baler stabilizer feet were extended and run continuously until the baler was moved to a new location. Digital video files were transferred to an office computer for analysis and to the company's file server for archiving. The video was analyzed using video playback software that showed continuous time information. A 10-minute technician-training video file was prepared and analyzed three times by the Project Director. Work element descriptions were revised as needed to enable crisp determination of the start and end points for sequential work elements. An Excel® workbook and data entry template were prepared for recording the beginning and ending time stamps for sequential work elements. The complete video for production of three bales was analyzed by a technician after he was trained by repeated analysis of the 10-minute training file until his observed times closely matched those of the Project Director. The digital video file from a camera having the best overall view was opened in Windows® Media Player. The video was paused at the start of each bale, then at the transition from each work element to the next in sequence. If needed, the video could be backed-up a few seconds

Table 1. Work elements defined for baling of forest residuals with the Forest Concepts baler

Pre-Baling Work Element (Activity)	**Description**
Accessing and leaving forest	Time from when the equipment leaves public road into forest until stopping at first site of the day. Time to leave forest at end of day. Record distance moved as well as elapsed time.
Traveling within the forest	Time from when the wheels start to move until arrival at the next baling site or position. Record distance moved.
Positioning baler - Setting up and preparing to bale	Time from arriving at a baling site or pile and time beginning to move loader toward pile.
Pile sorting	Removing pole and chunk materials from pile and stacking for separate hauling with containers or log trucks.
Baling Work Element (Activity)	**Description**
Move baler – Move baler within a work area	Begins when operator stops baling and lifts the stabilizer legs to move the baler a short distance within the current work area. Ends when the stabilizer legs are reset.
Pile Working - Pulling pile apart / arranging slash / re-bunching	Handling of slash to pull pile apart or gather slash into reasonable grapple loads
Pile to Baler - Loading bale chamber	Begins when the boom moves to grasp the residues and ends when it releases them into the baling chamber infeed or positions the grapple bunch at the slashing saw for slashing. Does NOT include waiting for slashing saw to cycle.
Slashing - Slashing of a grapple load	Begins when operator lets go of boom controls to cycle slashing saw and ends when hands go back to boom controls.
Rotating – Rotating grapple load for second slashing	Begins when operator lifts the grapple after slashing and ends when load is set for cycling the slashing saw.
Place in chamber	Begins when slashing saw has completed its cycle and ends when the grapple bunch is released into the baling chamber.
Packing	Begins when the operator closes the grapple and uses it to pack biomass into the baling chamber. Includes using the grapple to rearrange material in baler.
Platen Cycling	Begins when the grates begin to close and ends when they open for next push or at time of full bale indication.
Saw maintenance and repair	Fixing, tightening chain, chain off bar resetting, etc. List reason with time.
Baler maintenance and repair	Refueling, adjusting sensors, cleaning debris, etc. List reason with time.
Preparing to move baler to new location	Time from completing last baler push at current site and time that operator leaves operator station to climb down off the trailer. Includes time to clean debris off the baler for transport.
R&D delay	Non-baling time while data is being taken or R&D instructions are discussed.
Other on-site working time	Moving bales around site into sets or piles for handling, stacking on pallets, dealing with oversize logs and chunks, etc.
Break – Operator break	Planned stoppage including breaks, lunch, or other scheduled stoppage.
Other	Time and work elements that do not belong to the above categories. List with time.
Finishing Work Element (Activity)	**Description**
Bale tying and ejection	Begins when the operator begins to open the ejection door and ends when operator is ready to use grapple to move finished bale.
Bale handling & stacking	Begins when operator begins to move grapple to pick up bale and ends with bale in storage position or on haul vehicle.

and replayed to enable determination of the transition point from one work element to another. The time stamp at each transition was recorded on an Excel® worksheet with one complete bale per worksheet. Each bale for a field trial was documented as a separate worksheet in a workbook. Summary worksheets were created to combine data across bales, display averages, and display other statistical results.

The core worksheet for each bale computed the time interval for a work element segment by subtracting the ending time stamp for that element from the ending time stamp for the prior element. Time durations were converted to decimal minutes and summed for each bale. Since individual measurements were obtained for every instance of a work element, analysis of frequency, variance, etc. could be calculated.

To compare with the earlier 2009 study results, the 2016 video was reanalyzed using the moment method to produce percentage-of-time data using the same technique as used in the 2009 urban baling study (Dooley et al. 2009).

Results from the 2015 forest residuals field trial were then input into workbooks created for the previously reported 2009 urban baling study (Dooley et al. 2009). The workbook added estimated and previously measured times for bale tying, moving, bale handling and other work elements not measured in this forest residuals study. The workbook enabled simulations of gross productivity for baling forest residuals. By using the same non-baling times the effects of baler mechanical improvements and the forest residuals context effects on gathering biomass could better understood.

