COMPARISON OF A LARGE AND SMALL GRAPPLE SKIDDER IN A PINE PLANTATION THINNING APPLICATION

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(ABSTRACT)

The objective of this research was to compare the performance of a small (92 horsepower) grapple skidder with that of a large (185 horsepower) grapple skidder in corridor thinning applications in southern pine plantations. Comparisons included (1) time and production, (2) residual stand damage, (3) soil compaction, (4) cost, and (5) the impact of tree size on productivity.

The large grapple skidder was found to be (1) more productive, (2) associated with slightly more residual stand damage, (3) associated with less soil compaction, (4) less expensive on a cost per ton of production basis, and (5) more sensitive to variation in tree size than was the small grapple skidder.

The results of this research suggests that large grapple skidders are capable of excellent performance in corridor thinning of southern pine plantations.

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INTRODUCTION

Timber harvesting in the South has evolved from a low-capital, labor-intensive industry to a highly capitalized, highly mechanized industry. This change has been brought about by a decline in the availability of woods labor and a considerable increase in the demand for timber from the southern United States (Tufts and Stokes, 1986).

The continuing mechanization of thinning operations and the economic harvesting of small timber are of concern to the Southern forest products industry. Estimates indicate that 22 million acres of pine plantations have been established in the South (Knight and Sheffield, 1980). Of these 22 million acres, approximately 800 thousand acres will reach the age class (15 to 19 years) generally required for initial commercial thinning. The acreage available for initial commercial thinning during the next decade is estimated to be three times the current amount (Thomas and Hedlund, 1980). Combining the above acreage estimates with average stand diameters of six to nine inches at the time of initial thinning indicates the vast amount of small timber available for harvest now and in the near future.

Reisinger (1983) found that thinning was only slightly favored when the economic returns from thinning were compared with those of a no-thin management regime. This slight difference suggested that decisions to thin or not to thin may be influenced by short-term operating conditions such as wood flow and tax advantages rather than expected future returns. Consequently, he concluded that short-run cost differences between mechanized thinning systems are more significant than the long-term investment effects.

One of the most important factors influencing the productivity of harvesting equipment in the South is the size of the timber harvested (Hypes, 1979). The productivity of most conventional systems drops greatly when the average stand diameter is less that ten inches (Stuart, 1981). The most successful approach for reducing the impact of harvesting small timber has involved shifting from individual tree systems to batch handling systems. This approach is typified by the feller-buncher, grapple skidder, and gate delimbing system (Stuart, 1981).

Foresters have long harbored the dream that a small machine was the solution to small timber harvesting. The ideal grapple skidder for use in thinning is often described as being small, narrow and light. However, the general rule for harvesting machinery has been that "bigger is better". A large grapple skidder is expected to be more productive than a small grapple skidder and should attain a lower cost per unit value of production. But, low levels of residual stand damage are thought to be difficult to accomplish with large, heavy machinery. Because of this, small skidders are considered by many to be the answer for thinning with low levels of residual stand damage. Unfortunately, this thinking may cause logging contractors to use less efficient machinery.

Thus, determining optimal skidder size for use in thinning would seem to involve finding the balance between productivity and residual stand damage. To explore this question of balance, the objective of this research was to compare the performance of a small grapple skidder with that of a large grapple skidder in a corridor thinning application. Comparisons included (1) time and production, (2) residual stand damage, (3) soil compaction (4) cost, and (5) the impact of tree size on grapple skidder productivity.

LITERATURE REVIEW

The development of the articulated rubber-tired skidder for use in logging was the result of a short evolutionary period following World War Two. The first wheeled tractors used in logging were four-wheel drive trucks. These vehicles outperformed farm tractors, but were unable to perform within accepted limits of reliability because of their rigid frames (Silversides, 1967). The need for a suitable wheeled unit to operate in the woods was first recognized by the Canadian Pulp and Paper Association. A mechanization project was established to fill this need, and resulted in the first articulated rubber-tired forwarder, the Mark V Bonnard Hauler, in 1955 (Silversides, 1967). According to Stenzel et al. (1985) the Garret Tree Farmer, introduced in 1958, is credited with being the pioneer articulated rubber-tired skidder. Since their introduction in the late 1950's rubber-tired skidders have continued to be the most popular skidding vehicle in the Southern United States. At least 95 percent of southern timber producers currently use rubber tired machines for skidding (Weaver et al., 1979).

Hydraulic grapples were designed to eliminate the need for chokers and choker setting. The Beloit skidding grapple is believed to be the first, and had the ability to gather, transport and drop several stems without the need of chokers. The acceptance of the grapple skidder first took place on sawlog operations. On pulpwood operations, the grapple skidder was not fully accepted until the advent of the feller-buncher (Stenzel et al., 1985).

The productivity of most conventional systems drops greatly when the average stand diameter is less than ten inches (Stuart, 1981). One approach used to reduce the response to stand diameter involves shifting from individual tree to batch handling systems. According to Stuart (1981), this approach is typified by the feller-buncher, grapple skidder, gate delimbing system. Feller-bunchers enhance skidding productivity by building bunches of felled trees, allowing a grapple skidder to acquire several trees at a time. Several reports on the use, productivity and cost of grapple skidders are available.

A six month study in British Columbia showed that skidding production with grapple skidders averaged 30 percent greater than with conventional choker skidders. It was found that travel time was the same for both machines and that the large increase in productivity was due to decreased hooking and unhooking time. The grapple skidder was the more expensive of the two to own and operate (Hart, 1970).

To evaluate production and cost, McDermid and Perkins (1971) compared choker and grapple skidders on several operations in Louisiana. They found that under uniform conditions, grapple skidders will outproduce choker skidders at virtually all distances, and were cheaper to operate per unit of volume beyond 250 yards of skidding distance.

Anderson and Granskog (1974) measured the productivity of three types of mechanized logging systems that could be used for row thinning slash pine plantations. One of the systems studied consisted of a Caterpillar 950 Tree Harvester and a Caterpillar 518 grapple skidder. It was found that one-way skidding distance (feet) and bunches of logs per load predicted 95.6 percent of the variation in skidding time.

