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Evaluation of two round baling systems for harvesting understory biomass

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ABSTRACT

The objective of this study was to evaluate the performance and to estimate costs of two round baling systems for harvesting understory biomass. One system was a cutter-shredder-baler prototype (Bio-baler). The other system required two successive operations. The first operation was cutting and shredding with a Supertrak tractor equipped with a Fecon mulcher head. The second operation was baling with a Claas baler. The machines were evaluated in three different pine stands on the Osceola National Forest in Florida, United States. Data collection included time study, fuel consumption and bale measurements. Material was collected from a sample of bales for heat and moisture content determination. On the most representative site (Site 2), the Bio-baler recovered 8.05 green t ha^{-1} while the mulcher and the Claas baler recovered 9.75 green t ha^{-1} (43 and 52 percent of original understory biomass, respectively). Productivity was 0.30 ha h^{-1} for the Bio-baler and 0.51 ha h^{-1} for the Claas baler. Density of the bales was 321 green kg m^{-3} for the Bio-baler and 373 green kg m^{-3} for the Claas baler. Average net heat content was 6263 MJ bale^{-1} for the Bio-baler and 6695 MJ bale^{-1} for the Claas baler with biomass containing 38 percent of moisture content on a wet basis. Cost per unit area was less with the Bio-baler (US$320.91 ha^{-1}) than with the mulcher-baler system (US$336.62–US$596.77 ha^{-1}).

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1. Introduction

Historically, the occurrence of frequent lightning-caused fires acted to control forest understory regeneration and the encroachment of certain species in pine ecosystems in the southern and western United States. Aggressive fire suppression has resulted in millions of acres of National Forests land with high fuel loads. These forests contain accumulations of flammable fuel that are much higher than historical conditions [1,2]. In addition to the risk of high intensity and catastrophic wildfires, the thick understory vegetation is susceptible to insects and diseases.

In order to achieve forest restoration, managers have been implementing some techniques such as thinning and

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Table 1 – Understory biomass levels in green tonnes per hectare for the study sites.

Site	Shrubs[a]	Saplings[b]	Pine		Total
			Dbh < 2.5 cm	2.5 ≤ Dbh ≤ 14 cm	
1	16.23	0.00	0.00	0.31	16.54
2	16.63	0.27	0.00	1.75	18.65
3 – Block 1	12.69	0.67	9.03	64.83	87.22
3 – Block 2	23.07	1.37	4.64	22.37	51.45

a Includes *Serenoa repens* (palmetto), *Ilex glabra* (gall berry), *Myrica cerifera* (wax myrtle) and *Persea borbonia* (red bay) with Dbh < 2.5 cm.
b Includes *Acer* (maple) and *Myrica cerifera* (wax myrtle) with Dbh ≥ 2.5 cm.

prescribed burning. However, the heavy fuel loading from a lack of natural burning creates problems related to fire control and smoke management [2].

Mechanical removal of the excessive understory biomass would reduce the risk of catastrophic wildfire, facilitate the safe use of prescribed fire and its reintroduction across a larger landscape and improve wildlife habitat. Besides the fuel loading reduction and the forest health improvement, benefits of harvesting understory may include the use of the biomass for renewable energy production.

Therefore, the objective of this study was to evaluate the performance and to estimate costs of two round baling systems for harvesting forest understory biomass, as well as to determine the feasibility of generating an alternative source of biomass fuel.

2. Materials and methods

2.1. Study area

The study area was comprised of three different stands located on the Osceola National Forest in Florida, United States. The area is covered by pine flatwood forests, whose overstory is dominated by *Pinus palustris* (longleaf pine) and *Pinus elliottii* (slash pine). Common understory species are *Serenoa repens* (palmetto) and *Ilex glabra* (gall berry), along with various species of grasses and woody shrubs. Prior to the machine evaluation, an understory survey was done on each site to determine biomass levels per area and species composition (Table 1).

