Economic evaluation of a roll-off trucking system removing forest biomass resulting from shaded fuelbreak treatments

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Abstract

Shaded fuelbreak treatments involve removal of understory brush and small-diameter trees to disconnect the continuity of fuels, improve firefighter safety, and confine wildfires to one watershed area. As a result of these treatments, piles of woody biomass (slash) are scattered throughout the treated stand and are typically treated by pile burning. Mechanical removal of slash has not been successfully implemented in many areas due to limited accessibility to sites and the high costs associated with collection and transportation of slash. To address these issues, a roll-off truck paired with a small skid-steer loader was used to collect and transport slash to a centralized processing site where slash was ground as hog fuel for energy production. "Roll-off" refers to a straight frame truck configuration in which a 40-yd^3 container is rolled onto and off the straight frame truck by means of a truck-mounted winch system. This study was to quantify the operational performance and costs of removing slash piles using a roll-off trucking system in mountainous conditions in northern California. The overall cost to collect and haul hand-piled slash was $22.95/green ton (or $230/acre if there were 10 tons of slash per acre). This indicates that mechanical removal of hand-piled slash through this method would be comparable to pile burning costs ($150 to $850/acre in northern California). Furthermore, slash burning options raise concerns related to air quality, risk of escaping fire, and limited burn opportunities. The roll-off trucking system should be used primarily for short hauling distances since trucking costs significantly increase with small increases in hauling distance due to slow traveling speeds (less than 10 miles per hour on gravel roads) and low slash weight being hauled (3.91 ton/trip on average). Financial analysis indicated that contractors can receive high rates of return on their invested capital after accounting for inflation and income taxes, but limited work opportunities are a concern for them.

Keywords: biomass energy, fuel treatment, forest fires, roll-off containers

Introduction

A fuelbreak is a strategically located wide block, or strip, on which a cover of dense, heavy, or flammable vegetation has been changed to one of lower fuel volume or reduced flammability (Green 1977). In northern California shaded fuelbreaks are often created by altering surface fuels, increasing the height to the base of live crowns, and opening the canopy by removing trees (Agee et al., 2000). For this project area on the Six Rivers National Forest, the selected shaded fuelbreak treatment involved removal of brush and small-diameter understory trees (<8 inches) while maintaining overstory crown closure (typically around 60%). In this mixed conifer vegetation type, high crown closure is recommended in order to reduce re-growth of brush and small trees after the treatments. This practice has been commonly implemented on National Forest lands in northern California to break up the continuity of fuels, improve firefighter safety, and confine wildfires to one watershed area. Chainsaws are often used to fell brush and small trees and cut them into small pieces for hand-piling. Piles of woody biomass (called "slash" hereafter) are placed throughout the treated stand, with adequate spacing to reduce residual stand damage from pile burning. These piles are eventually consumed by burning when weather conditions and moisture content of the slash are within specified prescriptions (Fig. 1).

Burning slash piles is a commonly used fuel treatment, but it is associated with several concerns including smoke production, residual tree mortality, and the risk of fire escape. These concerns limit the number of burning days, which often causes delays to the completion of the fuel treatment and subsequent forest management activities. Furthermore it can cost \$150 - \$850/acre to implement, depending on the amount of fuels and the characteristics (species, size, and arrangement) of slash piles to be burned (Curran 2008).

Figure 1. Slash burning. Hand-piled slash was created from shaded fuelbreak treatments designed to address wildfire hazard. Photo source: Nancy Curran

As an alternative to pile burning, mechanical removal of slash piles has been considered to avoid the negative effects and constraints associated with slash burning and can also create opportunities to utilize slash to produce energy. Slash can be ground into hog fuel which is transported using wood chip vans to a cogeneration/power plant to produce steam heat and/or electricity. Hog fuel is a term describing biomass fuel that has been processed by a mechanical shredder or grinder and is normally used as a fuel source for heat or energy production.

The idea of slash utilization also includes forest residues resulting from commercial thinning and timber harvesting operations. However, this approach has not been well implemented on a practical level because of limited accessibility on forest roads and the high costs associated with collection and transportation of these materials (Han et al. 2004). Typical slash recovery operations for energy production use a grinder and chip vans. These machines are brought to landings if chip vans can access these locations. Forest roads are built for hauling logs using logging trucks, and a typical chip van has limited access to harvesting sites due to sharp curves, steep grades, and low ground clearance issues. Because of limited accessibility, woody biomass amounts that can practically be supplied to utilization activities are substantially less than gross forest biomass available to harvest. The annual available biomass in California was estimated at 26.8 million dry tons, but the amount that could potentially be supplied to utilization activities amounts to only 14.3 million dry tons (Tiangco et al., 2005). This study also indicated that additional economic constraints can further limit utilization.

Besides limited accessibility for chip vans, high-cost machines such as grinders are significantly underutilized since landing slash piles are small (a grinder often spends less than one or two days grinding a pile of landing slash) and scattered over a large area. An expensive grinder (~$450,000) has to move frequently, resulting in low production rates. Logistical arrangements between on-site operations and transportation to an energy plant have been a challenge as well. These difficulties are further complicated in northern California where terrain is steep and roads are typically not favorable for efficient transportation.

In this study we examined an alternative method to remove woody materials and increase accessibility to slash piled as a result of shaded fuelbreak treatments. In particular a “roll-off truck” with roll-on/off containers was tested to carry non-merchantable materials for a short distance (less than 10 miles) to a centralized processing site. “Roll-off” refers to a straight frame truck configuration in which modular containers are “rolled” onto and off of the straight frame truck by means of a truck-mounted hydraulic winch and a hook. A previous study indicated that a roll-off trucking system would significantly improve both accessibility to more forest residues and economic efficiency of the recovering process (Rawlings, 2004). Further investigation is needed to broaden our knowledge for a wide range of applications of this technology.

Study Objectives

The overall objective of this project was to evaluate the economic feasibility of removing hand-piled slash using a roll-off trucking system in mountainous conditions. The specific research questions include:

- ✓ How much does it cost ($/hour) to run the system (roll-offs and a loader)?
- ✓ What are potential productivities (ft^3/hour or ton/hour) in a wide range of work conditions for loading and transportation?
- ✓ What is the economic maximum hauling distance that is comparable to the cost ($/acre) of pile burning?
- ✓ What would it take to develop a profitable business that utilizes roll-off trucks in slash collection and transportation?

Study Methods

Study site and a roll-off trucking system

A two-week trial of removing hand-piled slash using a roll-off trucking system was conducted on the Six Rivers National Forest in late July, 2007 near Mad River, California. Hand-piled slash (Fig. 2) was created by shaded fuelbreak treatments which also maintained 60% crown closure to reduce re-growth of brush and small trees within the understory. The shaded fuelbreak treatment prescription required cutting brush and suppressed understory trees less than 8 inches in diameter at breast height (DBH) which contribute to ladder fuels. The width of the shaded fuel break treatment varied with topography and vegetation but averaged 250 ft on ridge tops and Forest Service roads. Firewood was salvaged from the trees cut and the remaining unmerchantable woody biomass was hand-piled for burning. Realizing an opportunity for biomass research, a collaborative agreement was reached between industry, academia, and the Six Rivers National Forest to collect and transport slash piles to a central processing area using a roll-off trucking system. Once at the processing area, slash could be ground and transported for use at an energy plant.

The slash removal system utilized in this study consisted of a loader and a roll-off truck equipped with roll-off containers (Fig. 3). These two machines were leased during the study from two local contractors who are currently using the roll-off trucks to collect and transport urban waste and the loader to handle various tasks related to brush and tree removal.

Containers were placed along the roadside and loaded with slash in the woods using a small rubber tracked skid-steer front-end loader (ASV RC100). A typical loading cycle included unloaded travel to the slash pile, compiling/picking-up slash, loaded travel back to the container, and the subsequent loading of the container with the slash. This particular loader was chosen for use on this project due to its ability to travel swiftly around residual trees while exerting minimal ground pressure (<4 psi). The loader operator compacted the slash in the container using the bucket to increase the slash weight within the container. The loader is small enough to be transported inside a container when moving to the next job. In this study, the loader was carried to the work site using a large pickup truck ($40,000) and a trailer ($10,000) which would not be needed if one contractor owns both a roll-off truck and loader.

