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Innovative Solutions for Bioenergy and the Environment

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Design of a Forest Residue Baler – BRDI Task 2.2 (Public)

Specification of Bale Dimensions

Statement of Problem or Functional Requirement:

Forest residual biomass (aka logging slash), comprised of branches, tops, and stem sections left on the landing after harvest needs to be removed from the site and delivered to in-woods or near-woods centralized storage and processing sites. Pole-like stem sections longer than about eight-feet will be sorted from the residuals and hauled in dump or log trucks. The remainder needs to be baled.

A baler needs to be designed that compacts the tops and branches into rectangular bales that deliver the following benefits in the biomass supply chain:

- Achieve a truck-transport bulk density that minimizes the fossil fuel used to transport biomass from a landing to central processing site which may be 2-20 miles distant. Bales are expected to enable full legal payloads on conventional flat-bed trucks and tractor-trailer units.
- Enable rapid loading, unloading, and handling of biomass. Bales are perceived to be efficient packages that are self-stable after tying with twine, wire, or strapping. A bale is expected to contain significantly more biomass than can be grappled from loose or ground biomass.
- Enable high density, space-efficient storage on landings prior to hauling and at central processing sites. Bales are perceived to be prismatic with high stacking strength, regular dimensions, and sufficient durability to be stackable after handling, transport, and long-term storage.
- Enable efficient and high throughput grinding at central processing sites. Bales that are properly sized to match with fleets of grinders are perceived to be very labor-efficient to place onto the infeed of grinders and maintain full loading of infeed conveyors.

Constraints on the Design Space:

1. We are constraining the solution by California highway transport regulations for trucks and tractor-trailers.
2. A loader with grapple is part of the baler system. The grapple loader will be used for bale handling within the forest and loading bales onto trucks. The loader and grapple may be either self-propelled or integral to the baler machine.
3. Bale handling and stacking at a centralized storage and processing site will be with conventional machinery as used in the hay and biomass industries. No new equipment should need to be invented for handling and processing the forest biomass bales.

4. Bales must be able to be fed into one or more current models of Peterson brand horizontal grinders without breaking the bale.
5. The baler itself will be designed around (constrained by) the preferred bale dimensions and bale density.

Order of Design Decisions

Our Appreciative Design (AD) method (Dooley & Fridley, 1996, 1998a, 1998b) avoids the problem of solving for a global optimal specification of all design features at once. Appreciative Design is predicated upon parsing a design problem into a logical order for establishing functional requirements and associated constraints. Design features (such as bale size, allowable total weight, cut-to-length system) chosen during each sequential stage of design become conditional constraints further into the process.

Just as we did with our earlier USDA-funded development of a street-legal chipper-replacement baler (USDA SBIR Agreement 2006-33610-17595), we will start with the design of biomass bales (D. N. Lanning, Dooley, DeTray, & Lanning, 2007). Bale dimensions, weight, and density will then become constraints as we establish required platen pressure, hydraulic capacity, basic baler configuration, etc. (Dooley, Lanning, & Lanning, 2011; Dooley, Lanning, Lanning, & Fridley, 2008; Dooley, Lanning, Lanning, Broderick, & Fridley, 2009).

Truck/trailer Constraints

This constraint is "owned" by the trucking firms that deliver baled biomass on public highways.

The current commercial semi-trailer size limits for California are 48-ft length (14.63 m) x 102-inches width (2.60 m) x 13.5 ft total height (4.11 m). If we allow for a trailer deck height of 4.5 ft, then the maximum payload height is 9-ft. Although the maximum legal payload height is 9-ft, we will target a maximum of 8-ft for our design purposes. This would allow for "straggler" sticks extending above the top surface of stacked bales. Although the current maximum payload width is 102-inches, a majority of the flatbed trailers in use in the western U.S. are 96-inches wide, which was the previous standard.

The payload weight limit for California is typically 44,000 – 48,000 lb (20,000 – 21,800 kg) for 48-ft long trailers depending on the specific truck/trailer configuration and trailer construction. Although weight limits are constraining to the total payload, if we bale to densities higher than about 15.6 lb/ft^3 (250 kg/m^3), the effect will be that fewer bales are carried per truckload and a portion of the deck will be unused.

We have some support from other Task 2 participants for not constraining upper bale density in this BRDI project to enable very high payload hauling on private non-public forest roads to central processing sites. High density bales may be efficiently hauled on all-wheel-drive straight trucks or on short-deck trailers pulled by all-wheel-drive truck-tractors.