Site 1 had the lowest amount of understory biomass with 16.54 green t ha^{-1}. The area had an overstory density of 43.2 trees ha^{-1} with 2.79 m^2 ha^{-1} of basal area. Site 2 was considered more representative of conditions found in most areas on the forest. It contained 18.65 green t ha^{-1} of understory biomass. The area had an overstory density of 205.1 trees ha^{-1} with 13.57 m^2 ha^{-1} of basal area. Site 3 was a former shelterwood stand with a light density of 24.0 trees ha^{-1} of slash pine overstory and a very dense stand of slash pine saplings in the midstory.

2.2. Evaluated systems

The first system was a cutter-shredder-baler prototype developed by Agriculture and Agri-Food Canada in collaboration with Université Laval in Québec City. The Bio-baler cut, shredded and baled biomass in a single operation. Originally intended to harvest long-stem willow in plantations, the prototype included a modified commercial round baler (New Holland BR740) as the harvest platform. The original cutter-head was made of four horizontal saw blades and a shredder with 12 hammers [3,4]. However, a new cutter-head designed in spring 2007 and intended to harvest brushes in fallow land and rough terrain was composed of a wide shredder (2.30 m) with 20 flail hammers which combined cutting and shredding (without saws) [5]. A 108 kW (145 hp) Caterpillar Challenger MT565B tractor pulled the Bio-baler and provided PTO power (Fig. 1).

The second system required two successive operations. The first operation was cutting and shredding performed by a mulcher attached to a forestry tractor. Two different size mulching units were used. One was a 104 kW (140 hp) Supertrak tractor, model SK 140 TR with a 1.52 m wide BH-74 SS Fecon head utilizing 30 chipper teeth. The other was a 224 kW (300 hp) Supertrak tractor, model SK 300 TR with a 2.16 m wide BH-120 Fecon head utilizing 48 carbide teeth (Fig. 2). The second operation was collecting the mulched biomass left on the ground with a round baler Claas Rollant 250, whose pickup width was 1.85 m. The Claas baler was pulled and powered by a Caterpillar Challenger MT545B tractor, with 89 kW (120 hp) PTO (Fig. 3).

Fig. 1 – The Bio-baler operated by the Caterpillar Challenger MT565B tractor.

Fig. 2 – Supertrak tractors, SK 140 TR and SK 300 TR, with Fecon mulcher heads.

2.3. *Data collection*

2.3.1. *Time study*

The time study method was used to separate productive time from operational delays. Production estimates for the evaluated machines were obtained through on-site production studies. The machines were timed and data were also collected with activity recorders. Operations were performed in areas which were defined using a compass and flagging and were located so both machines worked side-by-side.

2.3.2. *Distances and areas*

Distances traveled by the baling machines were measured with a distance measuring wheel, while area treated was measured with a handheld GPS.

2.3.3. *Bales*

Bales were measured in the field. Dimensions were measured with a tape and weights were measured with a hanging scale. Four bales from the Bio-baler and six bales from the Claas baler were weighed on Site 1. Eight bales from the Bio-baler and twelve bales from the Claas baler were weighed on Site 2. Four bales provided only by the Claas baler were weighed on Site 3.

Material was collected from a sample of bales for heat and moisture content determination. Two bales from the Bio-baler and four bales from the Claas baler were sampled on Site 1. Five bales from each of balers were sampled on Site 2. Four bales provided only by the Claas baler were sampled on Site 3.

2.3.4. *Fuel consumption*

Fuel consumption rate was determined on a shift-level basis using a metered refueling tank. Fuel tank capacity was 189 L (50 gal) for the SK 140 mulcher, 246 L (65 gal) for the SK 300 mulcher, 378 L (100 gal) for the MT565B tractor, and 269 L (71 gal) for the MT545B tractor.

2.3.5. *Costs*

Hourly costs were estimated using the machine rate approach described by Miyata [6] based on assumptions in Tables 2 and 3. Cost per bale, cost per tonne, and cost per hectare were calculated by combining hourly costs with production rates and fuel consumption estimated in this study.

Fig. 3 – The Claas baler operated by the Caterpillar Challenger MT545B tractor.

Table 2 – Balers cost worksheet.

