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An ASABE Meeting Presentation
DOI: 10.13031/aim.20
Paper Number: 162455264

Conceptual Specification of Forest Utility Balers for Woody Biomass

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Written for presentation at the
2016 ASABE Annual International Meeting
Sponsored by ASABE
Orlando, Florida
July 17-20, 2016

Abstract.

A new class of modular woody biomass baler is designed to maximize recovery of forest residuals from small/remote/stranded landings, scattered roadside windrows and piles, thinnings from hand crews, and forest management prunings. The baler module is designed to be incorporated onto a wide range of undercarriages and prime movers. The baler module can be mounted on and powered by a forestry log forwarder when in-woods mobility is needed. Such configuration takes advantage of the forwarder's mobility, onboard log crane, and hydraulic power capacity. Balers may also be mounted on highway or forestry trailers, with self-contained power and loading. The bale size for the utility baler was established to be easily lifted by small-log loaders, skid-steer loaders with forks, and the like.

Keywords. *Bale, baler, densification, biomass, feedstock supply, logistics, forest engineering, energy.*

Introduction

Forest residual biomass represents a large untapped resource of cellulosic feedstocks for conversion into biofuels and bio-based products. Although millions of tonnes per year are available at low or negative price, the costs for collection, transport, and comminution generally exceed the value to bioenergy and bio-based products producers. Baling and bundling have been proposed as methods to convert loose-bulky tops, branches, and brush into a higher density and more easily handled form. Improved bulk density reduces both the transport and storage costs. Baling and bundling also improve throughput of grinders used for comminution at the point of biomass use.

Substantial research and development in Europe and North America has focused on bundling of residuals into round log-shaped units that can easily be handled with existing log forwarders and log trucks (Pottie & Guimier, 1986; Timperi, 2002). More recently, new bundler-type machine systems have been introduced in Europe (Forbes, Easson, Fairgrieve, Wilson, & Olave, 2014; Nuutinen & Björheden, 2016). While bundlers are technically effective for densifying forest residuals for hauling with pulpwood trucks, they have proven uneconomical in most situations.

Baling of forest residuals into large rectangular bales was explored by Dr. Bill Stuart at Virginia Tech in 1978 (Stuart & Walbridge, 1978; Walbridge & Stuart, 1981). Further research was conducted by Dr. Peter Schiess at the University of Washington in 1982 as a response to the energy crisis of the time (Schiess & Stuart, 1983; Schiess & Yonaka, 1982). The attractiveness of rectangular bales over bundles is that bales can be handled with conventional agricultural bale stackers and hauled on hay trucks. Unfortunately, neither program advanced beyond the conceptual and experimental stage.

Beginning in 2002, Forest Concepts assessed the problem of forest residuals and urban woody biomass collection, transport, from a complex social, technical, and operational systems perspective. That effort, with partial funding from USDA NIFA SBIR program concluded that large rectangular bales would be much preferred over bundles (Dooley, Fridley, DeTray, & Lanning, 2006). Forest Concepts' earlier development of mobile woody biomass balers was focused on street-legal "chipper replacement" balers for use in urban and rural environs. That work is documented in a number of publications (Dooley, Lanning, & Lanning, 2011; Dooley, Lanning, Lanning, & Fridley, 2008; Dooley, Lanning, Lanning, Broderick, & Fridley, 2009). The earlier work was also the subject of five United States Patents (798776, 7992491, 8205546, 8850970, and 8925451) directly related to baling of woody biomass.

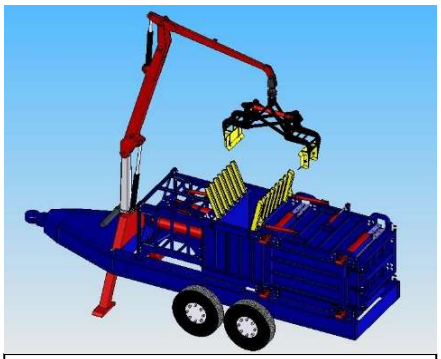

Figure 1. Concept rendering of forest utility baler on straight trailer and with 17-ft reach self-loader.