Czerepinski (1978) reported the results of an evaluation of harvesting systems used in pine plantations in the Southeast. In this study, cycle time and productivity were observed for a Franklin 170 grapple skidder operating in plantation thinning. Times per turn ranged from 3.43 minutes at a 700 foot skidding distance to 4.60 minutes at a 1400 foot skidding distance. For the seven inch diameter class, production ranged from 10.5 cords per hour at a 700 foot skidding distance to 7.9 cords per hour at a 1300 foot skidding distance. He found minimal damage to the residual stand except where skidders turned at the end of the rows.

Hypes (1979), used computer simulation to explore the impact of tree size on harvesting production and cost. Individual harvesting functions as well as specific harvesting systems were studied to determine which harvesting activities are most sensitive to tree size. Of the eight functions analyzed, tree length cable skidding was the most severely affected. Even with two stems per choker in small timber, average volumes per turn were far below capacity. Grapple skidding with gate delimbing was affected by decreasing stand diameters, but only to a limited extent. Grapple skidding productivity of previously delimbed material was insensitive to variations in tree size.

Strickland (1980) looked at nine combinations of equipment used in plantation thinning. He ranked these systems by relative productivity and relative initial capital investment. The system using feller-bunchers and grapple skidders was ranked first in productivity and was found to have a relatively low initial capital investment.

Lane (1981) used computer simulation to evaluate the productivities and cost associated with two mechanized harvesting systems. He found that grapple skidder productivity was affected by the harvesting system chosen. Due to the limited number of trees per drag caused by gate delimbing, skidder production for the gate delimbing longwood system was much lower than for the whole-tree chipping system.

Stokes and Lanford (1982) conducted a series of thinning studies with the goal of determining feasible harvesting patterns and productivity rates for various equipment combinations. Production ranged from five cords per hour for a small grapple skidder performing selective thinning to over 14 cords per hour for a medium size grapple skidder performing row thinning. They concluded that the use of a small grapple skidder during selective thinning offers an excellent opportunity for a silviculturally improved stand at an acceptable cost.

Tufts and Stokes (1986) studied six different models of rubber-tired grapple skidders. They found that load size was the most important variable affecting skidder productivity and that skidding distance was the most important variable affecting time per cycle. Smaller skidders were found to be more maneuverable, and cycle time may have been reduced because of this. Underpowered machines were considered to be more productive in a comparative sense if large machines never skid a maximum load. The larger skidders did not travel faster with the same size load, and may have been underutilized because load size decreased slightly as horsepower increased. Large machines skidding large loads were considered to be inefficient when gate delimbing because large loads were too wide to successfully delimb at the gate. Correct bunch size for gate delimbing was considered to be such that the skidder was required to grapple only one bunch per turn.

Corwin (1987) surveyed industry procurement personnel to identify successful small tree harvesting systems and to document and analyze characteristics of these systems. Of the systems identified as successful, a vast majority were of the feller-buncher, grapple skidder system type. He gathered further information on the business aspects of six feller-buncher, grapple skidder systems and found significant differences in skidder productivity, but was not able to determine factors which caused the differences without additional information in the form of intensive time studies.

Green and Stokes (1988) quantified productivity and costs for small grapple skidders in southern pine thinning applications. Two Franklin 105 grapple skidders were examined. They found that when gate delimbing was used, production was reduced from 11.47 cords per hour to 7.85 cords per hour. However, the reduction in skidder productivity was compensated for by a reduction in total cost per cord of production due to the high cost of manual delimbing.

While mechanization has dramatically increased harvesting productivity, questions of residual stand and site damage have been raised. Because of the high cost of plantation establishment and protection, precautions must be taken to minimize residual stand damage and soil compaction when operating in these stands. Young trees with thin bark and rapidly growing succulent root systems cannot be subjected to stresses that older stands can withstand (Kluender, 1984). According to Pierrot (1984), a large portion of damage incurred during mechanical thinning is caused during the skidding phase. According to Tufts et al. (1986) damage to the residual stand in thinning operations occur in three ways: (1) ground compaction, (2) damage to roots and root mats due to high local pressure and (3) stem damage due to contact with moving machinery.

Kluender (1984) considers compaction of the upper soil layers to be the single most significant threat to the site in a partial harvest. When heavy equipment passes over a site, the air space may be collapsed, leaving a compacted soil. A high proportion of a pine tree's roots lie close to the surface of the ground and are in the region of maximum compaction. A significant problem arises when root hairs that take up nutrients cannot penetrate new areas because of compaction (Kluender, 1984). Karkkainen (1968) studied injuries to roots and stems of spruce during thinning and found that the amount of root injuries was positively correlated to the weight of the machine. During a thinning study conducted in Northern hardwood stands, Biltonen (1976) found that the harvesting method exerted a strong influence on the occurrence of root injuries. Mechanical row thinning with selection caused root damage to nine percent of the residual stand.

In addition to the potential damage caused by compaction and root breakage, scraping of the stem from machinery travel may lead to discoloration and decay (Hoffman, 1981). Biltonen et. al. (1976) found that injuries to stems during harvesting operations were the most prominent form of tree damage and that mechanical row thinning with selection caused stem damage to 14 percent of the residual stand. Bryan (1971) studied damage done to standing timber during thinning and found that skidders damaged about eight percent of the residual stand. Green and Stokes (1988) found that fewer than three percent of the residual stand showed stem damage due to skidding during thinning.

Kluender (1984) offered several operational guidelines toward the formation of a soil-site protection plan. One of these guidelines was tailoring the machine to the operation and involved the use of smaller machines wherever possible. According to Lanford and Stokes (1984), many companies have attempted to convert a harvesting system designed for clearcutting into one for thinning. They state that equipment designed for clearcutting will probably not perform well in thinnings and that thinning machines need to be smaller. Green and Stokes (1988) believe that minimal damage is often difficult to accomplish with machinery commonly used in clearcut operations and that smaller machines are needed to perform selective thinning with low levels of residual stand damage.

Hoffman (1981) writes that equipment constraints result from both silviculture and economics, and that silvicultural considerations impose size and weight restrictions. The size restriction relates to the spacing of the trees and the dimensions of the machine. Lanford and Stokes (1984) agree with this, and suggest that skidders must be narrow to keep corridor width to a minimum.

Hoffman's (1981) second equipment constraint involves weight. Compaction depth can be ameliorated by lightweight equipment or by improving flotation through the use of wider tires. Stuart and Greene (1985) found that reducing ground pressure of skidding equipment by using larger tires or lighter machines can directly reduce soil compaction. Similarly, Kluender (1984), reported that ground pressure can be reduced by the use of wide, low pressure tires.