In any event, we would like the bale dimensions and bale density to be sufficient to effectively use the volume available on highway-legal 48-ft trailers.

Bale shedding of chunks and debris is a liability for bales hauled on public highways. Trailers should be tarped, Connestoga-type trailers, or have side panels added to minimize debris-shedding risks. Design of the bales and bale-tie systems should help to minimize shedding during handling and transport.

Grinder Constraints

For the purposes of this BRDI project, bale grinder constraints are "owned" by our grinder manufacturing partner Peterson Pacific Corporation (an ASTEC company), and by our conversion team. They will specify the production rate for grinding bales just-in-time for use in their conversion process equipment.

There are currently two operational scenarios for grinding of baled forest residuals.

- One scenario is that baled biomass is stacked and stored until it is needed for conversion. Bales will be taken from storage (aka bale stacks) and ground for immediate use in one or more of the conversion systems. In the current distributed processing scheme envisioned by the BRDI project, the demand for biomass would likely be only 2-10 tons per hour.
- The other scenario is that baled biomass is transported, stacked and stored at a central processing yard where it is ground to a user specification and reloaded into chip trucks for delivery to conversion and biopower facilities. When the end user is a biomass power plant, the desired rate of grinding would be limited only by the availability of chip trucks for hauling. In this case, the expected grinding production rates would likely be in the 40-100 tons per hour.

From our earlier bale processing work, there is a strong preference among baled biomass processors (constraint) for feeding biomass bales directly into horizontal grinders without a need to break the bale first. Thus, bale height and one other dimension may be constrained by the infeed dimensions of select models of Peterson's horizontal grinders. Although Peterson offers higher optional infeed heights, we are limiting our discussion to their standard infeed dimensions.

Table 1. Infeed openings of current model Peterson® horizontal grinders (from Peterson literature)

Peterson	Infeed		Comments
Horizontal Grinder Model	Width(in)	Height (in)	
2700C, 2710C	60 ¾	32	
4700B, 4710B	60	37 1/2	
5700C, 5710C	60	40	
6700B	66	50	

Table of Candidate Bale Dimensions, Density, Bale Weights, and Truck Payloads

It is axiomatic in agricultural baling that the ideal bale configuration would simultaneously fully load a hauling truck or trailer at both volumetric and payload capacity. However, in forestry baling the optimal situation is not quite so clear. Particular to the BRDI project where centralized in-woods processing is envisioned, bales may be hauled exclusively on private roads not subject to state load size and weight regulations. Another element of the BRDI project where longer distance hauling is necessary, the concept includes decoupling of in-woods hauling from highway hauling at a reload point at or near the highway entrance. Since in-woods hauling is at very low travel speeds, there may be an economic benefit to using high payload trucks or trailers for the in-woods portion of the transport system. In that case, high density bales might be more "system-optimal" even though the on-highway trucking is necessarily at less than full volumetric payload. Given this discussion, optimal bale sizes would still need to be able to be arranged on highway-legal trucks/semi-trailers within the regulatory constraints of width, height, and trailer length.

Logical bale heights range from 30 to 48 inches. The selection of bale height may limit the Peterson horizontal grinder models that can be used at central processing sites to process baled forest residuals into feedstock. The table includes "cotton module" 96-inch high and wide compressed bales for completeness since those sizes are being explored by Texas A&M (An & Searcy, 2012; Searcy, Hartley, & Thomasson, 2014) for use with energy crops and mesquite woody biomass. The modules require specialized hauling and handling equipment (much of which exists only in the Texas cotton industry) and a need to be broken down into loose biomass for feeding into grinders. Thus, we will not consider module-sized bales further in this project.

One other bale dimension (either length or width) is set to be divisible into the trailer net width of 96-inches. We are using the 96-inch width as our target since this enables use of legacy 96-inch wide truck and trailers, as well as allows for inevitable bale bulge and straggler pieces that extend out the sides of a loaded set of bales. (We are assuming that loads are tarped when transporting on public highways.)

In order to feed bales into Peterson horizontal grinders without breaking the bale, either the bale width or length must be smaller than the infeed width of a current-model Peterson grinder – constrained to be less than 60-inches for most machines and less than 66 inches for the largest Peterson grinder.