Description	Bio-baler	Claas baler
Purchase price (US$)	60,000	25,000
Life (years)	4	4
Bale net wrap (US$ per roll of 3000 m length)	250	250
No. of wraps per bale	2	2
Salvage (% of purchase price)	25	25
Repair & Maintenance (% of depreciation)	150	150
Interest annual rate (%)	10	10
Insurance rate (% of the AYI[a])	2	2
Scheduled hours (SMH) per year	2000	2000
Utilization (%)	70	70

a Average yearly investment.

3. Results and discussion

3.1. System performance

3.1.1. Site 1

On Site 1, the Bio-baler produced four bales from 0.42 ha in 1.02 h while the Claas baler produced six bales from 0.45 ha in 0.62 h (Table 4). The average operational time per bale was 15.3 min for the Bio-baler (3.92 bales h^{-1}) ranging from 12.7 to 18.4 min. The Claas baler averaged 6.2 min per bales (range 5.2–11.0 min) (Table 5). The Bio-baler required more time per bale than the Claas baler since it had to cut and shred the material in addition to baling. As the Claas baler is only designed for baling, the Supertrak mulcher performed the cutting and shredding functions. From data in Table 4, the production rate of the SK 140 mulcher is estimated as 0.3 ha h^{-1}. The SK 300 mulcher was not evaluated on Site 1.

The productivity reported in Table 5 is based on area covered divided by time. Values were 0.42 ha h^{-1} for the Bio-baler and 0.72 ha h^{-1} for the Claas baler. Material was already mulched and the path was cleared for the Claas baler so it could travel relatively easily through the forest understory. On the other hand, the Bio-baler had to make its way through an unprepared forest. Also the relatively wide cutter of the Bio-baler (2.3 m) resulted in more overlap when the machine returned on a parallel path and could reduce the effective cutting width because of trees and other obstacles.

The average distance traveled per bale was 580 m with the Bio-baler and 312 m with the Claas baler. Although the Bio-baler traveled almost twice as far to produce a bale, its bales averaged less weight (513 kg) than the ones produced by the Claas baler (627 kg). Therefore, the Claas baler recovered more

Table 3 – Tractors cost worksheet.

Description	SK 140	SK 300	MT545B	MT565B
Purchase price (US$)	140,000	300,000	86,000	105,000
Fecon head (US$)	25,000	50,000	–	–
Tooth (US$ per tooth)	22	70	–	–
No. of teeth	30	48	–	–
Life of teeth (hours)	200	400	–	–
Life of tractor (years)	5	5	5	5
Salvage (% of purchase price)	20	20	20	20
Repair & Maintenance (% of depreciation)	100	100	100	100
Interest annual rate (%)	10	10	10	10
Insurance rate (% of the AYI[a])	3.5	3.5	3.5	3.5
Fuel cost (US$ per liter)	0.86	0.86	0.86	0.86
Lube & Oil (% of fuel cost)	36.8	36.8	36.8	36.8
Scheduled hours (SMH) per year	2000	2000	2000	2000
Utilization (%)	70	70	70	70
Operator wage (US$ per SMH)	12.00	12.00	12.00	12.00
Operator benefits (%)	30	30	30	30

a Average yearly investment.

Table 4 – Operational data on Site 1.

Machine	Area (ha)	Time (h)	Fuel (liters)	Distance per bale (m)	Bales	
					No.	Weight (kg)
SK 140 mulcher	0.45	1.48	21.77	–	–	–
Bio-baler & MT565B	0.42	1.02	13.97	580.3	4	513.0
Claas baler & MT545B	0.45	0.62	9.27	312.4	6	627.4

Table 5 – Machine performance and productivity on Site 1.

	Bio-baler & MT565B	Claas baler & MT545B
Time per bale (min)	15.30	6.20
Bales per hour	3.92	9.68
Hectares per hour	0.42	0.72
Green tonnes per productive hour	2.01	6.07
Green tonnes per hectare	4.83	8.46
Fraction of understory harvested	0.29	0.51

Table 6 – Operational data on Site 2.