Utilizing its 425 horsepower engine, short truck length (30 ft) and high clearance design, the roll-off truck can negotiate sharp curves (~ 40 ft radius) and travel on steep grades where typical log trucks can travel. A trailer used to carry an additional container (often referred to as a “pup”) can be pulled by the truck as well. The roll-off containers used for this study were 7 ft tall, 8 ft wide, and 20 ft in length with a capacity of 40 cubic yards. Although the containers were similar, one had a non-removable stabilizer bar over the rear doors. With two containers, the truck can carry up to 20 tons of woody biomass. The truck travelled on four different standards of roads during the study: paved highway, main gravel, secondary gravel, and spur (Table 1). Each trucking cycle consisted of travel to a loaded container, loading (rolling on) a container filled with slash, loaded transport to a centralized processing area, dumping the slash from the container, transporting an empty container back to the loading area, and rolling off the empty container. Slash that was removed during the study was compiled at a central location where it was ground to hog fuel and delivered to a local energy plant (Fig. 4); however, this grinding phase was not included in our study

Figure 2. Hand-piled slash from a shaded fuel break treatment. There were 80 slash piles per acre on average.

Figure 3. A roll-off trucking system consisting of a roll-off truck equipped with roll-off containers and a loader.

Figure 4. Slash was compiled at a central processing location where it was ground to hog fuel and delivered to an energy plant.

Table 1. Characteristics of roads used to transport slash.

	Paved highway	**Main Gravel**	**Secondary gravel**	**Spur**[2]
One-way distance (miles)	0.35	1.15	0.85	Up to 0.38 (or 2000 ft)
Road surface	asphalt paved	aggregate surfaced	aggregate[1] surfaced	native soils
# lanes	two	two	single	single
Road grade (%)	mean: 2 min.: 0 max.: 2	mean: 10 min.: 2 max.: 15	mean: 15 min.: 2 max.: 21	mean: 10 min.: 2 max.: 15
Curvature	low-boy accommodated	low-boy accommodated	low-boy not accommodated	low-boy not accommodated
Maximum design speed (mph)	45-55	15	10	5
Actual observed speed (mph)	35 – 40	10 – 11	8 - 10	2 – 6

[1]A low component of fine soils mixed with less than three inch size gravels.
[2]Spur roads did include rough road surface, water bars, and windy curves.

<u>Data collection</u>

Machine rates ($/hour) for each machine were calculated using standard methods (Miyata 1980 and Brinker et al. 2002). Cost factors and assumptions were collected from the contractors and summarized in Table 2. Time and motion methods were used to collect productive and non-productive time data for each machine. These data were used to examine interactions between equipment, personnel, and slash collection attributes. Equipment cycle times were recorded with one of two different stopwatches. Extremely short cycle elements observed during the loading cycles necessitated the use of a decimal stopwatch (hundredth of a minute), while longer trucking cycles allowed the use of a conventional stopwatch using minutes and seconds. Working conditions such as distances, weights, residual trees per acre, and pile size were measured and noted during each cycle element. Delays (i.e. machine not working) that occurred during the study were recorded and distributed within four categories: mechanical, operational, administrative, and personal delays. Research-related delays such as weight measurements were excluded from the production analysis.

A portable weighing system (Intercom PT 300) was used to measure slash weight carried in each container. The roll-off truck and two empty containers were weighed at the central processing site before the operation started to obtain a tare weight. After hauling the biomass to the central processing site, the truck and load were weighed. Weight measurements were recorded along each of the trucks three axles, and summed to obtain an overall weight. The slash weight was calculated by subtracting the empty truck weight including a container (tare weight) from the gross loaded weight.

Table 2. Summary of cost factors and assumptions used to calculate hourly costs.

Cost factors	**Roll-off truck**	**Loader**	**Pick-up truck**[1]
Purchase price ($)	98,000[2]	58,000	40,000
Salvage value (% purchase price)	20	20	10
Economic life (years)	7	5	7
Interest (% average yearly investment)	8.9	10	10
Insurance (% average yearly investment)	3	3	3
Taxes (% average yearly investment)	2	2	2
Repair & Maintenance (% depreciation)	65	75	50
Fuel consumption (gallons/hour)	4	3	6 gal./day[3]
Fuel cost ($/gallon)	3.30	3.30	3.30
Lube and oil cost (% fuel cost)	37	37	37
Wages ($/hour)	20	23.40	0
Fringe benefits (% wage)	12	30	0
Scheduled machine hour (SMH)/year	1600	1600	1600
Productive machine hour (PMH)/year	1440	1360	1360
Utilization rate (%)	90	85	85
Machine cost ($/SMH)	55.82	56.38	9.43
Machine cost ($/PMH)	62.02	66.32	11.89[4]

[1]The pick-up truck used to carry the loader to the study site and daily trip for workers.
[2]The price includes two 40 cubic yard containers ($4,000 each).
[3]Fuel consumption for daily trip to the study site (20 miles one-way distance).
[4]The machine cost includes the trailer used to carry the loader ($0.80/PMH)

Truck travel distances on paved and gravel roads, as well as the central processing area were measured by vehicle odometer down to a tenth of a mile. Measurements were further estimated to the nearest 0.05 mile. Distances on spur roads within the treatment area were measured by fiberglass tape and/or impulse laser. Distances were marked and flagged along the spur road for convenient identification while collecting data. Locations where road types changed were flagged to identify them during data collection.

Slash moisture measurements were recorded daily during the study in order to determine the average moisture content of the material being hauled. Data were collected for three diameter size classes: small (<1 in.), medium (3-6 in.), and large (>6 in.). Biomass was randomly selected from slash piles within the three size classes for measurement. Moisture samples were taken using a Delmhorst BD-2100 moisture meter. A single measurement was recorded for small class materials. The moisture meter sensor penetrated through the bark on these small materials to measure moisture content. For medium and large materials, pieces were cut using a chainsaw to obtain a cross-sectional area that was not exposed to ambient air. Three measurements were taken diagonally across each cross-sectional area (top, bottom, and center). Average moisture content was obtained by averaging the three measurements. Tenth acre sample plots were used to determine the average number of piles and residual trees per acre for each treatment area. The number of sample plots measured varied based on the size the each unit (3 -7 sample plots established per unit).

Data analysis

Recorded data were analyzed using the Microsoft Excel program. Using this program, averages such as an individual loading cycle, and the number of loading cycles per loaded container were calculated. In addition to these basic statistics, individual delay free cycle times were calculated and paired with measured variables (e.g., distances, trees per acre, load size) observed during the cycle. Regression analysis was conducted to determine if variables had a significant effect on productivity. Variables were considered significant if the p-value of the associated regression coefficient was less than 0.05: a variable which had a p-value greater than 0.05 was not included in the regression model. Each model was evaluated for its suitability through analysis of residual plots and statistical tests.

Before running regression analysis, the data were evaluated for outliers using scatter plots of dependent variable (i.e. time) versus independent variables. The assumptions for multiple regression analysis were evaluated for the data collected during the study. Normal probability plots were used to assure that the assumptions of zero expected value and normal distribution for the residuals were not violated. Scatter plots of the residuals versus the predicted values and the independent variables were used to detect any systematic order (i.e. non-random distribution).

The White test and the Goldfeld-Quandt test were used to test the significance of the heteroscedasticity (non-constant residual variance) (α=0.05). When there was the significant violation of homoscedasticity, estimated generalized least squares estimators were used in the regression analysis to correct heteroscedasticity problems. The Durbin-Watson test was used to detect the significance of the first order autoregressive error terms. Estimated generalized least squares estimators were used in the regression analysis provided that the Durbin-Watson test statistic is less than the lower bound of the Durbin-Watson interval. The variance inflation factor (VIF) and condition index (CI) were used to detect the severity of the multicollinearity (linear dependence between independent variables). A VIF value greater than or equal to 5.0 and a CI value of 30 to 100 were used simultaneously as indicators of severe multicollinearity. Restricted least squares estimators were used to remove any insignificant independent variables in the regression model.