Results

During the baler trials, a total time of 62.4 minutes was analyzed using the work element method and moment method. The productive machine hours without delays during the time study was 1 hour and 1.3 minutes, and delays accounted for 1.0 minutes of the monitored time. The three bales produced by the machine during the study had an average baling completion time of 20.8 minutes with a range of 19.1 to 22.2 minutes (Table 2). A simulated on-site full-workday estimate would include moving time, bale handling, fueling, repairs, maintenance, etc. Gross productivity based on a simulated on-site full-workday estimate from the data collected would have a gross production of 13 bales per day based on an eight-hour work day (Table 3).

On average, the most time-consuming (primary) work elements in bale construction include the following: platen cycling, pile working, and slashing (Table 3). The platen cycling work element of bale construction had the largest proportion of time at 23.8% (Figure 2). The time for platen-cycling to produce a bale varied from 6.4 minutes to 3.8 minutes, and for pile-working varied from 5.7 minutes to 3.9 minutes (Table 3). The percentage of time for slashing during production of bale 1 and bale 3 was 4.0 min while the percentage of time for slashing during production of bale 2 was 3.9 minutes.

Table 2. Measured work element time, percent time for each bale, and totals for each bale and work element.

	Bale 1		Bale 2		Bale 3		
Work element	mm:ss	percent	mm:ss	percent	mm:ss	percent	Total
Platen cycling	04:41	21.1%	03:46	19.8%	06:25	30.4%	14:52
Pile working	05:43	25.8%	04:52	25.5%	03:51	18.2%	14:26
Slashing	04:01	18.1%	03:53	20.4%	04:01	19.0%	11:55
Pile to baler	02:49	12.7%	02:09	11.3%	01:57	9.2%	06:55
Place in chamber	01:25	6.4%	01:16	6.6%	01:26	6.8%	04:07
Rotating	01:20	6.0%	01:40	8.7%	00:56	4.4%	03:56
Packing	01:34	7.1%	00:35	3.1%	01:34	7.4%	03:43
Move baler	00:36	2.7%	00:25	2.2%	00:25	2.0%	01:26
Break	00:00	0.0%	00:28	2.4%	00:33	2.6%	01:01
Total Time	22:09	100.0%	19:04	100.0%	21:08	100.0%	1:02:21

The primary work elements accounted for 66.0% of productive machine hours. The proportions of the primary work elements accounted for 23.8%, 23.1%, and 19.1% (Table 3).

Table 3. Work element measured average of total production time, measured percentage of total production time, which was calculated using total work element production time over total production time (average of 3 replications), SD=standard deviation, average measured production time in decimal minutes and total time including finishing and estimated bales per day.

	Average of total time (for 3 reps)			Average bale minutes	
Work element	mm:ss	percent	SD		SD
Platen cycling	04:57	23.8%	5.8%	4.9	1.2
Pile working	04:49	23.1%	4.3%	4.8	0.9
Slashing	03:58	19.1%	1.1%	4.0	0.2
Pile to baler	02:18	11.1%	1.8%	2.3	0.4
Place in chamber	01:22	6.6%	0.2%	1.4	0.0
Rotating	01:19	6.3%	2.2%	1.3	0.5
Packing	01:14	6.0%	2.4%	1.2	0.5
Move baler	00:29	2.3%	0.4%	0.5	0.1
Break	00:20	1.6%	1.5%	0.3	0.3
Total	20:47			20.8	4.1
			finishing	13.0	
		min/dy	total	33.8	
		440.0	8 hr day	13.0	bales

Discussion

Operator-specific variance due to experience, coordination, skill, and other factors were mitigated by only using one operator for this study. Platen cycling time is a direct function of engine power and available hydraulic flow. Cycle time of the prototype baler was limited by the small engine used on the baler and limited hydraulic flow to the platen cylinders.