The work reported in this paper is part of a recent effort to apply the Forest Concepts woody biomass baling technologies to a specific application within forest residuals collection. The research team at Humboldt State University, under the direction of Dr. Han-Sup Han, has found that the utility of forest residuals can be maximized when the material is first sorted in the woods at the time of harvest or through merchandising of slash piles (Bisson & Han, 2016; Bisson, Han, & Han, 2013; Kizha & Han, 2015). They recommend that sub-merchantable poles be collected and hauled as roundwood to centralized chipping sites. This left tops, branches, and brush on-site. Fortunately, this fraction is much easier to bale than commingled logs and fine materials. Concurrently, a team led by Dr. John Sessions at Oregon State University came to parallel conclusions (Zamora-Cristales, Sessions, Boston, & Murphy, 2015; Zamora-Cristales, Sessions, Murphy, & Boston, 2013).

Forest Concepts was invited to participate as an industrial cooperator in an interagency Biomass Research and Development Initiative (BRDI) proposal led by Humboldt State University. The proposal included Dr. Sessions from Oregon State University and Dr. Jim Dooley from Forest Concepts as co-PIs. Once funded in 2014, Forest Concepts set out to define baler(s) that would be optimal for use in forest settings.

Overview

An objective of the Biomass Research and Development Initiative (BRDI) forest residues collection task team is to

conceptualize new versions of the Forest Concepts biomass baling technology that would be more optimal for use on large-scale logging operations in the western United States.

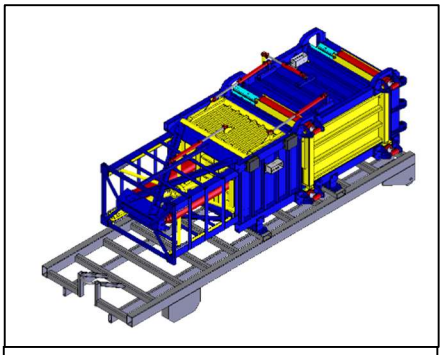

Figure 2. Concept rendering of forest utility baler module for installation on forwarder, truck chassis, hook lift skid, etc.

The new-concept biomass balers stem from recommendations of the forest engineering team at Humboldt State University to sort logging slash into poles that can be transported with conventional log trucks and into piles of finer tops and branches. While cost-effective collection and transport of small-diameter poles is well understood, handling and processing of branches and tops is problematic. Thus, the conventional forest management practice is to burn the piled fine woody biomass when weather conditions allow. Instead of burning the slash piles, the finer materials from slash including brush, tree tops and limbs can be ground into hog fuel on-site and transported in chip vans, or potentially can be baled by the envisioned new class of forestry balers for removal from the forest and processed into higher value products off-site.

Fine forest residuals are in three levels of concentration across a harvest unit (aka logging site). Some of the material is distributed across the landscape where it fell during harvest operations. Other material is concentrated within the unit or along roadsides either as small piles or low windrows. Very large piles (aka haystacks) and windrows are common at large centralized landings and processing sites within an active harvest unit. In most situations, the dispersed fine branches are left on-site to protect the soil, provide habitat values and decay to release nutrients for the next generation of the forest. Excess biomass is gathered by the logging crew into in-unit small piles, roadside debris windrows, and large roadside piles containing woody biomass that must be removed from the forest.

Figures 3. Forest residuals dispersed across ground and collected into in-unit piles (left); along roadsides (center), and at central landings/processing sites (right).

Forest Concepts uses the Appreciative Design Method to guide the development and specification of new products, processes, and equipment (Dooley & Fridley, 1996, 1998a, 1998b). The Appreciative Design Method merges elements of soft systems and social network analysis with traditional engineering design to establish functional requirements, operational objectives, and constraint sets that limit selection of design attributes and features.