Wasterlund (1987) studied machine forces that have the potential to cause stem damage and soil compaction in stands of Norway spruce during thinning operations. He found that stem damage was concentrated on the lower part of the stem and occurred most frequently during the sap period (the period of weakest bark). Wheel ruts were found to be sign of reduced tree growth as many of the finer tree roots can be destroyed by a six-centimeter deep wheel rut. He estimated that this type of damage my reduce the growth of Norway spruce by 25 to 30 percent. To reduce stem damage and soil compaction when thinning a spruce stand located on fine, sandy till soil, he recommended that harvesting machinery should stay clear of residual stems during the sap period and should not have a ground pressure higher than 30-50 KPA.

Contrary to some of the above arguments, Karkkainen (1968) found that even though the amount of root injuries could be explained by machine weight, other variables concerning transportation devices could not be converted to factors explaining the amount of stem damage. He observed that 30 percent of the injuries tallied during the study could have been avoided by increased operator caution. The professional skill of the skidder operator has a significant impact on the amount of tree injuries.

The ideal skidder for use in thinning has been described as being small, narrow and light. According to Stuart (1981), foresters have long harbored the dream that a small machine was the solution to small timber harvesting. The concept is that machine size should vary in direct proportion to the size of the timber being harvested. But, if machine size varied by piece size in other industrial applications, sand would be moved in wheelbarrows and rocks would be moved with tractor trailers (Stuart 1981). Lanford and Stokes (1984) consider that the general rule for logging machinery is that "bigger is better". It is less expensive per person to transport 40 people in a bus than to transport four people in a car. Likewise, large skidders are usually more productive than small skidders and should attain a lower cost per unit of production. However, in thinning, space among residual trees restricts the size of machines which are suitable. Because of this, smaller skidders are generally considered to be the answer for thinning with low levels of residual stand damage. Thus, preconceived ideas about thinning may force the logger to use less efficient machines (Lanford and Stokes, 1984).

METHODS AND PROCEDURES

The purpose of this study was to compare the performance of a small grapple skidder (Franklin 105) with that of a large grapple skidder (Franklin 170) in corridor thinning applications. The data were collected during September, October and December of 1987 in the lower coastal plain of South Carolina. Comparisons included elemental time, productivity, corridor width, residual stand damage, soil compaction and the effect of tree size on productivity.

System Descriptions

Description of system using the Franklin 105 grapple skidder.

System A had performed corridor thinning operations in the lower coastal plain of South Carolina for about 28 months prior to the time of study. The operation is owned by a wood dealer who also leases equipment to other independent contractors. The operation usually harvests tree length pine pulpwood from industry-owned plantations, but also contracts for thinning on private lands. The owner did not take an active role in job management, leaving this to a working foreman and an associate. During the study, the crew worked an average of nine hours per day and shipped an average of 120 tons of wood per day. The crew was paid on a per-load basis, with the individuals rate per load set according to his job responsibility.

System A's crew consisted of four men plus a contract trucker. The feller-buncher operator had five years of harvesting experience, and had been with the crew for six months. The skidder operator had no prior harvesting experience, and had been with the crew for two years. The deck man has been with the crew for four months, and had twelve years of harvesting experience elsewhere. The loader operator (working foreman) has been with the crew since it was formed, and has over twenty years of harvesting experience. All of the crew members were cross-trained and able to perform other tasks.

Figure 1 shows the wood flow of system A. The feller buncher used was a Franklin 405 equipped with a Franklin Model 16 accumulating head. A Franklin 105 grapple skidder (the study machine) was used to skid bunches out of the woods. The trees were gate delimbed by the skidder operator as they were skidded to the landing. The loader was a trailer mounted Husky XL-185 with a fixed heel and log grapple. The contract hauler used a White Road Boss tractor and a pole trailer. The condition of this equipment is detailed in Table 1.

The Franklin 105 grapple skidder (Figure 2) was 36 months old at the time of the study, with 2720 engine hours on the clock. The engine had been rebuilt (pistons, sleeves, rings, inserts, head grinding) six months prior to the time of study. The machine is 109 inches wide, 235 inches long and weighed 19,950 pounds with optional tires. The 3-53N50/3 Detroit Diesel engine has 159 cubic inches of displacement and generates a maximum of 92 horsepower at 2800 RPM. The skidder was equipped with Champion Spade-grip 28L-26 tires on 25 inch rims, and a grapple with 74 inch openings. Franklin 105 grapple skidder specifications are further detailed in Appendix A.