Sensitivity analysis was performed to evaluate the maximum economic hauling distance on forest roads. This is useful to examine when the overall cost of slash removal becomes unacceptable for the Forest Service and/or private landowners. Hauling distance also directly affects the number of containers required to balance the workload between truck and loader. For loading, our sensitivity analysis was focused on residual stand density and forest travel distance to understand how these variables affected loading productivity and cost.

A cash flow analysis that includes all the costs and revenues was conducted to evaluate the profitability of the business over the life of the machines. The ChargeOut! (Bilek 2006) program was used to calculate internal rate of return, break-even charge-out rate, and net present values. This program also allows a user to perform sensitivity and breakeven analysis to understand the business conditions that are required to make the business profitable, including the number of work days, loan interests, risk premium, and charge-out rates.

Results and Discussion

Loading slash into roll-off containers

Containers were placed along the roadside in specified locations chosen by the loader operator. Prior to loading, the operator prepared an approach path to the container by removing rocks, stumps, and other debris to facilitate smoother loading conditions. As the loader operator traveled into the woods to collect slash, stumps and fallen logs were removed. Once a path was established, subsequent cycles could be performed faster since the path was clear and the operator knew the trail conditions he had previously traveled on. In order to maximize the load volume, the operator compiled two or three piles of slash using the grapple and bucket combination to compact and consolidate the piles. Time spent compiling and compacting slash in the forest significantly increased the average loading cycle time ($p<0.05$). Compaction of slash in the forest occurred during 85% of the total cycles observed ($n=891$). The average weight of a load varied with the amount of bole wood in the pile and averaged 446 lbs ($n=889$).

Since the loader had rubber tracks, there was a concern by the operator that the tracks could be seriously damaged by stumps left by the thinning crew. Flat or flexible stumps were not as damaging compared to stumps cut on an angle. In addition to physical damage, traveling over stumps slowed travel time since the slash grappled often was unacceptably shaken and loose. The loader operator removed the stumps during 7.7% of the overall cycles though it did not significantly contribute to individual cycle times. Although care was taken, by the end of the operation, the tracks had been severely damaged by stumps. The stump height should be reduced to ground level if this type of loader is expected to be used to remove slash.

The number of loading cycles needed to fill a 40-cubic yard container averaged 17.53, ranging from 13 to 26. Small limbs and branches were difficult to compact in the container and caused lighter container loads. Areas with more bole material had more weight and compaction was achieved primarily by the weight of the material. Increased cycles were needed to fill containers in areas with bole wood, but container weight increased significantly.

The average cycle time for the loader to make a round trip between a container and the slash piles took 1.68 minutes (Table 3). The largest time component of an average cycle time (35.7%) was travel from the slash pile back to the container (forest travel loaded) (Fig. 5). Piling represented 33.6% of the average cycle time, indicating that a different type of grapple for the loader may be used to more efficiently grab the slash pile. Residual tree density often slowed loaded travel time due to limited maneuverability and increased care needed to reduce residual stand damage. This was particularly noticeable when the number of trees per acre exceeded 200.

Table 3. Summary statistics of observed loading cycle time and its variables (n = 891)

Loading cycle component	**Variable**	**Mean**	**Standard Deviation**
Forest travel empty[a]	time (sec.)	0.41	0.19
	distance (ft)	99.42	61.54
	TPA[e]	179	61.37
Piling[b]	time (sec)	0.56	0.40
	distance (ft)	15.28	18.41
	# of piles	3.42	2.29
Forest travel loaded[c]	time (sec.)	0.59	0.28
	distance	113.24	64.04
	slope (%)	15.70	7.97
	TPA[e]	179	61.37
Compacting load[d]	time (sec.)	0.10	0.29
	cycle # [f]	10.13	5.85

[a]Loader driving to the slash piles
[b]Loader piling slash to make a full load
[c]Loader traveling back to the container with a full load of slash
[d]Loader compacting to increase the slash weight in the container
[e]Trees per acre
[f]The number of cycles in which the loader starts compacting the slash to increase the slash load weight

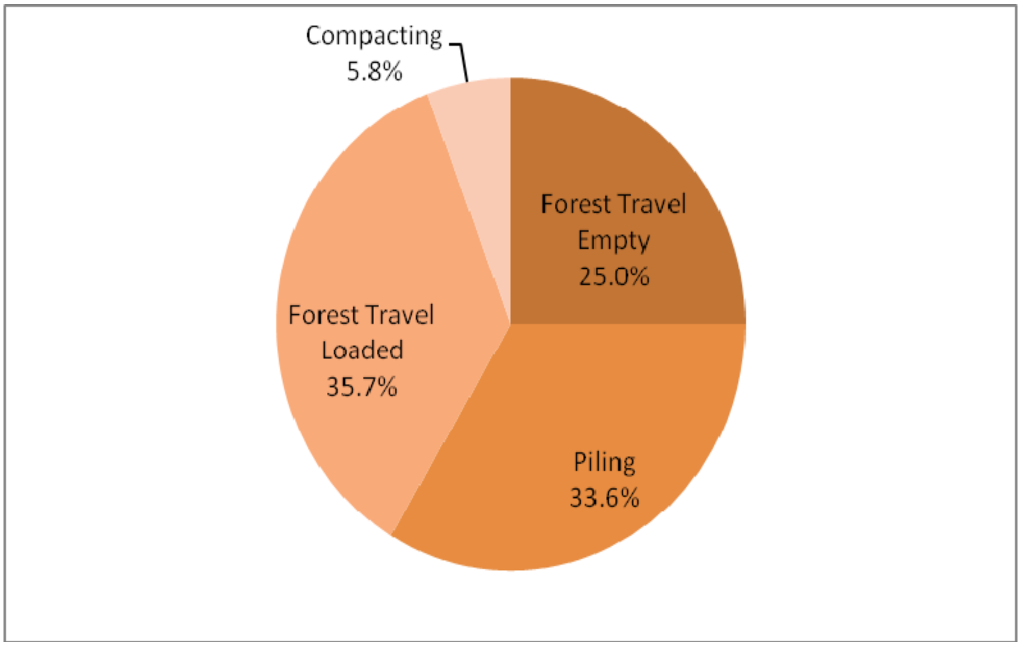

Figure 5. Elements of the loading cycle time. The average cycle time was 1.68 minutes.

Regression models for delay-free cycle time were developed, using the corresponding independent variables for each cycle element (Table 4). For the models, all the coefficients were significant ($p<0.05$) and R^2 values were generally high, indicating the average cycle time equation for loading may be effectively used to estimate loading productivity. Ground slopes were generally gentle (<32%) and did not significantly affect the average cycle time ($p>0.5$). The combined model was developed to estimate an average loading cycle time for a certain work condition.

Dummy variables were used to examine the effect of operators (i.e., experienced and less experienced), time for stump removal, and different container types. All dummy variables were significant, indicating that a less experienced operator and stump removal could increase delay-free average loading cycle time. This also indicates that container type has an effect on loading time: the container with a stabilizer bar could not be filled as high as the container without a stabilizer bar because the slash above the bar may cause hang-ups delaying the slash unloading process. This resulted in decreased loading time and reduced slash weight in a container.

Table 4. Regression models for average loading cycle time (estimates of time in centi-minutes; n = 891)

Operation element	Regression model	R^2	Prob. > F	Std. Err.	p-value
Forest travel empty	time = 0.340	0.83	<0.0001	0.013	<0.0001
	+0.002 (distance in ft.)			0.001	<0.0001
	+0.073 (operator indicator [a])			0.011	<0.0001
Piling	time = 0.049	0.76	<0.0001	0.012	<0.0001
	+0.004 (distance in ft.)			0.004	<0.0001
	+0.124 (# of piles)			0.003	<0.0001
	+0.314 (remove stump indicator [b])			0.025	<0.0001
Forest travel loaded	time = 0.238	0.81	<0.0001	0.042	<0.0001
	+0.002 (distance in ft.)			0.001	<0.0001
	+0.008 (cycle # in loading a container)			0.002	<0.0001
	+0.001 (TPA [d])			0.001	<0.0001
	+0.109 (operator indicator [a])			0.019	<0.0001
Compacting load	time = 0.251	0.96	<0.0001	0.019	<0.0001
	+0.189 (cycle # in loading a container)			0.003	<0.0001
	+0.208 (operator indicator [a])			0.208	<0.0001
Combined	Total cycle time = -0.009	0.78	<0.0001	0.053	0.8620
	+0.006 (cycle # in loading a container)			0.002	0.0141
	+0.005 (slope in %)			0.002	0.0022
	+0.001 (TPA [d])			0.002	<0.0001
	+0.282 (operator indicator [a])			0.026	<0.0001
	+0.003 (forest travel empty distance in ft.)			0.006	<0.0001
	+0.005 (piling distance in ft.)			0.008	<0.0001
	+0.137 (# of pilings)			0.006	<0.0001
	+0.451(remove stump indicator [b])			0.045	<0.0001
	+0.258 (# of compacting)			0.010	<0.0001
	+0.090 (container indicator [c])			0.024	0.0002
	+0.002 (forest travel loaded distance in ft.)			0.005	0.0001