We are assuming that bales can be loaded onto a grinder either length or width orientation, whichever better utilizes the allowable infeed width of the grinder. We do not believe that there is a constraint on any bale's longest dimension along the infeed of a grinder. In many of the plausible bale sizes, one dimension is 48-inches to enable stacking two-bales wide on trucks/trailers. Such dimensions underutilize the full feed-width of current Peterson grinders. However, experience with grinding bales suggests that the material quickly spreads out to fully occupy the grinding head as it feeds into the grinding chamber. Thus, the only consequence of "narrow" bales is that more bales would need to be fed per oven dry ton (odt) than for bales that use the full width.

Table 2. Plausible set of bale dimensions when constrained by truck dimensional payload and Peterson grinder infeed. Preferred bale sizes are highlighted in yellow.

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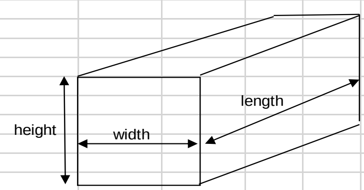
Candidate Forest Residual Bale Dimensions

Constraints
48-ft California semi-trailer (potential for 24-ft in-woods AWD flatbed truck)
fill 9x8x48 volume
stack in units or interweave
load with grapple
unload with grapple, fork lift, or bale squeeze



			Payload dimensions (in)					Bale Wt. (lb)			Truckload Payload (lb)			Truckload Payload(tons)		
		=48 or 96	108	96	576		Bale	Bale Density (lb/cu. Ft)			Bale Density (lb/cu. Ft)			Bale Density (lb/cu. Ft)		
height (in)	length (in)	width (in)	bales high	Bales wide	bales long	Bales/Trk	Vol (cu. Ft.)	30	23	15	30	23	15	30	23	15
30	40	48	3	2	14	84	33.3	1,000	767	500	84,000	64,400	42,000	42	32	21
30	48	96	3	1	12	36	80.0	2,400	1,840	1,200	86,400	66,240	43,200	43	33	22
32	44	48	3	2	13	78	39.1	1,173	900	587	91,520	70,165	45,760	46	35	23
32	48	48	3	2	12	72	42.7	1,280	981	640	92,160	70,656	46,080	46	35	23
32	**56**	**48**	**3**	**2**	**10**	**60**	**49.8**	**1,493**	**1,145**	**747**	**89,600**	**68,693**	**44,800**	**45**	**34**	**22**
32	64	48	3	2	9	54	56.9	1,707	1,308	853	92,160	70,656	46,080	46	35	23
32	72	48	3	2	8	48	64.0	1,920	1,472	960	92,160	70,656	46,080	46	35	23
32	82	48	3	2	7	42	72.9	2,187	1,676	1,093	91,840	70,411	45,920	46	35	23
32	82	96	3	1	7	21	145.8	4,373	3,353	2,187	91,840	70,411	45,920	46	35	23
34.4	96	47.2	3	2	6	36.61	90.2	2,706	2,075	1,353	99,072	75,955	49,536	50	38	25
34	**96**	**48**	**3**	**2**	**6**	**36**	**90.7**	**2,720**	**2,085**	**1,360**	**97,920**	**75,072**	**48,960**	**49**	**38**	**24**
36	72	48	3	2	8	48	72.0	2,160	1,656	1,080	103,680	79,488	51,840	52	40	26
36	82	96	3	1	7	21	164.0	4,920	3,772	2,460	103,320	79,212	51,660	52	40	26
36	96	48	3	2	6	36	96.0	2,880	2,208	1,440	103,680	79,488	51,840	52	40	26
40	48	48	2	2	12	48	53.3	1,600	1,227	800	76,800	58,880	38,400	38	29	19
40	56	48	2	2	10	40	62.2	1,867	1,431	933	74,667	57,244	37,333	37	29	19
40	84	48	2	2	6	24	93.3	2,800	2,147	1,400	67,200	51,520	33,600	34	26	17
40	96	48	2	2	6	24	106.7	3,200	2,453	1,600	76,800	58,880	38,400	38	29	19
48	84	48	2	2	6	24	112.0	3,360	2,576	1,680	80,640	61,824	40,320	40	31	20
48	96	48	2	2	6	24	128.0	3,840	2,944	1,920	92,160	70,656	46,080	46	35	23
96	96	96	1	1	6	6	512.0		11,776	7,680		70,656	46,080	-	35	23
96	192	96	1	1	3	3	1024.0		23,552	15,360		70,656	46,080	-	35	23

At the moment, we are not necessarily establishing target bale bulk density and resulting bale weight. In earlier experiments, the Forest Concepts engineering prototype woody biomass baler produced bales up to 30 lb/ft^3 with green residuals, and up to 23 lb/ft^3 for field-dry residuals. We are including in the table a bale density of 15 lb/ft^3 which would result in a semi-trailer payload of approximately 20-23 tons, typical of allowable payloads on steel or aluminum trailers in California. The higher payloads may be allowable under situations where hauling is entirely on private forest road systems from the location of baling to centralized biomass processing sites. The design of the baler will have a capability to produce bales having a green bulk density of up to 30 lb/ft^3 with green residuals. Lower density can be attained by lowering the platen pressure when needed for a particular hauling scenario or to reduce the LCA fuel consumption of a baler.