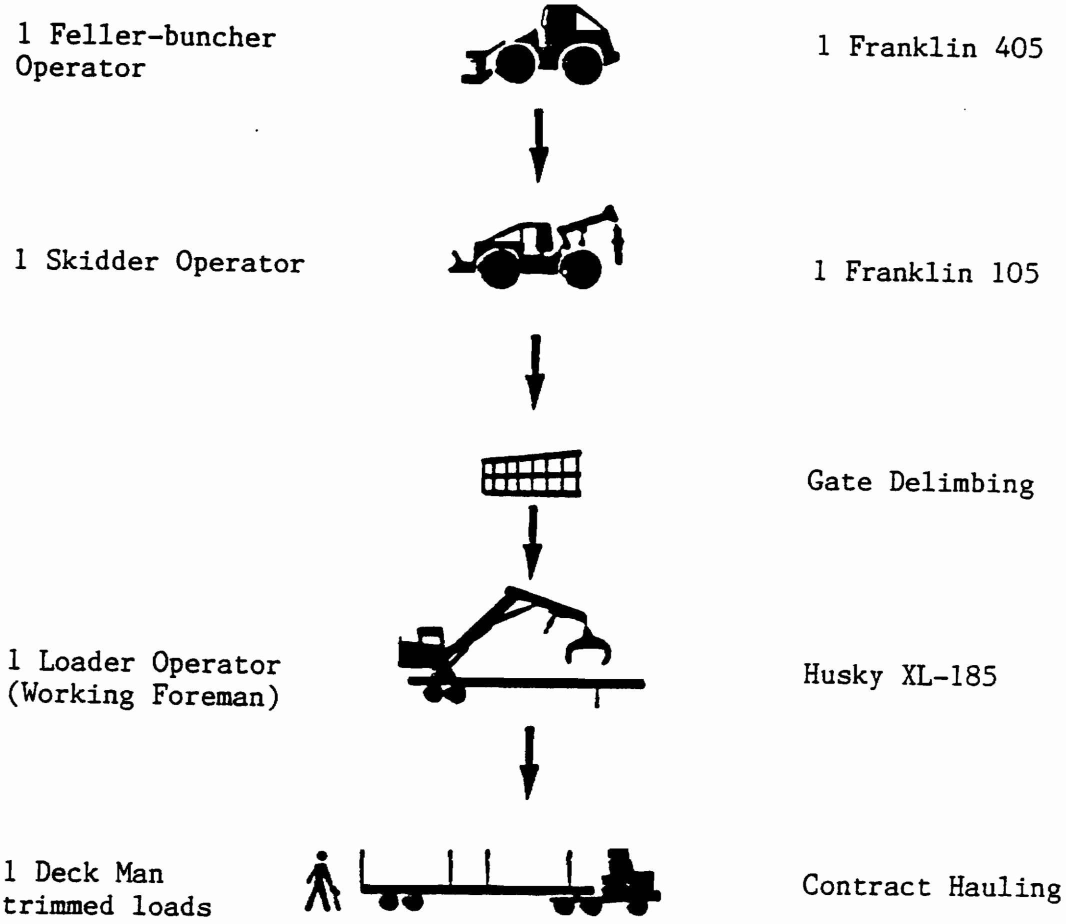

Figure 1. System A material flow.

Table 1. System A equipment condition.

Equipment	Age (months)	Engine Hours	Condition
FR 405 Feller-buncher	3	215	Excellent
FR 105 Skidder	36	2720	Good
Husky XL-185 Loader	78	3532	Good
White Road Boss Tractor	132	---	Fair

Figure 2. Franklin 105 grapple skidder.

To initiate a thinning, the feller buncher operator cut the main skid trail from the landing perpendicular to the rows. Next, two or three corridors were cut on seventy foot centers at right angles to the main skid trail. The grapple skidder worked behind the feller-buncher acquiring bunched trees in the corridors The feller-buncher operator would then perform operator selection, thinning between corridors that had been previously cleared of bunches, placing more bunches in the corridor. As before, the skidder worked behind the feller-buncher, skidding the bunches to the edge of the deck where they were gate delimbed and then dropped near the loader. After acquiring a new bunch, the skidder would back-up slightly to pack the turn and break off some limbs. When large amounts of slash had accumulated around the delimbing gate, the skidder would pick up a grapple load of limbs and slowly release them as it traveled back along the corridor.

The system using the Franklin 105 was working in a Loblolly pine (Pinus Taeda) plantation in Williamsburg County, South Carolina. The plantation is located on a dry, well-drained sandy ridge, and the soil is classified as Dunbar fine sandy loam. The plantation was 19 years old at the time of the thinning with a site index of 71 (base age 25). The stand contained an average of 315 trees per acre, with the average tree being 7.9 inches in diameter and 38 feet tall to a four inch top. Merchantable volume was estimated to be 34.2 cords per acre.

Description of system using the Franklin 170 skidder.

System B is a sole proprietorship which had been performing corridor thinning operations in the lower coastal plain of South Carolina for about 36 months prior to the time of study. This operation usually harvests tree length pulpwood from industry owned plantations, and is production oriented. The owner of this operation has a close working relationship with a local wood dealer, and has leased some of his equipment from this wood dealer. The owner/foreman was always present, did not have any operating responsibilities and took a very active role in job management. During the study, the crew worked an average of nine hours per day, producing an average of 309 tons of wood per day. The crew was paid on a per load basis with the wage rate per load depending on the individual's job responsibility. A weekly bonus was paid to all crew members after the 50th load of the week was delivered.

System B's crew consisted of the owner and eight men. Their experience and job responsibilities are described in Table 2. The crew can be characterized as highly motivated.

Figure 3 shows the material flow of system B. Two Franklin 105 feller-bunchers were used; one feller-buncher was equipped with a 14 inch Morbark rapid buncher shear head and the other was equipped with a 17 inch accumulating head. A Franklin 170 grapple skidder skidded bunches to the landing. A Timberjack 350-A grapple skidder was used to pick up scattered wood in the corridors and occasionally assisted with production skidding. The loader was a trailer mounted Husky Brute XL 220. The owner of the operation also owned three trucks (an International 4300 and two Whites), and three pole trailers. The condition of this equipment is detailed in Table 3.

The Franklin 170 grapple skidder (Figure 4) was five months old at the time of the study and was leased. The machine is 120 inches wide, 252 inches long, and has an equipped weight of 26,325 pounds. The 4-53TC60 Detroit diesel has 212 cubic inches of displacement and generates a maximum of 185 horsepower at 2500 RPM. The skidder is equipped with Firestone flotation 23 DT Logger 67X34.00-25 tires and a 90 inch grapple. Specifications for the Franklin 170 grapple skidder are further detailed in Appendix B.

As with system A, the feller-bunchers cut the main skid trail perpendicular to the rows. Next, each feller buncher cut two or three corridors on 70 foot centers at right angles to the main skid trail. The grapple skidder worked behind the feller-bunchers acquiring bunched trees in the corridors. The feller buncher operators would then perform operator selection thinning between corridors that had been cleared of bunches. The skidder would once again work behind the feller bunchers, skidding the bunches to the edge of the deck where they were gate delimbed and then

Table 2. System B crew description.