[a] Indicator variable: 0 for experienced operator, or 1 for less experienced operator.
[b] Indicator variable: 0 if stump is not removed, or 1 if stump is removed.
[c] Indicator variable: 0 if container with bar is used, or 1 if container without bar is used.
[d] Trees per acre

Hauling slash to a central processing area

Once a container was loaded, the roll-off truck transported the slash to a central processing area located approximately 2.8 miles away from the loading site. Due to poor road conditions, a round trip (~5.5 miles) took slightly over 52 minutes. A typical trucking cycle began with the truck moving toward a loaded container after dropping an empty container at the loading site. The average travel time to a loaded container was approximately two minutes with an average travel distance of 300 feet (Table 5). At times, however, the truck had to back over 1,000 feet to a loaded container due to highly limited turn-around locations on the spur road. Backing the truck long distances (particularly over steep or uneven terrain) could severely lower the production rate. The average total time to drive to a loaded container, position the truck, and load a full container was 6.79 minutes, representing 12.9% of the average total cycle time.

Delays were seldom observed during the loading stage. The truck driver was highly skilled at positioning the truck for optimum hooking and loading (rolling-on the loaded container). The major challenge associated with rolling-on and rolling-off containers was the uneven terrain adjacent to the spur road which caused a container to drop off the rails (frames). When this occurred, extra time was needed to drop the container, and the likelihood of mechanical damage to the truck increased. Sideslopes should be avoided when loading/unloading containers. As the container is raised, the trucks center of gravity shifts to the side increasing the chance of a rollover.

Table 5. Summary of observed trucking cycle time and its independent variables (n = 61)

	Cycle Elements	**Distance (feet)**	**Time**		
			Minutes	**%**	**Total %**
Roll-on	Travel to container filled with slash	300	1.90	3.6	
	Positioning	161	1.36	2.6	
	Loading container filled with slash	N/A	3.53	6.7	12.9
Travel Loaded	Spur road	1006	3.16	6.0	
	Secondary gravel road	4488	7.16	13.7	
	Main gravel road	6072	6.33	12.1	
	Asphalt paved road	1848	0.97	1.8	
	Central processing area	915	2.27	4.3	37.9
Unloading	Unloading slash	N/A	3.48	6.7	6.7
Travel Empty	Central processing area	912	1.98	3.8	
	Asphalt paved road	1848	0.99	1.9	
	Main gravel road	6072	6.93	13.2	
	Secondary gravel road	4488	6.40	12.2	
	Spur road	1103	3.19	6.1	37.2
Roll-off	Drop empty container	N/A	2.79	5.3	5.3
Total		29215	52.44	100%	

Travel speeds on spur roads were highly limited by steep grades and road surface conditions: the speeds on spur roads ranged from 2 to 6 miles per hour. Although the roll-off truck has almost a foot of ground clearance, extra time was spent traveling over rough road sections. The average time spent traveling over spur roads with a loaded container was 3.16 minutes (6.0 percent of the overall cycle time).

The average speeds for main and secondary gravel roads were shown in Table 6. Traveling loaded on gravel roads accounted for 25.8 percent of the overall cycle time (13.49 minutes) and was constrained by sections with steep slopes (e.g. 21% slope), and poor road surface conditions. Driving with a loaded container on favorable (downhill) slopes required the assistance of an engine compression brake. Without the compression brake, applying the air brakes on loose, 3-inch minus rocks caused the truck to skid, lose steering ability, and caused an overall loss of vehicle control. Though effective, the compression brake contributed to reduced speed (travel loaded) on secondary gravel roads. Compared to the main gravel road, the average speed on the secondary gravel road was considerably slower due to loose surface conditions.

Field observations verified that containers with heavier payloads increased the travel speed on gravel roads due to extra traction provided over the rear axles. This was particularly noticeable while traveling loaded on the main gravel roads. This, in combination with downhill traveling (loaded), increased the average speed on the main gravel road by 0.9 miles per hour (Table 6).

Short travel distance on the paved road to the central processing site prevented the truck from reaching its normal speed. For 0.35 miles of asphalt pavement, the loaded roll-off truck spent around 0.97 minutes with an average speed of 21.6 miles per hour. A separate test of asphalt pavement travel over longer distance showed that the normal speed was around 40 miles per hour. The travel speed of the roll-off truck at the central processing site (5 miles per hour) was comparable with the speed on the gravel road due to short travel distance and limited road width along with a required stop for research related weight measurements. This time represented 4.3% of the total cycle time.

Table 6. Average speed of the roll-off truck traveling on three different road sections. There was no significant difference ($p>0.05$) of traveling speeds between travel empty and loaded on the paved road, but this was not the case for the gravel roads ($p<0.05$).

Road sections	**Distance (miles)**	**Average travel speed (miles/hour)**	**n**
Pavement travel empty	0.35	21.3	61
Pavement travel loaded	0.35	21.7	68
Main gravel travel empty	1.15	10.0	61
Main gravel travel loaded	1.15	10.9	68
Secondary gravel travel empty	0.85	8.0	61
Secondary gravel travel loaded	0.85	7.1	68

Following weight measurements, slash was unloaded at the central processing area. This process involved positioning the truck at the proper location, opening the rear doors of the container, and raising the container to allow the biomass to slide out the back (similar to a dump truck). This operation was heavily affected by the design of the container. As noted previously, one of the containers had a bar on the back which hindered the smooth flow of slash out the back of the container. Occasionally slash would get caught on this bar preventing the slash from unloading. When this occurred, a chainsaw was needed to release the slash significantly increasing the unloading time. To mitigate the problems caused by the bar, the loader operator reduced the amount of slash loaded in this particular container. The average unloading time (including delays) was 3.48 minutes, representing 6.7 percent of the average total cycle time.

A large central processing area is needed in order to accommodate large amounts of slash. Each load delivered to the processing area was approximately 8 feet wide by 20 feet long. By backing the empty container against the recently deposited pile, this footprint could be slightly reduced. The area should also include sufficient room to maneuver the roll-off truck as well as a grinder, loader, and chip van.

The load capacity (weight limit) for the roll-off truck was 10 tons, during the study, the slash weight per load ranged from 1.9 tons to 6.2 tons, with an average of 3.85 tons per load. This was far less than the load capability of the truck. Larger stem material loaded on top of lighter tops and limbs would compact the load and increase the volume (and weight) of each load.

Overall, poor gravel road conditions affected travel speeds more than did slash weight. Observations showed that driving with an empty container on unfavorable (uphill) road grades required extra traction on the rear tires by either raising the container to move the center of gravity closer to the rear axles or moving slowly to ensure that the tires remained in complete contact with the ground. Uneven road surfaces occasionally caused slash to fall off of a container when traveling to the central processing area. As the truck driver traveled back to the loading area, he stopped and removed large wood that had fallen onto the road to avoid damaging the truck. This increased the travel time and lowered the production rate. Tree limbs along the haul route also slowed production as the truck had to slow down to avoid breaking the windshield and mirrors. Pruning the trees along the sides of the road prior to hauling could help shorten the travel time and increase the production rate.

Regression equations for delay-free trucking cycle elements were developed based on the data collected during the operation and contain the variables that significantly affected each elemental cycle time (Table 7). These regression models for each cycle element were combined to create a regression equation to estimate the average round-trip trucking time. This combined equation does not include the time required for loading/unloading containers, dumping the slash, and traveling all the road sections since cycle times spent on these operations were similar each cycle. All independent variables that were included in the regression models in Table 7 were significant ($p<0.05$).