We applied the appreciative design process to the problem of baling forest residuals during the first year of the BRDI project. We identified key stakeholders and documented what was important to them about biomass removal, forest operations, safety, logistics, and other criteria that resulted in a set of high-level requirements and specifications for forest residue balers (Dooley, Lanning, & Lanning, 2015a). That work also resulted in design and specification of bale sizes, densities, and weights (Dooley, 2015). The result of those analyses was that two substantially different baler “families” were needed to satisfy a bimodal distribution of forest operations constraints and centralized processing system constraints. A large-bale track-mounted self-propelled modular baler was defined and is detailed in a companion document (Dooley, Lanning, & Lanning, 2015c). This document details the conceptual specification and design elements of a general-purpose modular baler most suitable for baling of dispersed woody biomass along roads and in small piles. The modular baler may be mounted on a forwarder for off-road use within units to collect excess forest residuals.

Earlier stakeholder-driven requirements for forest balers (Dooley et al., 2015a) were used to guide the top-level specification of both the forest utility baler (Dooley, Lanning, & Lanning, 2015b) and the larger self-propelled grinder-replacement baler (Dooley et al., 2015c). Primary differences from design requirements document for the street-legal urban biomass baler are:

- Eliminate all ground crew members and ground based chainsaw slashing.
- Reduce baling cycle times to increase production rates. Note that urban balers supporting arborist and landscape crews only need to keep up with the hand crew. Forest balers with a single operator are not subject to the same limitations.
- Make the baler more modular to enable mounting on forwarders, all-wheel-drive truck chassis, or on trailers of various types.

The type of woody biomass subjected to baling is very similar for both forest residuals and urban woody biomass as a result of the merchandising/sorting recommendations made by the Humboldt State team (Bisson & Han, 2016; Kiza, Han, Montgomery, & Hohl, 2015; Kizha & Han, 2015). The materials range from small, short brushy material to several-meter long branches and tops. Most of the material is small diameter less than 150 mm diameter.

Forest Utility Baler Specifications

The forest utility modular woody biomass baler is designed to maximize recovery of forest residuals from small/remote/stranded landings, scattered roadside windrows and piles, thinnings from hand crews, and forest management prunings.

The baler module is designed to be incorporated onto a wide range of undercarriages and prime movers. The baler module can be mounted on (and powered by) a forestry log forwarder when in-woods mobility is needed. Such configuration takes advantage of the forwarder's mobility, onboard log crane, and hydraulic power capacity.

In other configurations, the baler module can be paired with an optional engine/hydraulic power-pack and a small-log loader for stand-alone use on a trailer frame or truck chassis as shown in Figure 3.

Modularity particularly enables users to minimize capital by mounting the baler on existing forwarders, truck chassis, or trailers. When use is seasonal due to markets, fire, snow, etc., the baler can be removed to free the prime mover for other uses.

Figure 4. Forest Concepts' engineering prototype forest utility baler collecting forest residuals from roadside windrows on Snoqualmie National Forest.

The 800x1220x1420 mm (32x48x56-inch) high density bale produced by the forest utility baler is designed to maximize trucking payload, minimize bale yard requirements, and be handled by lightweight skid-steer loaders as well as conventional agricultural bale handling equipment. Each bale is expected to weigh between 400 – 550 kg (900 and 1,200 pounds) depending on moisture content. The bale weight specification is constrained in-part by lifting limits for skid-steer loaders used in the forestry and vegetation management industries.

The baler infeed is approximately 1220 mm (48-inches) wide to maximize piece length that can be loaded without slashing. The compression direction is parallel to the 1420 mm (56-inch) bale dimension to maximize bale density. Productivity will be enhanced by inclusion of an automated wire-tie system that will reduce the tying time to approximately 30 seconds compared to five minutes for manual tying.