Employee	Time in Crew (yrs.)	Time in Harvesting (yrs.)	Primary Responsibility	Other Respons.
1	--	15	owner/foreman	all
2	3	5	skidder operator	loader
3	1½	½	truck driver	---
4	2	10	feller buncher	skidder
5	1½	10	feller buncher	skidder
6	4	8	loader	truck
7	2	2	skidder operator	---
8	1/3	1/3	deck man	skidder
9	3	3	truck driver	---

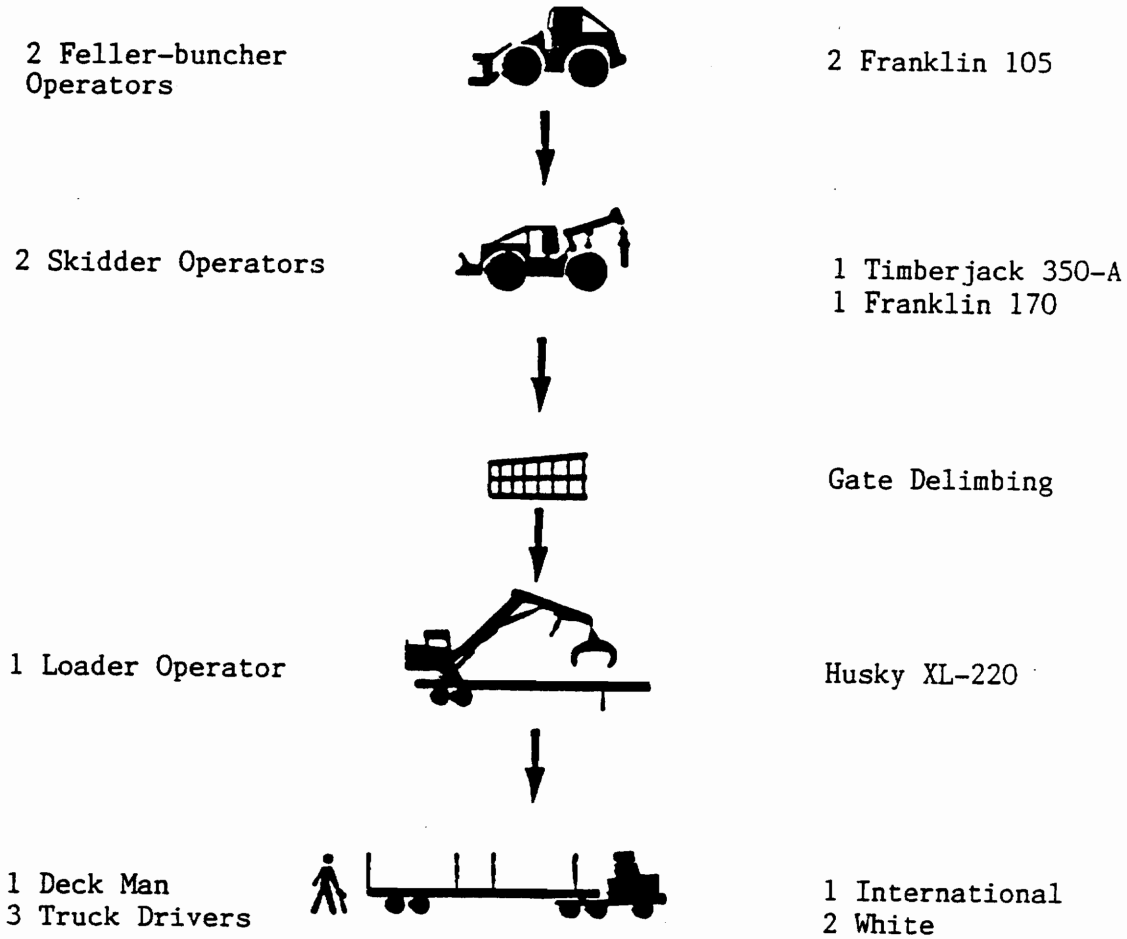

Figure 3. System B material flow.

Table 3. System B equipment condition.

Equipment	Age	Engine Hours	Condition
FR 105 FB 14″ morbark rapid buncher	24 mos.	---	Very good
FR 105 FB with 17″ morbark head	30 mos.	---	Very good
Franklin 170 grapple skidder	5 mos.	---	Excellent
Timber Jack 350-A	6 yrs.	---	Poor
Husky Brute XL-220	---	---	Fair
International 4300	10 yrs.	---	Good
White Road Boss	12 yrs.	---	Good
White Cab-over	15 yrs.	---	Good

Figure 4. Franklin 170 grapple skidder

dropped near the loader. This "leap-frog" process continued until the tract was thinned. The Franklin 170 grapple skidder often acquired multiple bunches, and generally skidded the production of both feller-bunchers. The Timberjack 350-A, an older machine, picked up scattered stems, occasionally skidded corridor bunches and was often involved with deck management activities such as removing accumulations of limbs from around the delimbing gate.

The operation using the Franklin 170 grapple skidder was working in a Loblolly pine plantation located in Georgetown County, South Carolina, approximately 22 miles from the System A study site. This plantation is growing on low-lying, poorly drained soils consisting of Eulonia loamy fine sand. The plantation was 16 years old at the time of the study with a site index of 77 (base age 25). The stand contained an average of 483 trees per acre. The average tree was 6.6 inches in diameter and 33 feet tall to a four inch top. Merchantable volume was estimated to be 34.7 cords per acre.

Time and Production Study

Time and production data were collected for 132 skidding turns for the small (Franklin 105) grapple skidder and 95 round trips for the large (Franklin 170) grapple skidder. This data was collected during two separate five-day studies in September and October 1987.

Elemental time measurement.

A stopwatch-equipped, one-half inch VHS video camera was positioned on the landing of the operation in a manner that allowed observation of skidder arrival and departure, gate delimbing and deck management activities. While the landing camera was running, the skidder was followed through the corridors where bunch acquisition activities were timed with a stopwatch. The stopwatch in the video camera and the stopwatch used to time acquisition activities were activated at the same moment to allow for continuity. Later, the videotapes were reviewed and skidder arrival, departure, gate delimbing and deck management times were noted. The landing activity times were then coupled with the corresponding acquisition times, thus forming a continuous record of skidder activity. Bunch acquisition times were measured to the nearest centiminute while landing times were measured to the nearest one-tenth of a second and later converted into centiminutes. Additionally, each skidder was equipped with a TRT service recorder (with a four hour clock) to determine machine availability and utilization. This unit allowed recording of operating time to the nearest minute.

The continuous record of skidder activity was reduced into the following seven elements:

1. Travel empty. Travel empty was defined as the elapsed time between releasing the previous bunch near the loader, and beginning to position to acquire the next bunch.
2. Positioning. Positioning was defined as the time difference between the end of forward movement in the corridor and the cessation of backwards movement after the skidder backed up to the bunch.
3. Acquiring. Acquiring was defined as the time difference between cessation of backwards movement over the bunch and the beginning of forward motion. Acquiring reflects the time taken to pick up the bunch after the grapple was positioned over the bunch.
4. Travel loaded. Travel loaded is the time difference between the beginning of forward motion in the corridor and the beginning of gate delimbing at the deck.
5. Delimbing. Delimbing started when the skidder started to move backwards at the delimbing gate and ended when the skidder started to leave the delimbing gate.
6. Releasing. Releasing began when the skidder started to leave the delimbing gate and ended when the bunch was dropped near the loader.