Machine	Area (ha)	Time (h)	Fuel (liters)	Distance per bale (m)	Bales	
					No.	Weight (kg)
SK 140 mulcher	1.24	2.84	41.79	–	–	–
SK 300 mulcher	0.40	1.10	22.45	–	–	–
Bio-baler & MT565B	0.93	3.15	43.19	406.3	14	535.4
Claas baler & MT545B	1.64	3.19	47.51	224.9	28	570.9

Table 7 – Machine performance and productivity on Site 2.

	Bio-baler & MT565B	Claas baler & MT545B
Time per bale (min)	13.50	6.84
Bales per hour	4.44	8.78
Hectares per hour	0.30	0.51
Green tonnes per productive hour	2.31	5.01
Green tonnes per hectare	8.05	9.75
Fraction of understory harvested	0.43	0.52

biomass per area (8.46 green t ha^{-1}) than the Bio-baler (4.83 green t ha^{-1}). The estimated understory biomass harvested (recovery) was 29 percent for the Bio-baler and 51 percent for the Claas baler. From data in Table 4, the average fuel consumption is estimated as 33.26 l ha^{-1} (6.81 l t^{-1} or 3.49 l $bale^{-1}$) for the Bio-baler system, and 68.98 l ha^{-1} (8.25 l t^{-1} or 5.17 l $bale^{-1}$) for the SK 140 mulcher-Claas baler system.

3.1.2. *Site 2*

The machines spent most of the time on Site 2, which was considered the most representative. The Bio-baler produced 14 bales from 0.93 ha in 3.15 h while the Claas baler produced 28 bales from 1.64 ha in 3.19 h (Table 6).

The Bio-baler had better performance on Site 2 (4.44 bales h^{-1}) than on Site 1 (3.92 bales h^{-1}) because of the higher amount of biomass per area. On the other hand, the Claas baler had some operational delays that resulted in fewer bales per hour on Site 2 (8.78 bales h^{-1}) than on Site 1 (9.68 bales h^{-1}) (Table 7).

As a result of the higher amount of biomass per area, both balers had a lower productivity on Site 2 than on Site 1. Values were 0.30 ha h^{-1} for the Bio-baler and 0.51 ha h^{-1} for the Claas baler. Understory biomass harvested (recovery) was 43 percent for the Bio-baler (8.05 green t ha^{-1}) and 52 percent (9.75 green t ha^{-1}) for the Claas baler. On Site 2, the SK 140 mulcher was unexpectedly more productive (0.44 ha h^{-1}) than the SK 300 mulcher (0.36 ha h^{-1}) possibly because of its better mobility between the trees and other obstacles.

From data in Table 6, the average fuel consumption was 46.44 l ha^{-1} (5.76 l t^{-1} and 3.09 l $bale^{-1}$) for the Bio-baler system, 62.67 l ha^{-1} (6.43 l t^{-1} and 3.67 l $bale^{-1}$) for the SK 140 mulcher-Claas baler system and 85.09 l ha^{-1} (8.73 l t^{-1} and 4.98 l $bale^{-1}$) for the SK 300 mulcher-Claas baler system.

Table 8 – Operational data on Site 3.

Machine	No. of passes	Area (ha)	Time (h)	Distance per bale (m)	Bales	
					No.	Weight (kg)
SK 140 mulcher	1	0.23	0.81	–	–	–
SK 140 mulcher	2	0.065	0.39	–	–	–
SK 300 mulcher	1	0.21	0.62	–	–	–
Claas baler & MT545B	1	0.065	0.43	317.6	1	627.5
Claas baler & MT545B	2	0.061	0.19	287.1	1	722.8

Table 9 – Machine performance and productivity on Site 3.

	Claas baler & MT545B	
No. of passes of mulcher	1	2
Time per bale (min)	25.8	11.4
Bales per hour	2.3	5.3
Hectares per hour	0.15	0.32
Green tonnes per productive hour	1.46	3.80
Green tonnes per acre	9.69	11.91
Fraction of understory harvested	0.19	0.23

Table 10 – Fuel consumption rates.