An on-board hydraulic chain-type slashing saw eliminates the need for chainsaw operators on the ground and to minimize the need for slashing of residuals during the harvesting operation. Although we believe the base-model will have one slashing saw, saws on both sides of the baler infeed opening may be a preferred option for some firms. For those users that have and/or prefer grapple loaders with slashing saws, the baler's on-board saw can be deleted.

Environmental and sustainablility features that can be incorporated into the baler include:

- Regenerative hydraulic system to reduce fuel consumption.
- Bio-based hydraulic oil that has low environmental footprint and non-hazardous spill risk.
- Tier-4 engine and emissions control system to anticipate future air quality regulations.
- Pressurized and automated fire suppression system when a self-contained engine and hydraulic power pack is incorporated into the baler system.

The forest utility baler module is specified as a commercial version of the engineering prototype currently in use by Forest Concepts. The performance and components included in this section of the design report represent the engineering team's current thinking about commercially available components and configurations.

The baler will be designed with side-eject and auto-tie around the 800x1420 mm direction similar to the engineering prototype. The baler module will include mounting plates to enable commercially available auto-tie or strapping systems to be installed from Signode, Cranston, L&P, Accent, etc. The side ejection will release the finished bale on the same side as the loader operates to enable rapid handling of bales by the loader. In operation, the loader will be picking and placing a finished bale onto a trailer or stack while the baler ejection door is closing and the platen is recycling to start the next bale cycle.

- Infeed opening: 1060 x 1220 mm (42-inches by 48-inches)
    - Infeed grates are of the patented Forest Concepts design
- Platen dimensions: 800 x 1220 mm (32-inches tall by 48-inches) +/- wide
- Platen hydraulic force: 623,000 Newtons (140,000 pounds-force)
- Platen and ejection hydraulic cylinders: double acting telescoping cylinders
- Baler module estimated weight: 5,500 kg (12,000 lbs) (Transport weight of the baler module itself excluding power pack, grapple loader, trailer, etc. estimated below)

A detailed conceptual design document is available as a work-product of the BRDI project (Dooley et al., 2015b).

Forest Utility Baler Field Trial Results

The prototype forest utility baler has undergone several field trials in the Pacific Northwest. One of the trials was conducted on the Snoqualmie National Forest near the Snoqualmie ski areas. The logging project was a forest thinning with removal of merchantable logs. Whole-tree logs were cable-skidded to roadside with a highly mobile small tower system. Tops and branches were removed at roadside and piled for grinding or windrowed along the road. The Forest Concepts prototype baler was used to bale a roadside windrow in this study.

The trial was filmed by two video cameras at different viewpoints and an observer logged significant events, start/stop times, and bale handling times. The video was first used to refine a list of work elements and train an observer to detect the start and stop points for each work element. It was then replayed with the video-observer logging the start and end points for each work element on an Excel® spreadsheet. The spreadsheet was programmed to calculate work element times, work element sequences, and produce summary data and graphics.

Figure 5. Forest residuals bales produced by utility baler from roadside windrows on Snoqualmie National Forest.

The primary analysis unit was each bale produced beginning with setting of the baler stabilizer feet and ending with the "full bale" signal and beginning of bale handling. Work elements were derived from earlier studies of bundlers and grinders (Bergström, Di Fulvio, & Nuutinen, 2016; Conrad Iv, Bolding, Aust, Smith, & Horcher, 2013; Facello, Cavallo, Magagnotti, Paletto, & Spinelli, 2013; Forbes et al., 2014; Lehtimäki & Nurmi, 2011; Manzone, 2015; Melemez, Tunay, & Emir, 2014; Nuutinen & Björheden, 2016; Vitorelo, Han, & Elliot, 2012). The work elements used in this study are listed in Appendix 1 at the end of this paper.