We are also not constraining the bale dimensions and weight by potential limitations of biomass track-loaders using brush grapples. Gripping capabilities and lifting capacity constraints for loaders used across the forest operations sector are assumed to be sufficient for all bales being considered.

The bale dimensions in the table are arranged by bale height with selections to fit existing Peterson grinder infeed limits and to be stackable on flatbed trucks or trailers. Bale lengths are suggested with much more latitude since grinders do not have a length constraint. Bale width is generally set at either 48 or 96-inches to fully utilize the width of truck beds and to enable safe tie-down.

Bale length and width as used here are not necessarily associated with the direction that bale ties or strapping is placed. Neither is bale length necessarily the predominant alignment of branches and stems in a bale. The baler infeed may be 48-inches wide as is the case for the engineering prototype, or could be 84 or even 96-inches wide in a new forest residuals baler. The case for a wider baler infeed width includes lesser demands for biomass slashing and potentially fewer grapple loads to make a bale. A discussion with Mr. Larry Cumming from Peterson (2014 per. comm.) suggests that orientation of branches and tops does not affect grinder performance of resulting feedstock particle geometry.

Slashing long branches and stems to fit into the baler can be accomplished ahead of baling during the sorting operation, with a slashing-type grapple loader, or on the baler itself. Since relatively few grapple loaders used in the forest industry have slashing saws, we are planning to include an on-board chainsaw-type cut-off saw or shear on the forest residuals baler (C. J. Lanning & Lanning, 2015).

Earlier work by Forest Concepts (Lanning 2007), and in the agricultural baler industry suggest that bales hold their shape better if they are more rectangular than square in the dimension the ties run. Thus, a bale that is 34-inches tall and 48-inches along the tie direction would be considered a better bale design than one that is 48x48.

The yellow highlighted rows in the table are preferred bale sizes (as discussed and debated by Forest Concepts) under infeed constraints of various models of Peterson grinders and constrained by truckloads. However, at this point, the Forest Concepts team considers all of the bale sizes shown in the table to be producible.

At any bale size, the bale density is a function of the moisture of the raw biomass and the compaction pressure used to form the bale. As noted earlier, bale densities of approximately 15 lb/ft^3 will concurrently achieve both cube and weight limits for 48-ft highway trailers. Thus, we use that density as a lower constraint limit. However, even though they take more compressive energy to make, higher density bales take less space to store, hit payload with fewer bales to handle, enable very high payload hauling on forest roads, and may consume less bale tying material per ton. On the other hand, higher density bales will be slower to dry under natural air conditions.

Immediately evident from the table is the range of potential bale weights and truck payloads. At higher bale densities, full legal weight payloads are achievable with relatively “inefficient” volumetric payloads. Thus, a key point of discussion among the economic and LCA task teams needs to be the tradeoff of smaller, more easily handled bales, with the increased compaction energy needed to make high density bales. Later in the design effort, we will be develop an equation for baler fuel consumption (carbon emissions) as a function of bale density.

We are not constraining bale dimensions to fit any particular loader/grapple at this time. Discussions with other BRDI Task 2 team members suggest that existing grapple loaders used for forest biomass will be able to grip and lift all of the bales in our design table. At some later point in the design process, we will specify loaders for use with balers at logging sites. At that time, we may readdress the bale dimensions question with an additional constraint if relatively small loaders appear to have substantial economic and LCA benefits.

Rationale for the Two Bale Sizes Selected from the Table
We chose two bale sizes from the table of possibilities. A “small bale” was defined that can be ground by all current models of Peterson horizontal grinders, thus has a bale height of 32-inches and a bale length of less than 60-inches. The 48-inch bale width enables stacking two-wide on trucks and trailers. The recommended small-bale dimensions are 32-inches tall by 56-inches long by 48 inches wide. A “large bale” was defined to be similar to large rectangular agricultural hay bales which are nominally called 3x4x8 foot bales. The bale height dimension is somewhat smaller than three feet due to stacking limitations on highway-legal hay trucks. The recommended large-bale dimensions are 34-inches tall by 96-inches long by 48 inches wide. For clarification, the 96-inch dimension is produced across the baler platen, and the 48-inch width is in the compression dimension. The bales would be loaded on a truck with the 96-inch dimension along the truck bed in most cases. However, bales may be cross-stacked for hauling, handling with agricultural hay squeeze machines, or to create large bale stacks if needed.