Operation	SK 140	SK 300	Bio-baler & MT565B	Claas baler & MT545B
Rate per operation ($l\ h^{-1}$)	14.73	20.40	13.70	14.91
Specific rate ($l\ kW^{-1}\ h^{-1}$)	0.141	0.091	0.127	0.167
Area capacity ($ha\ h^{-1}$)	0.37	0.36	0.36	0.62
Harvest capacity[a] ($t\ h^{-1}$)	3.31	3.22	2.2	5.54
Fuel per unit harvest ($l\ t^{-1}$)	4.45	6.34	6.23	2.69
Mulcher & Claas baler ($l\ t^{-1}$)	7.15	9.03		

a For SK mulchers, harvest capacity is in equivalent tonnage harvested subsequently as bales.

3.1.3. *Site 3*

On Site 3, the Claas baler produced one bale in 25.8 min from 650 m^2 mulched by one pass of the SK 140 mulcher, and one bale in 11.4 min from 610 m^2 mulched by two passes of the SK 140 mulcher. This difference in time is because biomass was mulched finer after two passes. Since Site 3 had a very large amount of midstory biomass per hectare, the Bio-baler did not attempt to work in those conditions (Table 8).

As expected, the Claas baler traveled less distance (287 m) and produced a heavier bale (723 kg) in the area mulched with two passes because of the finer material. For this same reason, the Claas baler productivity and the amount of biomass recovered per area were higher in the area treated by two passes (Table 9).

Table 11 – Size and density of the bales.

Machine	Site 1		Site 2		Site 3	
	Size[a]	Density[b]	Size[a]	Density[b]	Size[a]	Density[b]
Bio-baler	1.74	295	1.67	321	–	–
Claas baler	1.63	385	1.53	373	1.50	455

a Average, in cubic meters.
b Average, in green kilograms per cubic meter.

Table 12 – Moisture and heat content of the bales on an oven-dry basis (OD) or green weight basis (GW).

Machine	Bio-baler		Claas baler		
Site	1	2	1	2	3
Higher heat value ($MJ\ kg^{-1}$ OD)	20.58	20.40	20.43	20.45	21.03
Moisture content – wet basis (%)	45	38	42	38	44
Available heat ($MJ\ kg^{-1}$ GW)[a]	11.32	12.67	11.75	12.61	11.68
Net heat ($MJ\ kg^{-1}$ GW)[b]	10.19	11.70	10.80	11.73	10.68
Net heat per bale ($MJ\ bale^{-1}$)[b]	5229	6263	6776	6695	7209

a Without considering heat losses.
b Considering internal water evaporation at 2.5 $MJ\ kg^{-1}$ of water.

From data in Table 8, the production rate for the SK 140 mulcher is estimated as 0.28 $ha\ h^{-1}$ for one pass and 0.17 $ha\ h^{-1}$ for two passes. These operational data were measured in Block 2 of Site 3 with heavy understory biomass. The production rate for the SK 300 mulcher was 0.34 $ha\ h^{-1}$ and was measured in Block 1 of Site 3 with the heaviest understory biomass. On this latter area, conditions were considered extreme in terms of understory density and therefore the SK 300 mulcher had better performance.

3.2. *Fuel consumption*

The average fuel consumption on Sites 1 and 2 was 13.7 $l\ h^{-1}$ for the Bio-baler system, 29.64 $l\ h^{-1}$ for the SK 140 mulcher-Claas baler system, and 35.31 $l\ h^{-1}$ for the SK 300 mulcher-Claas baler system (Table 10). However, a more objective comparison is total fuel consumption per unit of harvested material. For the Bio-baler system where a single operation is needed, fuel consumption was 6.23 $l\ t^{-1}$ of biomass harvested (38.06 $l\ ha^{-1}$). For the Claas baler system, where two operations are required, the total fuel consumption was 7.15 $l\ t^{-1}$ with the SK 140 mulcher and 9.03 $l\ t^{-1}$ with the SK 300 mulcher (63.86 and 80.72 $l\ ha^{-1}$, respectively). The Bio-baler system required less fuel per tonne and per hectare, but the mulcher-baler system provided more biomass recovery. These trade-offs are discussed further in the cost analysis.