The variable of "site travel empty" was not included in the combined regression model due to severe multicollinearity with the variable of "site travel loaded" and its insignificance (p=0.97) in the model. The multicollinearity was caused by traveling on the same route in the fixed area.

As stated previously, the combined regression equation did not include the variables; dropping off empty container (167 seconds), loading a fully-loaded container (212 seconds), and dumping biomass at the central processing site (209 seconds). To calculate an average cycle time, a constant value of 588 seconds was used to reflect these elements in the cycle. In addition, the time for traveling on gravel (main and secondary) and paved roads was not included in the combined equation because the truck traveled over the same (i.e., fixed) distances of those road sections for every trip. The average speed for each hauling road section (Table 6) was used to estimate travel time which should be added to the total cycle time.

Table 7. Summary of regression analysis for trucking to carry roll-off containers.

Operation element	**Regression model**	**n**	**R^2**	**Prob.>F**	**Std. Err.**	**p-value**
Spur road loaded	time (sec) = 3.4783	68	0.81	<0.0001	12.02	0.7732
	+158.70 (spur loaded direction [a])				13.17	<0.0001
	+0.16 (spur loaded distance in ft.)				0.01	<0.0001
Spur road empty	time (sec) = 13.91	60	0.80	<0.0001	14.06	0.3265
	+127.41 (spur empty direction [a])				10.01	<0.0001
	+0.12 (spur empty distance in ft.)				0.01	<0.0001
Site travel loaded	time (sec) = -139.68	69	0.49	<0.0001	44.94	0.0029
	+0.30 (site loaded distance in ft.)				0.05	<0.0001
Site travel empty	time (sec) = -305.81	60	0.72	<0.0001	34.68	<0.0001
	+0.47 (site empty distance in ft.)				0.04	<0.0001
Positioning	time (sec) = 85.23	60	0.98	<0.0001	6.13	<0.0001
	+0.19 (positioning distance in ft.)				0.005	<0.0001
Drive to loaded container	time (sec) = 100.97	60	0.91	<0.0001	12.18	<0.0001
	+0.12 (drive-to-box distance in ft.)				0.01	<0.0001
Combined	time (sec) = -232.12	61	0.88	<0.0001	241.71	0.3413
	+0.16 (spur empty distance in ft.)				0.04	0.0001
	+131.76 (spur empty direction [a])				27.84	<0.0001
	+0.31 (positioning distance in ft.)				0.03	<0.0001
	+0.16 (travel to loaded container distance in ft.)				0.02	<0.0001
	+0.15 (spur loaded distance in ft.)				0.03	<0.0001
	+216.6 (spur loaded direction [a])				34.84	<0.0001
	+0.61 (site loaded distance in ft.)				0.25	0.0167

[a] Indicator variable: 0 for driving forward, or 1 for backing up the road

Collection and transportation cost

The overall cost to collect and haul hand-piled slash which resulted from shaded fuelbreak treatments was $22.95/green ton (Table 8), based on the observed loading and hauling cycle times that are presented in Tables 3 and 5. This cost figure may be converted into a $/acre-value if we know the amount of slash per acre. For example, it would be $230/acre to remove slash from the site if there were 10 tons of slash per acre. Estimated costs for burning slash piles on the site (Curran 2008) range from $150 to $850/acre.

Slash collection and transportation cost would be lower than $22.95/green ton on a weight basis if the moisture content in slash were higher since the truck hauling capacity was limited by volume, not by weight. Hourly cost ($/SMH) for the truck was lower than the hourly cost for the loader; however, the unit production cost ($/ton) was higher in trucking than loading because hourly production rates for the truck were lower than those for the loader. This indicates that it is important to reduce trucking distance to minimize the overall cost. It should be noted that the average cycle time for trucking needs to be matched with the average cycle time for loading to avoid either truck or loader being idled.

Increasing hauling capacity for the truck is another option to keep the overall operation efficient. The truck is able to carry another container on a trailer, which would bring the combined total to 80 cubic yards each trip. For example, under the current cycle times for loading and hauling (Tables 3 and 5), it would be a well-balanced system if the truck were able to carry two containers each trip since the loading time is about half of the trucking time. Two containers could be fully loaded with slash by the time the truck returns to the site from the central processing area. However, road conditions must allow for truck turn-arounds if the truck and trailer option were implemented.

Table 8. Productivity and cost of slash collection and transportation

	Trucking	**Loading**
Machine cost ($/PMH[a])	62.02	78.22
Average cycle time (minutes)	52.15[b]	27.48[c]
Hourly productivity (ton/PMH)	4.50	8.54
Cost ($/green ton[d])	13.79	9.16
Total cost ($/green ton[d])	22.95	

[a]Productive machine hour
[b]Time required to make a round trip including the time (9.80 minutes) for empty container dropping, picking up a fully loaded container and dumping slash at the central processing area
[c]Time required to fill a full load of slash in the 40-cubic yard container
[d]Cost at 22% average moisture content

A sensitivity analysis was performed to evaluate the effect of hauling distance on the total cost of slash collection and transportation. The regression equations developed from this study were used to estimate productivity for loading and trucking. We used the mean values presented in Tables 3 and 5 as input variables with the exception of hauling distance for main and secondary gravel roads: all values of variables were fixed while hauling distances for main and secondary gravel roads were changed on a 0.5-mile increment.

The costs of roll-off trucking operations significantly increased with small increase of hauling distance of gravel roads due to slow traveling speeds (less than 10 miles per hour on gravel roads) and low carrying capacity (less than 40 yd^3/trip). In particular, the total slash removal cost increased at a faster rate when hauling distance on the secondary road increased, compared to the cost increase with an increase of hauling distance on the main gravel road (Fig. 6). This was mainly due to the truck's ability to travel faster on main gravel roads compared to secondary roads (Table 6). The cost increase for each one mile increase of hauling distance on the main gravel roads was \$3.03/ton while it was \$4.11/ton for the secondary roads. Thus, it is critical to minimize hauling distance on forest roads to reduce the total slash removal cost.

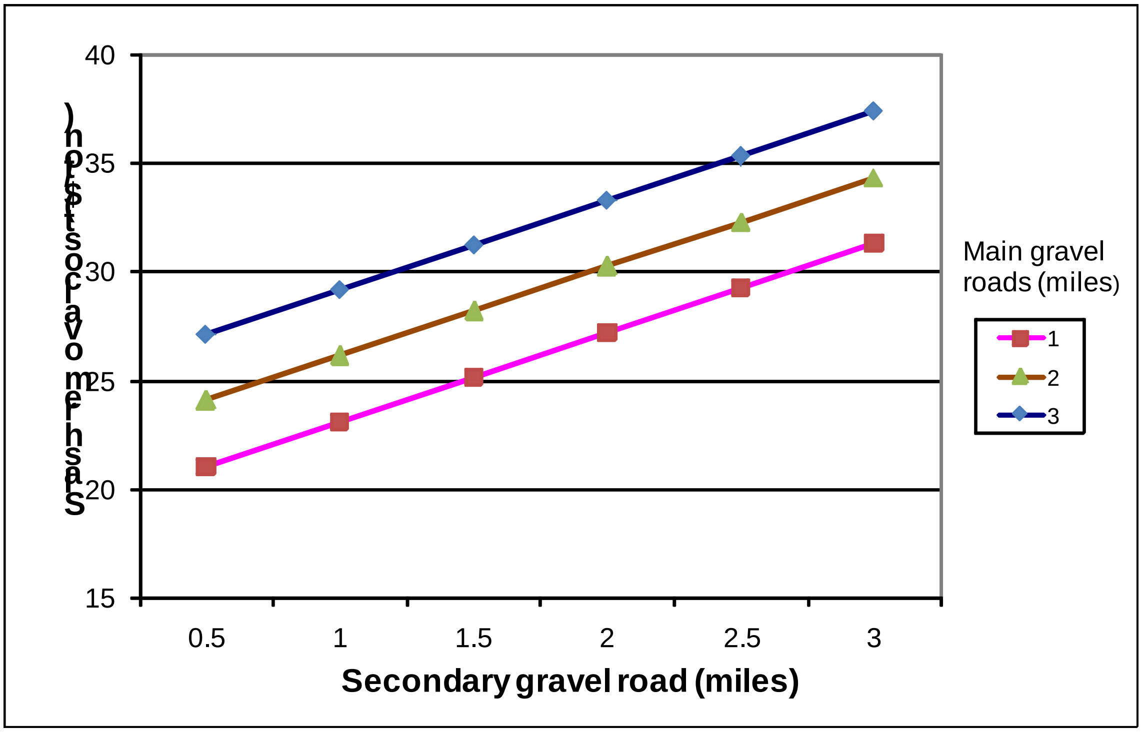

Figure 6. Effect of hauling distance on the total slash collection and transportation cost