The small bale is expected to contain approximately 750 pounds on a dry-weight basis and up to 1,500 pounds for green material at high density. The bale size is fairly close to that of the current Forest Concepts engineering prototype chipper-replacement baler, so the potential market for small-bale balers is an order of magnitude higher than for forestry balers. The larger market is likely to reduce the purchase cost of balers of this size by 30% or more compared to special purpose forestry balers.

The large bale is approximately twice the volume of the small bale, and thus represents half the units to handle, load, and process compared to small bales. In a major shift from conventional balers, we propose to use a platen that is 96-inches wide and 34-inches tall that compacts along the 48-inch dimension. This scheme has the potential to create bales that could migrate toward round “bundles” during handling if insufficient branchy material is not randomly oriented within the bale. However, this “wide/short bale” has a number of benefits:

- Branches and tops need only be slashed to the 96-inch length, which is likely to improve feed rates.
- Compression along the 48-inch dimension greatly reduces the volume of hydraulic oil used by compression cylinders, which is likely to increase production rates.
- Compression along the 48-inch dimension is likely to substantially reduce “spring-back” forces that may enable use of lighter tie material and lower cost for ties per ton.
- Other implications may reduce the overall length of a baler which will improve mobility.

There are likely to be many common components between the two sizes of baler. For example, we may be able to use the same main platen hydraulic cylinders on both machines by installing two on the small baler and four or five across the large baler. Other similarities in how the bale compression produces Poisson's forces will reduce engineering risk and design time.

Both balers will be top-loaded using the Forest Concepts patented infeed gate scheme (C. J. Lanning & Lanning, 2011, 2012) and use similar slashing saws on one end of the infeed for cutting over-length biomass (C. J. Lanning & Lanning, 2015). We expect that both balers will also fall within already-issued claims of Forest Concepts' woody biomass baling patents (D. N. Lanning, Dooley, Lanning, & Fridley, 2011, 2014).

Implications for Field Testing of Forest Concepts' Engineering Prototype

The Forest Concepts engineering prototype woody biomass baler currently produces a bale that is 32-inches high by 68 - 72-inches long and 48-inches wide. In earlier field trials sponsored by the NARA project and led by Dr. John Sessions, bale densities of up to 30 lb/ft^3 were attained. Thus, the existing prototype has the capability to make bales similar to the small bales specified for the BRDI project and "half-width" bales for the larger size.

We are considering reducing the bale chamber length to produce bales that are the same 48-inch compressed length as for the future baler. This would entail replacing a set of steel panels with new ones. We will likely still use side ejection for the finished bale. The new shorter bale compression length will enable more accurate measurement of platen force vs bale density and measurements of springback forces that constrain tying material.

Shorter bales will also result in more production of bales per day during the trials. More bales from limited number of days for field work will facilitate additional drying, handling, and grinding experiments.

Finally, shorter bales will be much lighter than those produced under the earlier NARA field trial. This will better enable lifting, handling, and stacking of finished bales with the Forest Concepts existing loader and grapple. The combination of shorter bales and easier handling may allow for production of 20-25 bales per field-day rather than the 12-15 achieved in the 2014 NARA field trial.

Summary and Conclusions:

Specification of bale dimensions, configuration, and density are among the first decision decisions to be made for the design of a new class of forest biomass balers. The engineering team at Forest Concepts updated earlier work on baling of urban woody biomass to the context of forest residuals and the BRDI project. Revised functional objectives and operational constraints resulted in a new bale size specification that should be near-optimal for the BRDI project context.

Two bale sizes are specified for further development. The recommended small-bale dimensions are 32-inches tall by 56-inches long by 48 inches wide. The small bale will weigh between 750 and 1,500 pounds depending on biomass moisture content and platen pressure. The recommended large-bale dimensions are 34-inches tall by 96-inches long by 48 inches wide. The large bale will weigh between 1,500 and 3,000 pounds depending on biomass moisture content and platen pressure. These bale sizes will be used in the next stage of baler design which entails both overall baler configuration and concurrent specification of hydraulic power packages.

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