7. Round trip cycle time. Round trip cycle time is the difference between releasing the previous drag and releasing the current drag. Cycle time begins and ends at the loader and is the sum of the previous six elements.

In the case of multiple bunch acquisition, the positioning element was used only once. Here, acquiring reflects the time difference between cessation of backwards movement over the first bunch and the beginning of forward motion after the last bunch was acquired.

The data were analyzed to determine if significant differences in elemental time measurements exist between skidder types. Two group T-tests and Wilcoxon rank sum tests were used for all comparisons.

Distance measurements

The location of each corridor was determined by measuring the distance along the main skid trail to the center of the corridor. The location of a particular bunch in the corridor was determined by measuring down the corridor to the bunch. Travel patterns along the landing were also measured. These measurements allowed the definition of three variables: round trip distance, distance loaded, and distance empty.

Round trip distance was defined as the distance traveled after releasing the previous bunch at the landing and beginning to delimb the following load. Distance full is the distance traveled after acquiring a bunch in the corridor and then beginning to delimb the load at the deck. Distance empty is the distance traveled in between releasing the bunch near the loader, and beginning to position in the corridor. In the case of multiple bunch acquisitions, distance full began after the first bunch was acquired.

The data were analyzed to determine if significant differences in distance measurements exist between skidder types. Two group T-tests and Wilcoxon rank sum tests were used for all comparisons.

Load weight measurements

The number of trees, butt diameters, and average tree length (to a four inch top) were recorded for each bunch along the corridor. Total weight per tree (lbs.) was estimated using the following equation (Scrivani, 1987):

$$\text{Total green weight for Loblolly pine} = 45.63 + .16\,(D^2L)$$

Where: $D =$ Butt diameter and $L =$ Length in feet to a four inch top.

The equation used for estimating total green weight per tree was checked against Sauciers (1981) equation for predicting total green weight of Loblolly pine. The results of forty comparisons indicated that green weight per bunch differed (depending on the equation used) by an average of five percent.

The data were analyzed to determine if significant differences in load weight exist between skidder types. Two group T-tests and Wilcoxon Rank sum tests were used for all comparisons.

Additional measures of skidder performance

The data were combined to form additional measures of skidder performance. These additional measures are the following:

1. Productivity. Productivity is the result of dividing the weight of the bunch(es) being skidded by the corresponding round trip cycle time. This measure is expressed in tons per productive hour.
2. Round trip speed. Round trip speed is the result of dividing round trip distance by round trip cycle time, and is expressed in feet per minute. For this application, round trip cycle time does not include delimbing or releasing.

The data were analyzed to determine if significant differences in activity or productivity measures exist between skidder types. Two group T-tests or Wilcoxon rank sum tests were used for all comparisons.

Residual Stand Damage and Site Disturbance

Residual stand damage survey.

Following each day's production data acquisition, corridors skidded that day were surveyed and all trees within six feet of either side of the corridor were inspected for damage. Each tree within this zone was classified as having (1) no damage, (2) minor damage or (3) major damage, depending on the amount of bark removed. In accordance with a study by Biltonen (1976), fifty square inches of exposed cambium was the threshold between minor and major damage. Also, tops and large branches broken off during harvesting were considered to be major damage. Trees which were located at the intersection of the main skid trail and a corridor (turn trees) were included in this count if they had not been removed. Categorical analysis of this data produced a per acre damage ratio or percentage associated with each skidder.

During this damage survey, corridor width was determined by measuring the distance between leave trees at narrow points in the corridor. These width measurements were used to evaluate stand loss associated with corridor removal.

In total, 828 trees were inspected and 103 corridor widths were measured on the operation using the Franklin 170 grapple skidder; 1134 trees were inspected and 107 corridor widths were measured for the operation using the Franklin 105 grapple skidder. To test the hypothesis that the incidence of stand damage increases with increasing skidder size, categorical data analysis techniques were employed. A two sample T-test was used to evaluate differences in corridor width by machine size.

Soil Compaction

During December of 1988, soil compaction data were collected from 101 locations in the 105 study area and 93 locations in the 170 study area. The compaction test sites were located along corridors where the skidder was known to have operated during the production study. At each corridor location changes in soil density were evaluated at the zero to six inch depth using a cone penetrometer. Penetrometer readings were taken in non-compacted areas to the left and right of the corridor and in compacted areas in the tire paths to the left and right of center in the corridor. The average of the non-compacted readings and the average of the compacted readings were used to obtain a paired sample for a particular corridor location. The differences between the paired samples were used to test the hypothesis that soil compaction differs with skidder type.

To help in explaining differences in soil density, five soil samples form each study site were analyzed to determine moisture content. Also noted was approximate litter depth at each compaction test site.

Cost Analysis

The production data collected during the field studies were combined with cost estimates to arrive at total weekly costs and costs per ton skidded for the 105 and the 170. Cost inputs used in the analysis were obtained from equipment dealers, tax commissioners, and insurance agents. A discounted cash flow analysis was performed to determine the effect on net present value of a system using a 105 skidder and a system using a 170 skidder in thinning applications.

Computer Simulation

The Generalized Machine Simulator (Stuart and Farrar, 1983) was used to determine the effect of tree size on grapple skidder productivity. Grapple skidder time and production data collected during the field studies and previously published feller-buncher production studies (Lanford and Sirois, 1983) were used as input for the simulation. In total, six separate simulations were performed using two different harvesting systems and three different forest models. Each simulation consisted of a feller-buncher and either a Franklin 170 or a Franklin 105 grapple skidder performing corridor thinning in three different aged Loblolly pine plantations.

RESULTS AND DISCUSSION

Time and Production

Time and production data were collected for 132 round trips for the 105 and 95 round trips for the 170. A continuous record of skidder activity was obtained and then reduced into the following six elements: travel empty, positioning, acquiring, travel loaded, delimbing, and releasing. Of these, delimbing time was the only element not showing a significant difference (alpha = .05) between skidders. Summary statistics for each of the above elements are presented in Table 4.