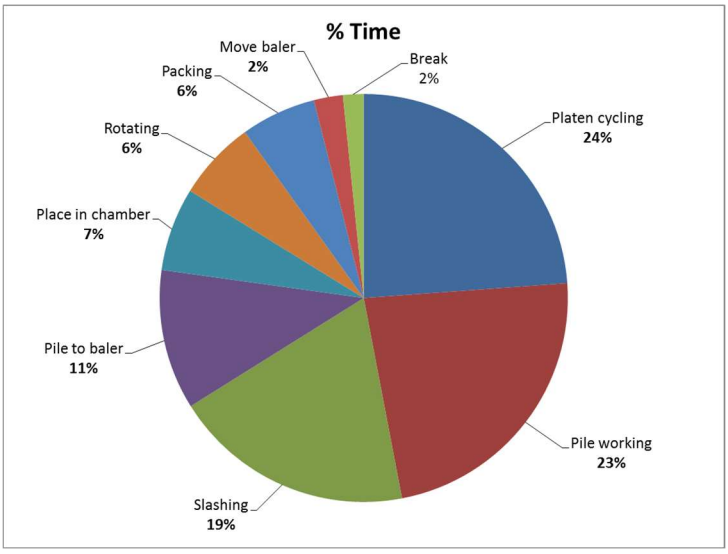

Figure 6. Allocation of work elements to the time for producing bales of forest residuals in August 2015 study.

The pie chart shows that slashing, platen cycling and pile working account for 2/3 of the total time per bale. Slashing of long material by the baler operator is higher than we found in the urban baler due to the fact that there is no ground-crew with chainsaws to shorten material as it is gathered. Pile working accounts for nearly 25% of the time. Pile working is similar to findings by others for feeding of in-woods grinders and bundlers. Platen cycling was reduced in the BRDI prototype baler, but obviously could be reduced further with higher power hydraulic units.

Conclusion

The Forest Concepts woody biomass baler design was revised to meet stakeholder-driven objectives and constraints for baling forest residuals. Incorporation of an on-board slashing saw eliminated all need for a ground-crew, but decreased baler productivity somewhat. Pile working with the grapple-loader remains a large component of baling time, but is similar to the time reported by others for bundling and in-woods grinding. While platen cycle-time was greatly improved compared to the earlier urban baler, it remains a significant factor in baling productivity.

The baler proved very effective and technically capable of baling woody biomass from logging sites, and particularly effective for sorted biomass as suggested by others on the BRDI feedstocks team.

Acknowledgements

This material is based upon work supported by a grant from the U.S. Department of Energy under the Biomass Research and Development Initiative program: Award Number DE-EE0006297.

Innovative designs, engineering data, and inventions disclosed in this report are the subject of provisional US Patent Application(s) filed by Forest Concepts, LLC under provisions of the Bayh-Dole Act of 1980 and other federal regulations.

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Appendix 1. Work Elements for Assessing Forest Baler Productivity

Work Element (Activity)	Description	
Accessing and leaving forest	Time from when the equipment leaves public road into forest to stopping at first site of the day. Time to leave forest at end of day. Record distance moved.	
Moving - 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 /prepare to bale	Time from arriving at a baling site or pile and actually 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.	
Pulling pile apart / Arranging slash / Re-bunching	Handling of slash to pull pile apart or gather slash into reasonable grapple loads	
Loading bale chamber	Begins when the boom moves to grasp the residues/slash and ends when it releases them into the baling chamber infeed. Does NOT include waiting for slashing saw to cycle.	
Slashing grapple load	Begins when operator lets go of boom controls to cycle slashing saw and ends when hands go back to boom controls.	
Packing	Begins when the operator closes the grapple and uses it to pack biomass into the baling chamber. May include using the grapple to rejigger material in baler.	
Baler Cycling	Begins when the grates begin to close and ends when they open for next push or the full bale indicator happens.	
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.	
Saw Maintenance & repair	Fixing, tightening chain, chain off bar resetting, etc. List reason with time.	
Baler Maintenance & 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 off of trailer. Includes time to clean debris off of 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.	
other	Time and work elements that do not belong to the above categories.	