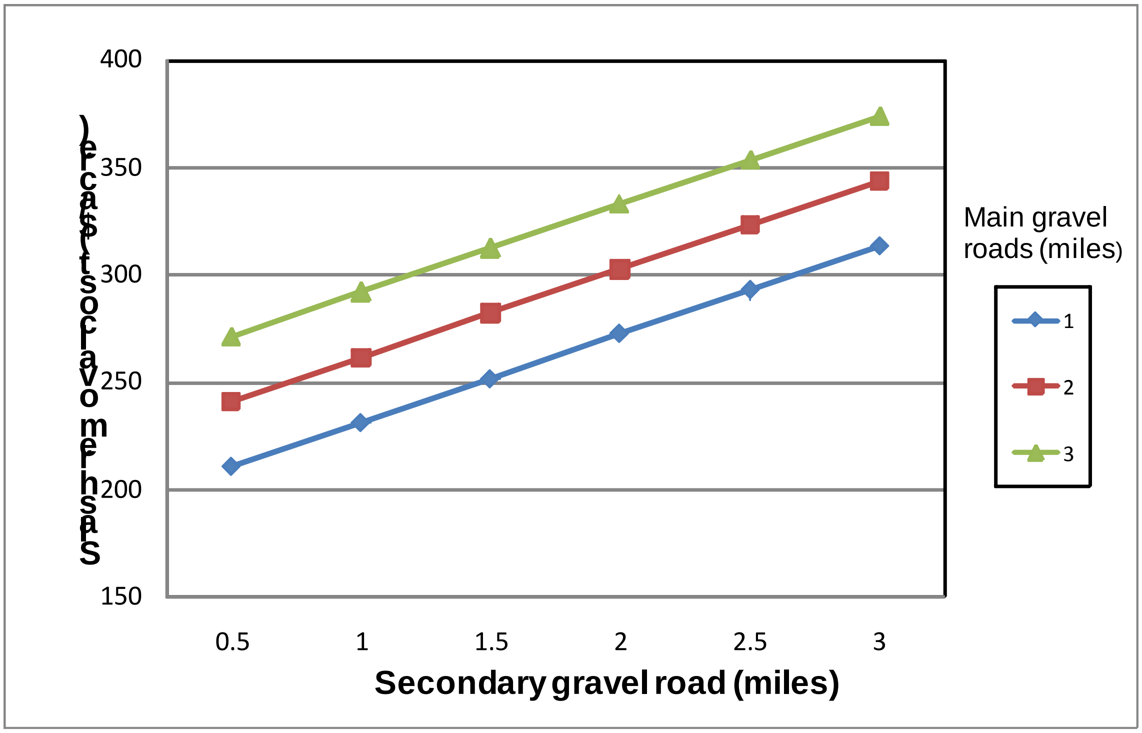

Figure 7. Effect of hauling distance on the total slash collection and transportation cost. The total cost ($/acre) was calculated based on 10 tons of slash per acre.

Figure 7 illustrates the same pattern of cost increase with increased hauling distance on main and secondary gravel roads, based on a $/acre-unit. This sensitivity analysis was based on the assumption that there were 10 tons/acre of hand-piled slash. If one assumes pile burning costs of $400/acre, there is no difference of slash disposal costs between burning and mechanical removal if hauling distances for main and secondary roads were 5 and 2 miles, or 3 and 2.5 miles, or 1 and 5 miles, respectively. Mechanical slash removal using a roll-off trucking system could be a lower cost option over burning if the hauling distances were less than those numbers. This also indicates that a central processing area which can be accessible by a chip truck should be located within those distances.

The effect of residual stand density and forest travel distance on loading cost ($/ton) was also investigated (Table 9). In this analysis all the cost variables for both trucking and loading were fixed as presented in Tables 3 and 5, except residual stand density and forest travel distance (empty) for loading. Loading cost increased by $0.58/ton for every 100 trees per acre increase of residual stand density and by $1.46/ton for every 50 ft increase in the forest travel distance, indicating that the forest travel distance had greater impact on the loading cost than did residual stand density increase. Loading costs represented 37 to 53% of the total slash removal cost when residual stand density ranges from 100 to 300 trees per acre and the forest travel distance ranges from 100 to 350 ft.

Table 9. Effect of residual stand density and forest travel distance on loading cost ($/ton). The values in ( ) indicate percentage of the total cost including loading and hauling.

		Residual stand density - trees per acre		
		100	200	300
		------------------------ $/ton -------------------------- (% of the total cost)		
Forest travel distance (ft)	100	8.72 (39)	9.30 (40)	9.89 (42)
	150	10.18 (42)	10.76 (44)	11.35 (45)
	200	11.64 (46)	12.22 (47)	12.81 (48)
	250	13.10 (49)	13.68 (50)	14.27 (51)
	300	14.56 (51)	15.15 (52)	15.73 (53)
	350	16.02 (54)	16.61 (55)	17.19 (55)

The small loader used in this study was carried to the work place by a pick-up truck and a trailer. There were two contractors in our study - one for trucking and the other for loading. The loader can be carried inside of the roll-off container, eliminating the requirement of the pick-up truck and a trailer if the trucking contractor owns both the roll-off truck and the loader. Table 10 presents the loading cost without a pick-up truck and a trailer, along with the effect of residual stand density and forest travel distance on loading cost ($/ton). The difference of loading costs with or without a pick-up truck and trailer was $1.63/ton ($10.76 vs. $9.13/ton) or 4% of the total slash removal cost (44% vs. 40%) at 200 trees per acre of residual stand density and 150 ft for the forest travel distance. It was noted that the loading cost increases with an increase in residual stand density and forest travel distance, but the % difference of the loading cost remains the same at 4%.

<u>Financial analysis and business requirements for a roll-off trucking system</u>

The ChargeOut! (Bilek 2007) spreadsheet program was used to evaluate the business potential for the two machines: a roll-off truck with roll-off containers, and a loader. The program performed discounted cash-flow analysis to determine break-even rates at a required rate of return on invested capital (ROIC) and internal rate of return (IRR) with input values shown in Table 11. Based on a nominal (i.e., including inflation) deposit interest rate (4%), expected before-tax risk premium (21%), inflation (3%) and income tax rate (33%), a real (i.e. inflation-adjusted) after tax return on invested capital (ROIC) of 13.4% was calculated. This latter value was used to determine break-even charge rates for both machines.

Table 10. Effect of residual stand density and forest travel distance on loading cost ($/ton) without costs ($11.89/PMH) for a pick-up truck and a trailer used to carry the loader. The value in ( ) indicate percentage of the total cost including loading and hauling.

		Residual stand density - trees per acre		
		100	200	300
		------------------------ $/ton -------------------------- (% of the total cost)		
Forest travel distance (ft)	100	7.39 (35)	7.89 (36)	8.38 (38)
	150	8.63 (39)	9.13 (40)	9.62 (41)
	200	9.87 (42)	10.37 (43)	10.86 (44)
	250	11.11 (45)	11.60 (46)	12.10 (47)
	300	12.35 (47)	12.84 (48)	13.34 (49)
	350	13.59 (50)	14.08 (51)	14.58 (51)

Table 11. Business items included in the financial analysis, in addition to the cost variables (Table 2) used in the machine rate calculations.