Prediction of round trip cycle time

Round trip cycle time (Table 5) is the sum of the above elements. Round trip cycle times for the 170 were found to be significantly longer than those of the 105 (alpha = .05). Round trip distance (Table 6) was defined as the distance traveled after releasing the previous load at the landing and beginning to delimb the load in question. It was found that round trip distances for the 170 were significantly longer (alpha = .05) than were those for the 105.

Table 4. Summary statistics for time study elements.

Element	Skidder	Min	Median	Mean	Standard Deviation	Max
Travel empty	105	0.47	1.49†	1.69‡	0.85	5.99
	170	0.63	1.80†	2.02‡	1.02	7.05
Positioning	105	0.05	0.32†	0.36‡	0.21	1.45
	170	0.11	0.54†	0.67‡	0.45	2.66
Acquiring	105	0.05	0.35†	0.45‡	0.42	2.53
	170	0.10	0.66†	0.95‡	0.92	4.68
Travel loaded	105	0.30	1.83†	1.84‡	0.89	5.27
	170	0.60	2.01†	2.14‡	0.94	7.00
Delimbing	105	0.12	0.35	0.51	0.45	3.19
	170	0.13	0.41	0.51	0.46	2.52
Releasing	105	0.25	0.66†	0.74‡	0.38	
	170	0.14	0.36†	0.43‡	0.26	2.03

† Indicates significantly different at alpha = .05 using a Wilcoxon rank sum test.

‡ Indicates significantly different at alpha = .05 using a T-test.

Table 5. Summary statistics for round trip cycle time (minutes).

	105	170
Mean‡	5.59	6.71
Median†	5.39	6.56
Standard deviation	1.56	1.70
Minimum	2.95	3.30
Maximum	11.06	11.61

† Indicates significantly different at alpha = .05 using a Wilcoxon rank sum test.

‡ Indicates significantly different at alpha = .05 using a T-test.

Table 6. Summary statistics for round trip distance (feet)

	105	170
Mean‡	1585	1824
Median†	1601	1992
Standard deviation	551	456
Minimum	393	588
Maximum	2783	2650

† Indicates significantly different at alpha = .05 using a Wilcoxon rank sum test.

‡ Indicates significantly different at alpha = .05 using a T-test.

Regression analysis was used to determine the effect of distance on travel time. A zero-intercept model was constructed for both machines to predict travel time (travel empty plus travel loaded) using round trip distance as an independent variable. These equations and their respective R-square values (based on uncorrected sum of squares) are as follows:

105: Travel time in minutes = Round trip distance (0.0022)
R-square = 0.94.
170: Travel time in minutes = Round trip distance (0.0022)
R-square = 0.90

The equality of slope in the above equations was expected since average round trip speed for the 170 (444 feet per minute) was very close to the average round trip speed for the 105 (438 feet per minute).

To predict round trip cycle time using round trip distance as an independent variable, the sum of the means of the distance independent variables (positioning, acquiring, delimbing, and releasing) were used as intercept terms. These intercept terms were combined with the previous equations to yield the following:

105: Cycle time in minutes = 2.06 + Round trip distance (0.0022)
170: Cycle time in minutes = 2.55 + Round trip distance (0.0022)

These equations are represented graphically for the 105 and 170 in Figures 5 and 6, respectively.

To check this method of cycle time prediction, regression analysis was used to predict cycle time using distance as an independent variable. This check produced slope terms that were nearly identical to the previous no intercept models and intercepts that were close to the sum of the means of the distance independent variables. The predictability of the fixed times can be explained by the fact that the feller buncher operators constructed piles in accordance with a fixed grapple capacity and the skidder operators had little control over the size of the bunches that they acquired.

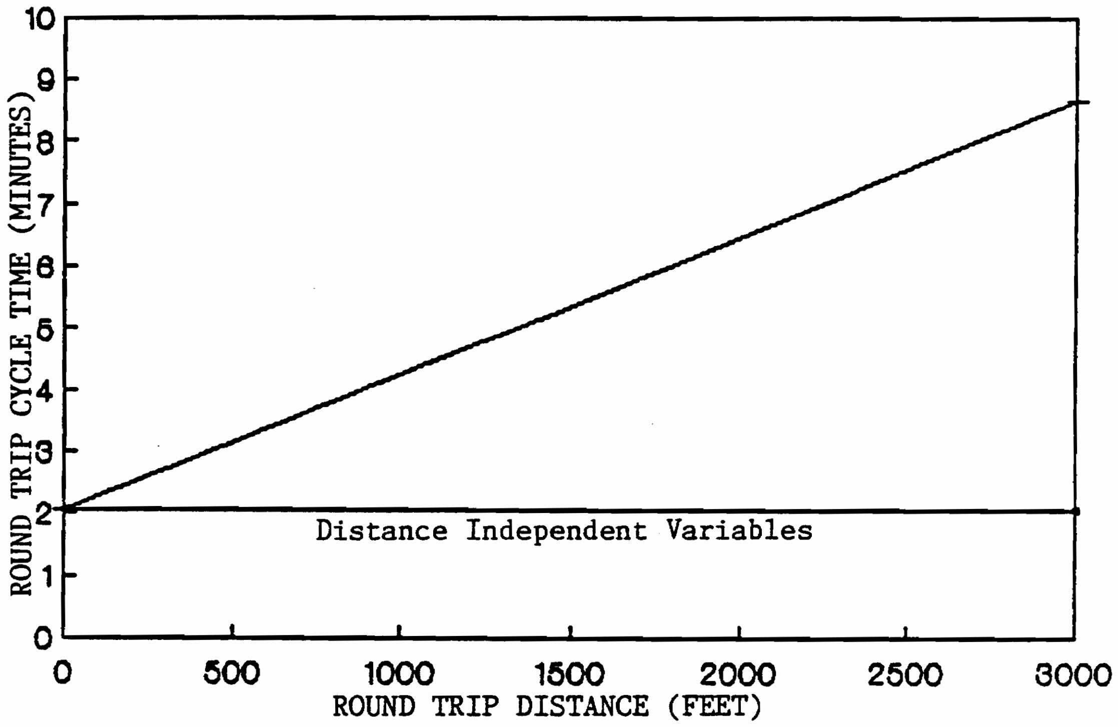

Figure 5. Graphic representation of round trip cycle time for Franklin 105 grapple skidder.