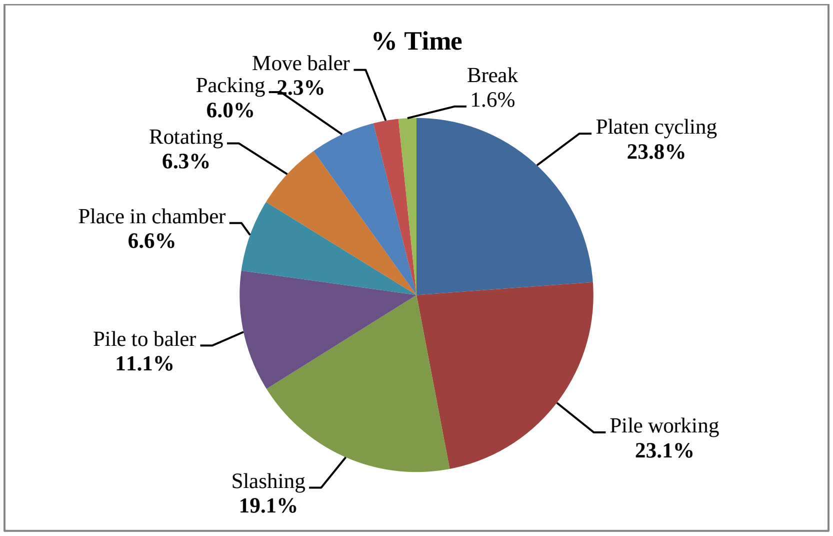

Figure 2. Work elements expressed as a percentage of total bale production time (average of 3 replications).

The pie chart above displays the same results that are in Table 3 in a format that facilitates discussion of results and potential improvements.

Platen cycling was among the three most time-consuming work elements for the prototype baler. The range of baling times from 3.8 to 6.4 minutes per bale can be explained by the number of platen cycles used to make each bale. Individual platen cycle times were in the range of 1.2 minutes and full bales were made in 3-5 platen cycles. Each platen cycle produces a compressed “flake” much like agricultural bales. The amount of material in a forest residuals flake is dependent on whether grapple loads are primarily fine branches and brush that can be packed into the compression chamber by the loader or less-compressible wood chunks, broken log sections, and tops.

Increasing the hydraulic power and flow may reduce the platen cycle time from 1.2 minutes per cycle to a much-faster 0.5 minutes per cycle. However, reducing the cycle time by two-thirds will only result in an improvement of 2-3 bales per workday since no other work element was limited by available hydraulic flow. Careful engineering and operations analyses will need to assess the trade-off between higher fuel consumption, higher capital cost, and potentially limited increased productivity resulting from larger engines. However, if biomass arrangement can be improved, as in the Rummer et al. (2004) study, and large, well-organized windrows can be prepared by the harvesting crew, then gains from faster platen cycling may justify higher engine power.

Upgrades to the 2009 urban biomass baler for use with forest residuals included adding a hydraulic slashing saw to eliminate the need for a ground crew and to improve worker safety. Slashing with a hydraulic chainsaw attached to the baler infeed consumed a nearly identical percentage of time as was measured in the 2009 study when ground crews with chainsaws did the slashing (Dooley et al. 2009). Observation of video from the earlier and present studies suggests that slashing times are similar. Thus, the primary gains from addition of the slashing saw onto the baler are improved worker safety and reduced crew size.

Slashing time for the forest residuals accounted for approximately 19% of the baling time. Conifer branches and tops averaged more than three meters in length. Nearly every grapple of biomass needed to be trimmed from one or both ends to fit into the 1.22-meter-wide baler infeed opening. If a bunch of branches were all oriented with the large end to one side of the grapple, that end could be cut off and then the branch-tip material could be folded over into the baling chamber to reduce the number of slashing events. However, good biomass organization was rare at the study site.

This study focused on the collection of woody biomass from forest residuals. The results are likely to be applicable to other woody biomass produced from urban vegetation management, land-clearing, highway and utility construction, and agricultural residues. It is expected that results will be directly applicable to collection of vine and orchard residues for energy production, biofuels, and bioproducts (Torquati et al. 2016).

Conclusions

A prototype woody biomass baler was used to gather and densify forest residuals into large rectangular bales to enable lower cost transport and storage. Forest residual biomass after commercial harvest in a conifer forest was concentrated by the logging contractor along unpaved roads within the harvest unit. No special effort was made to arrange the material for subsequent collection and handling.

An experienced operator produced three bales from similar materials in a single operating session while being observed and video-recorded. Digital video was analyzed by a trained technician to quantify work element times, operating sequences, and time distribution using both direct time measurement and moment methods. Primary work elements were baler platen cycling (24%), pile working and grappling (23%), and slashing (19%). Average gross baling time of 19-22 minutes per bale suggests a daily production rate of 10-13 bales per shift.

Productivity could be improved by improved biomass organization during the logging operation and by increasing the hydraulic flows available to the baler platen cylinders. Specific work element data and system simulations produced during this study may inform designers of future commercial forestry balers as they make trade-offs of power, weight, manufacturing cost, and productivity.

Geolocation Information

The baling time studies were conducted in the Pacific Northwest region of the United States in Washington State. GPS coordinates for the location of study in Easton, WA USA are 47°22'16.0"N and 121°24'04.6"W. In decimal degrees the latitude of the location is 47.371111, and the longitude is -121.401278.

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