Business items	**Roll-off truck**	**Loader**
% of total purchase price financed	40%	
Loan term at a fixed rate	5 years	3 years
Loan and deposit payments per year	12 payments	
General depreciation system (GDS) life	5 years	
Depreciation method	Double declining balance with the option to change to straight line method	
Section 179 deduction[a]	$99,000	$59,500
Fixed loan interest rate (APR)	8.9%	
Deposit interest rate (APR)	4.0%	
Expected risk premium on invested capital	21.0%	
Inflation	3.0%	
Income tax rate	33.0%	
Tire cost (per set)	$1,000/year	$1,500/year
Tire life	1,600 hours	
Other fixed costs (e.g. business license, road use permit, etc.):	$2,650/year	$1,000/year

[a]The Section 179 deduction allowed up to $108,000 write-off against taxable income in the first year in 2006 (Internal Revenue Service Publication 946, 2006). In 2007, this increased to $125,000. In 2008, it is scheduled to increase to $128,000.

The break-even charge-out rates for the truck and loader were $57.56/SMH and $69.54/SMH, respectively. At these rates, the contractors receive a 13.4% return on their invested capital after accounting for inflation and income taxes. The contractors would earn additional profits beyond 13.4% return if they could negotiate charge rates higher than those break-even rates. These additional profits may be used to cover cost items that are not included in the analysis such as overhead and other indirect cost items. The current contracting rates for these machines was $85 for the roll-off truck and $100/hour for the loader, which resulted in 79.3% and 124% of IRR (overhead and indirect cost not included), respectively. It is interesting to note that these break-even charge rates are slightly higher than the machine rates presented in Table 3. This is due in part to a discounted cash flow analysis included risk premium (21%) and deposit interest rate (4%) on their capital investment for the business, while the machine rate calculations did not include these items. Figures 8 and 9 illustrate the change in after-tax real IRR with a $2.00/hour incremental change in charge-out rates for trucking and loading. These results show that the after-tax real rates of return are quite sensitive to charge-out rates.

Positive cash flows over the life of the machine were shown after initial investments (Table 12), indicating that this business may be profitable as long as the input values correctly reflect the business conditions. Year 1 had the highest earning due to the assumption that the Section 179 deduction was used against other taxable income. It was further noted that the last two years (3^{rd} and 4^{th} years for the loader; 6^{th} and 7^{th} years for the truck) also had high positive cash flows because they did not include any loan payments. It was assumed that loan payments were completed by the end of 3^{rd} (loader) and 5^{th} (truck) year.

One may wonder if there is enough work opportunity for the machines, which directly impacts the overall business profitability. A sensitivity analysis indicated that to earn at the specified ROIC, the break-even charge-out rates need to be higher with a decrease in operating hours per year (Fig. 10). For, example, the break-even rate should be increased to $79.03/hour for the loader and $70.02/hour for the truck if those machines were used only 1,000 hour per year. These represent 13.6% and 21.6% increases of the break-even rates, respectively, compared to the equivalent rates that were based on 1,600 hours per year.

The relationship is not perfectly linear because it is assumed that if the number of operating hours changes, the maintenance and repair costs will change, also. In the ChargeOut! model, maintenance and repairs costs do not have to be fixed. Rather, they may be allowed to change along with the number of annual productive hours or may be entered individually for each year.