3.3. *Bales*

Size and density of the bales are presented in Table 11. The Claas baler produced relatively small bales with an average volume of 1.55 m^3, 1.22 m diameter and 1.28 m width. The Bio-baler produced slightly more voluminous bales with an average 1.70 m^3, 1.28 m diameter and 1.31 m width. The Claas bales were considerably denser (404 green $kg\ m^{-3}$) than the Bio-baler bales (308 green $kg\ m^{-3}$), in large part because of pre-mulching which occurred only for Claas bales. This pre-treatment facilitated compression in the bale chamber.

Moisture and heat content of the bales are presented in Table 12. The higher heat value is the heat of combustion of a unit weight of dry woody fuel (oven dried heat of combustion) determined in a bomb calorimeter [7]. The available heat content per unit green weight is proportional to the dry matter content (100%-moisture content) in the biomass. As the moisture content increases, the proportion of oven-dry biomass declines, and likewise the available heat declines [7]. The net heat per unit green weight was higher on Site 2 (11.71 $MJ\ kg^{-1}$ GW), than on Sites 1 or 3 due to the lower moisture content (38%-wet basis) of the bales.

On Site 1, the input of energy by the fuel consumed by machines in cutting, shredding, and baling operations was 127 $MJ\ bale^{-1}$ (3.49 $l\ bale^{-1}$) for the Bio-baler system and 188 $MJ\ bale^{-1}$ (5.17 $l\ bale^{-1}$) for the SK 140 mulcher-Claas baler system. On Site 2, values were 112 $MJ\ bale^{-1}$ (3.09 $l\ bale^{-1}$) for the Bio-baler system, 134 $MJ\ bale^{-1}$ (3.67 $l\ bale^{-1}$) for the SK 140 mulcher-Claas baler system, and 181 $MJ\ bale^{-1}$ (4.98 $l\ bale^{-1}$) for the SK 300 mulcher-Claas baler system. However, the energy input by the fuel consumed in loading and transportation also has to be considered in an energy balance. Considering only harvesting, the ratio of net heat from the bales over the tractor fuel energy ranged from 36 to 50. Even after adding transport energy, it is expected that the forest understory biomass will provide a substantially positive net energy benefit at a conversion plant or for small scale heating.

Table 13 – Operational costs by site.

Machine	Site 1			Site 2			Site 3		
	US$ PMH^{-1}	$ha\ h^{-1}$	US$ ha^{-1}	US$ PMH^{-1}	$ha\ h^{-1}$	US$ ha^{-1}	US$ PMH^{-1}	$ha\ h^{-1}$	US$ ha^{-1}
SK 140 (1 pass)	91.41	0.30	304.70	91.41	0.44	207.75	91.41	0.28	326.47
SK 140 (2 passes)	–	–	–	–	–	–	91.41	0.17	537.71
SK 300 (1 pass)	–	–	–	157.64	0.36	437.90	157.64	0.33	477.71
Bio-baler & MT565B	95.89	0.42	228.31	96.27	0.30	320.91	–	–	–
Claas baler & MT545B[a]	81.64	0.72	113.40	81.02	0.51	158.87	76.55	0.15	510.35
Claas baler & MT545B[b]	–	–	–	–	–	–	78.62	0.32	245.70

a Baling on the area treated with one pass by SK 140 mulcher.
b Baling on the area treated with two passes by SK 140 mulcher.

Table 14 – System costs per unit by site.

System	Site 1		Site 2		Site 3	
	US$ bale^{-1}	US$ t^{-1}	US$ bale^{-1}	US$ t^{-1}	US$ bale^{-1}	US$ t^{-1}
Bio-baler & MT565B	24.43	47.27	21.66	39.86	–	–
SK 140 (1 pass) + Claas baler & MT545B	31.18	49.42	21.48	37.60	54.30	86.36
SK 140 (2 passes) + Claas baler & MT545B	–	–	–	–	51.60	80.85
SK 300 (1 pass) + Claas baler & MT545B	–	–	34.87	61.21	–	–

Table 15 – Costs* and benefits (biomass harvested, percentage of understory recovered) from mechanical harvesting per site.