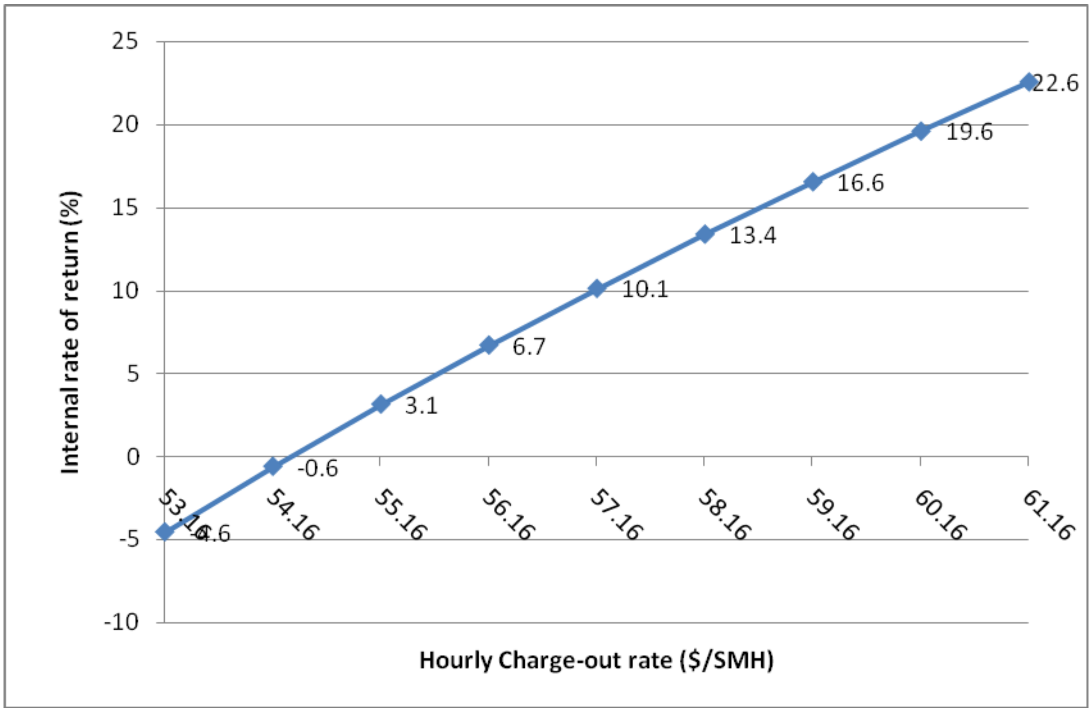

Figure 8. Effect of charge-out rates on rate of return: roll-off truck

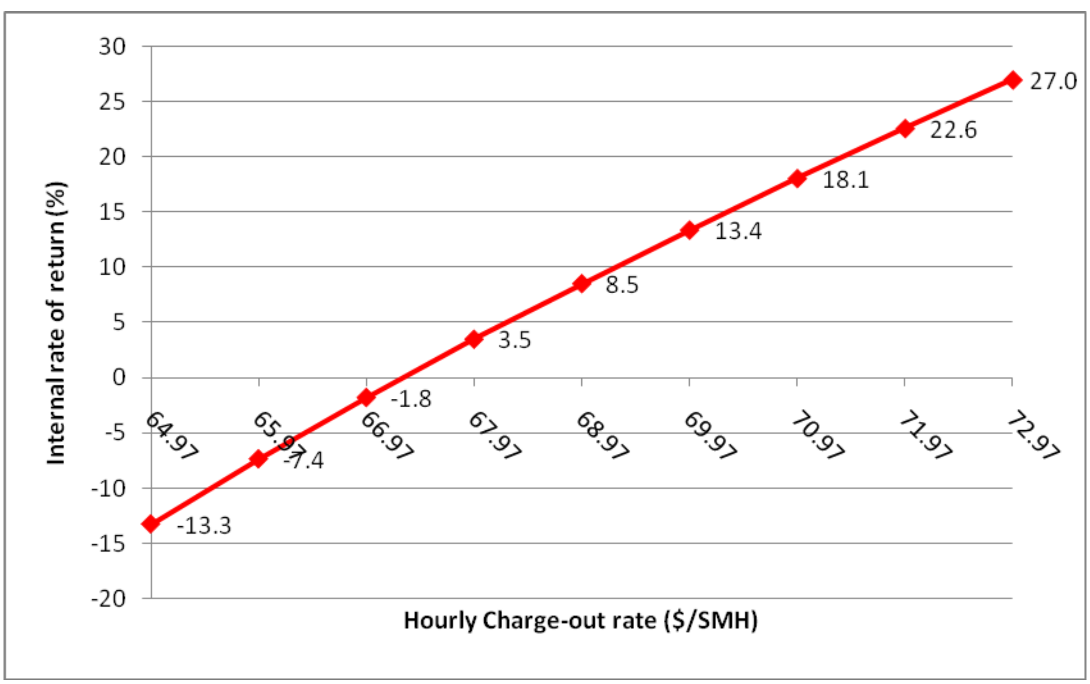

Figure 9. Effect of charge-out rates on rate of return: Loader

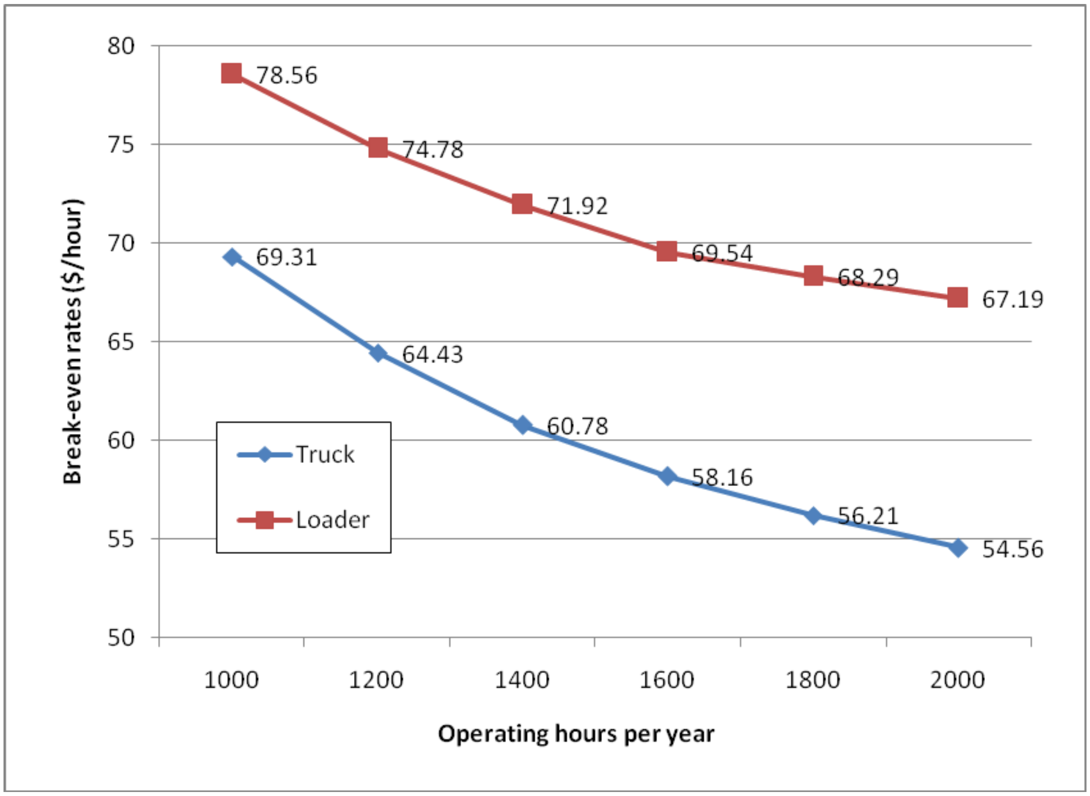

Figure 10. Effect of operating hours on break-even charge-out rates required to provide a 13.4% after-tax real rate of return on investment. It was assumed that the repair and maintenance cost increases by 50% of the base rate after 4,000 hours of machine operation.

Table 12. Summary of cash flows for trucking and loading in slash collection and transportation business. The annual operating hours was assumed to be 1,600 SMH each year over the economic life of each machine.

	-------------------- Year --------------------							
	0	1	2	3	4	5	6	7
Roll-off truck								
Cash flow before tax and financing	-99,000	20,766	20,169	20,774	21,397	22,039	22,700	43,181
Cash flow before tax	-59,400	10,925	10,328	10,933	11,556	12,198	22,700	43,181
Cash flow after tax	-59,400	37,818	4,546	4,732	4,909	5,076	15,209	28,931
Loader								
Cash flow before tax and financing	-59,500	16,527	15,193	15,648	16,118	28,501	-	-
Cash flow before tax	-35,700	7,458	6,124	6,580	16,118	28,501	-	-
Cash flow after tax	-35,700	22,242	1,492	1,555	10,799	19,096	-	-

Conclusion

Roll-off trucking systems can be cost-effectively used to remove slash resulting from shaded fuelbreak treatments without burning. The overall cost to collect and haul hand-piled slash was $22.95/green ton, based on forest road hauling distances (less than 3 miles). This can be translated to $230/acre to remove slash from the site if there were 10 tons of slash per acre. This indicates that mechanical removal of hand-piled slash would be cost-competitive with pile burning options. The cost for burning slash piles to mitigate fuels range from $150 to $850/acre in northern California. Furthermore, slash burning options raise concerns related to air quality, risk of escaped fires, and limited burn opportunities.

The costs of roll-off trucking operations can however significantly increase with increased hauling distance on gravel roads due to slow traveling speeds (less than 10 miles per hour on gravel roads) and low slash weight being hauled (3.91 ton/trip on average). For example, the overall cost of slash removal using the roll-off trucking system increases by $4.11/ton with each one-mile increase in hauling distance over secondary gravel roads. This suggests that roll-off trucking systems should be used primarily for short hauling to a central processing area where sufficient access for highway chip vans is provided. The slash piled at central locations could be ground to hog fuel for energy production. The roll-off trucking system allows for removal of hand-piled slash from inaccessible areas without pile burning and creates an opportunity for utilizing slash to generate energy; however, detailed planning should occur to minimize hauling distances for roll-off trucks.

The loader efficiently loaded slash into the containers at low cost ($9.16/ton), but costs could be decreased if the roll-off trucking system and loader were owned by a single contractor. This may eliminate the need for an additional pick-up and a trailer used to haul the loader to and from a job site. The loader is small enough to be carried inside a 40-yd^3 container. Loading cost can be further lowered if whole tree skidding methods are used. Trees and other vegetation which are skidded and piled along the roadsides can decrease costs since the loader does not need to travel throughout the stand.

The break-even charge-out rates for the truck and loader were $57.56/SMH and $69.54/SMH, respectively. At these rates, the contractors receive a 13.4% real rate of return on their invested capital after accounting for inflation and income taxes. These rates did not include overhead and other indirect cost items. The current contracting rates for these machines are $85 and $100/hour, respectively and provide favorable returns. This being said, break-even charge rates could significantly increase with decreases in work days per year. The investor should diversify work opportunities (e.g., waste management and construction sites) that could utilize a roll-off trucking system to keep their business profitable.

Literature Cited:

1. Green, L.R., Schimke, H.E., 1977. Guides for fuel-breaks in the Sierra Nevada mixed-conifer type. USDA Forest Service, Pacific Southwest Forest and Range Expt. Station, Berkeley, CA
2. James K. Agee, Berni Bahro, Mark A. Finney, Philip N. Omi, David B. Sapsis, Carl N. Skinner, Jan W. van Wagtendonk and C. Phillip Weatherspoon, The use of shaded fuelbreaks in landscape fire management, Forest Ecology and Management Volume 127, Issues 1-3, March 2000, Pages 55-66.
3. Bilek, E.M. 2007. ChargeOut! Determining machine and capital equipment charge-out rates using discounted cash-flow analysis. General Tech. Report FPL-GTR-171. Madison, WI: USDA Forest Service, For. Prod. Lab. 33p.
4. Brinker, R.W., J. Kinard, B. Rummer, and B. Lanford. 2002. Machine rates for selected forest harvesting machines. Circular 296 (revised). Alabama Agri. Exp. Sta.29 p.
5. Curran, N. 2008. Personal communication. Forester, of Mad River Ranger District, Six Rivers National Forest, USDA Forest Service, Mad River, CA.
6. Han, H.-S., H.W. Lee, and L.R. Johnson. 2004. Economic feasibility of an integrated harvesting system for small-diameter trees in southwest Idaho. For. Prod. J. Vol.54 (2): 21-27.
7. Miyata, E.S., 1980. Determining fixed and operating cost of logging equipment. General Technical Report NC-55. USDA Forest Service, North Central For. Exp. Sta. St. Paul, MN. 16.p
8. Rawlings, C., B. Rummer, C. Seeley, C. Thomas, D. Morrison, H.-S. Han, L. Cheff, D. Atkins, D. Graham, K. Windell. 2004. A Study of how to decrease the costs of collecting, processing and transporting Slash. Montana Community Development Corporation, Missoula, Montana, 21 p.
9. Tiangco, V., G. Simons, R. Kukulka, and S. Matthews. 2005. Biomass resource assessment in California. Prepared for the California Energy Commission, Public Interest Energy Research Program, CEC-500-2005-066-D, 54p.