System	Site 1			Site 2			Site 3		
	Cost (US$ ha^{-1})	H[a] (t ha^{-1})	R[b](%)	Cost (US$ ha^{-1})	H[a] (t ha^{-1})	R[b](%)	Cost (US$ ha^{-1})	H[a] (t ha^{-1})	R[b](%)
Bio-baler & MT565B	228.31	4.83	29.2	320.91	8.05	43.2	–	–	–
SK 140 (1 pass) + Claas baler & MT545B	418.10	8.46	51.1	336.62	9.75	52.3	836.82	9.69	18.8
SK 140 (2 passes) + Claas baler & MT545B	–	–	–	–	–	–	783.41	11.91	23.1

*Costs for mulcher-baler system assume independent operation of the mulcher and the baler. Otherwise, costs of 418.10, 336.62, 836.82, and 783.41 could be as high as 576.85, 391.90, 1119.75 and 1000.20 (US$ ha^{-1}), respectively.
a Harvest.
b Recovery.

3.4. *Costs and benefits*

Operational costs for the machines are summarized in Table 13. The heavy duty SK 300 mulcher was more expensive on Site 2 than the SK 140 mulcher, but it became more competitive when working in high density understory biomass on Site 3. The Bio-baler was more expensive than the Claas baler, basically due to its higher purchase price and lower productivity. However, the Bio-baler performs the cutting, shredding and baling operations, while the Claas baler requires a Supertrak mulcher to perform the cutting and shredding functions. Thus, a more objective comparison is system costs. A two-pass treatment by the SK 140 mulcher on Site 3 increased the mulching cost. However, mulching with two passes added the benefit of better preparing the biomass and allowing higher work throughput and higher biomass recovery with the baler. Consequently, the cost of the SK 140 mulcher-Claas baler system decreased with two-pass mulching (Table 14).

Because bales were not the same weight, a more objective comparison in Table 13 is cost per tonne. On Site 1, the Bio-baler cost slightly less than the SK 140 mulcher-baler system, while the opposite was true on Site 2.

Table 15 summarizes the operating costs and some of the potential benefits of mechanical harvesting of forest understory. The operation cost per unit area with the Bio-baler is always less than with the mulcher-baler system. Actually, the mulcher-baler system can be more expensive than values indicated if the most efficient component of the system (mulcher tractor or baler tractor) cannot be used for other activities while waiting for the other unit. In some cases, idling time of one of the system components can be more than 50 percent of the time.

Baling understory biomass reduces fuel loading and may reduce fire risk as well as provide some product value to offset costs of treatment. In this study, the baling treatments recovered between 19 and 52 percent of the understory biomass while also mulching nearly all of the standing understory. The resulting stand condition was equivalent to typical mulch-only fuel reduction outcomes. Some clumps of untreated understory are left behind, particularly around residual overstory trees. The cost benefit of the baling and the product recovery is clearly affected by the collection efficiency of the machines. Future improvement of collection efficiency would a) reduce cost per ton of the biomass, b) increase value per acre returned to the treatment and c) increase the fuel reduction benefit of the treatment.

4. Conclusion

The Bio-baler system has the advantage of performing the cutting, shredding and baling operations with one machine. Further, this system has a lower purchase price, lower fuel consumption rate and, therefore, lower cost per acre. However, the Bio-baler was less productive and encountered limitations to work on the densest site. In addition, it recovered a lower amount of biomass per area than the Claas baler following a mulching treatment.

The mulcher-baler system has a higher purchase price, higher fuel consumption rate and, therefore, a higher cost per acre. Cost per ton harvested was similar between the two systems when the mulcher-baler system was assumed to be operated very efficiently (i.e. no idling time of the faster unit operation which would work at other chores when the other unit operation lagged). In practice, cost per ton would likely be slightly higher with the mulcher-baler system.

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