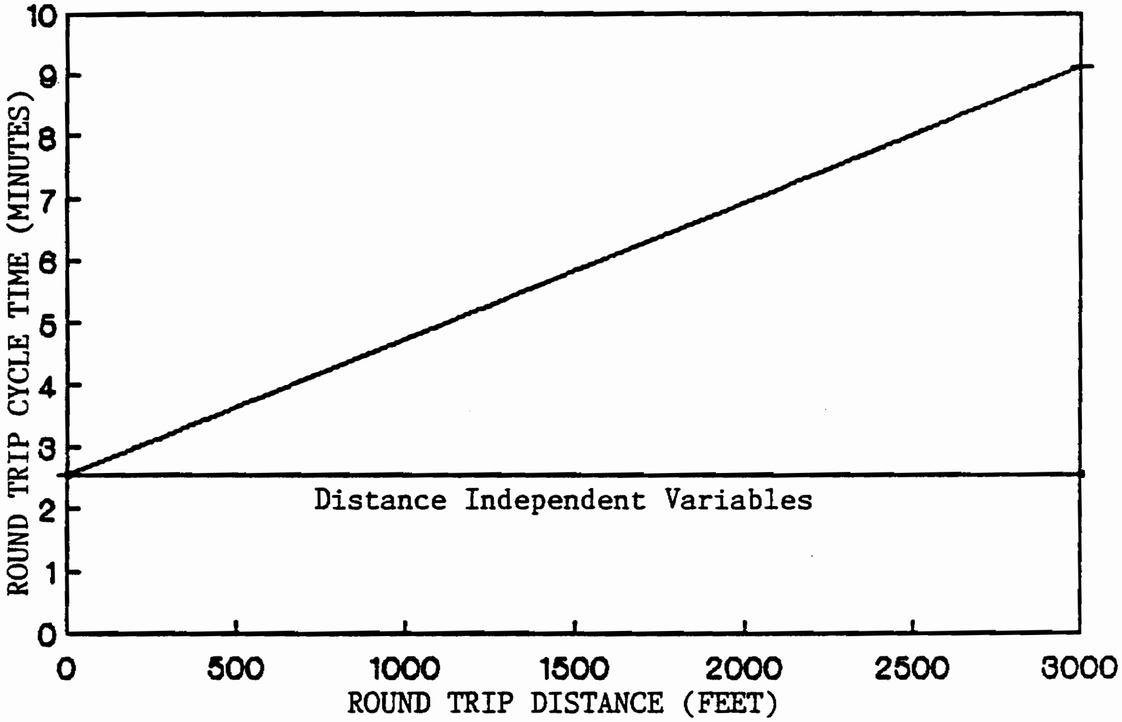

Figure 6. Graphic representation of round trip cycle time for Franklin 170 grapple skidder.

Prediction of machine productivity

Round trip cycle times and weight of turns were combined to express machine productivity. Here, productivity is the result of dividing the weight of the turn by its corresponding round trip cycle time and is expressed in tons per productive hour.

The number of trees, butt diameters and average tree length (to a four-inch top) were recorded for each bunch along the corridor. The average number of trees skidded per turn was significantly larger (alpha = .05) for the 170. The 170 averaged 20 trees per turn with a minimum of nine and a maximum of 33, while the 105 averaged 10 trees per turn with a maximum of 18 and a minimum of four. However, the average butt diameter per turn was significantly larger for the 105 at 8.6 inches, ranging from 5.5 to 11.9 inches. For the 170, butt diameters averaged 7.7 inches and ranged from 6.2 to 10 inches. The average tree length per bunch was determined to be 39 feet for the 105 and 40 feet for the 170.

Summary statistics for the weight of turns, in pounds, are presented in Table 7. Close inspection of Table 7 shows that the maximum load skidded by the 105 was less that the average load skidded by the 170. A two sample T-test and a Wilcoxon rank sum test both concluded that the average weight per turn was significantly greater for the 170.

Summary statistics for productivity are expressed in Table 8. A two sample T-test (based on arithmetic means) and a Wilcoxon rank sum test concluded that the 170 was significantly more productive that the 105.

Since productivity is the result of dividing the weight of the turn by its round trip cycle time, increasing weight while holding cycle time constant or decreasing cycle time while holding weight constant will increase productivity. If the distance independent time variables are considered to be

Table 7. Summary statistics for weight of turns, in pounds.

	105	170
Mean‡	5075	8974
Median†	4947	8786
Standard deviation	1396	2625
Minimum	1872	4265
Maximum	8916	18129

† Indicates significantly different at alpha = .05 using a Wilcoxon rank sum test.

‡ Indicates significantly different at alpha = .05 using a T-test.

Table 8. Summary statistics for productivity in tons per productive hour.

	105	170
Harmonic Mean	25.9	37.5
Mean‡	28.3	41.8
Median†	27.6	41.2
Standard deviation	8.2	13.1
Minimum	9.6	16.0
Maximum	55.5	87.0

† Indicates significantly different at alpha = .05 using a Wilcoxon rank sum test.

‡ Indicates significantly different at alpha = .05 using a T-test.

fixed, then distance could be used to explain some of the variation in productivity. Regression analysis was used to predict the effect of distance (in feet) on productivity (tons per productive hour), and yielded the following equations:

105: Productivity = 37.17- 0.0053 (round trip distance)
170: Productivity = 61.85- 0.0104 (round trip distance)

These equations are represented graphically in Figure 7. Slopes of -0.0053 and -0.0104 are interpreted to mean that for every one foot increase in round trip distance, productivity decreases by .0053 tons per hour for the 105 and by .0104 tons per hour for the 170. The small magnitude of these slopes and low R-square values (.13 for both machines) indicate that grapple skidder productivity is relatively insensitive to distance over the range of distances encountered during the study.

Impact of distance on load size

To determine if the skidder was acquiring larger loads as round trip distance increased, regression analysis was used to predict the weight of loads using distance as an independent variable. The results of this regression indicated that there was a slight trend for load to increase with increasing distance. However, R-square values of 0.02 for the 170 and 0.08 for the 105 indicate that distance did not explain much of the variability in load weight. Thus, it seems as though the feller bunchers were not consciously trying to even out productivity by building larger piles for the skidders as distance from the landing increased.

These findings support the concept that grapple skidder operators have little choice concerning the load size that they carry, and that the feller-buncher operators tend to construct piles in accordance to a fixed grapple size, regardless of skidding distance. The use of grapple skidders has removed much of the distance and weight induced variability in skidder productivity.

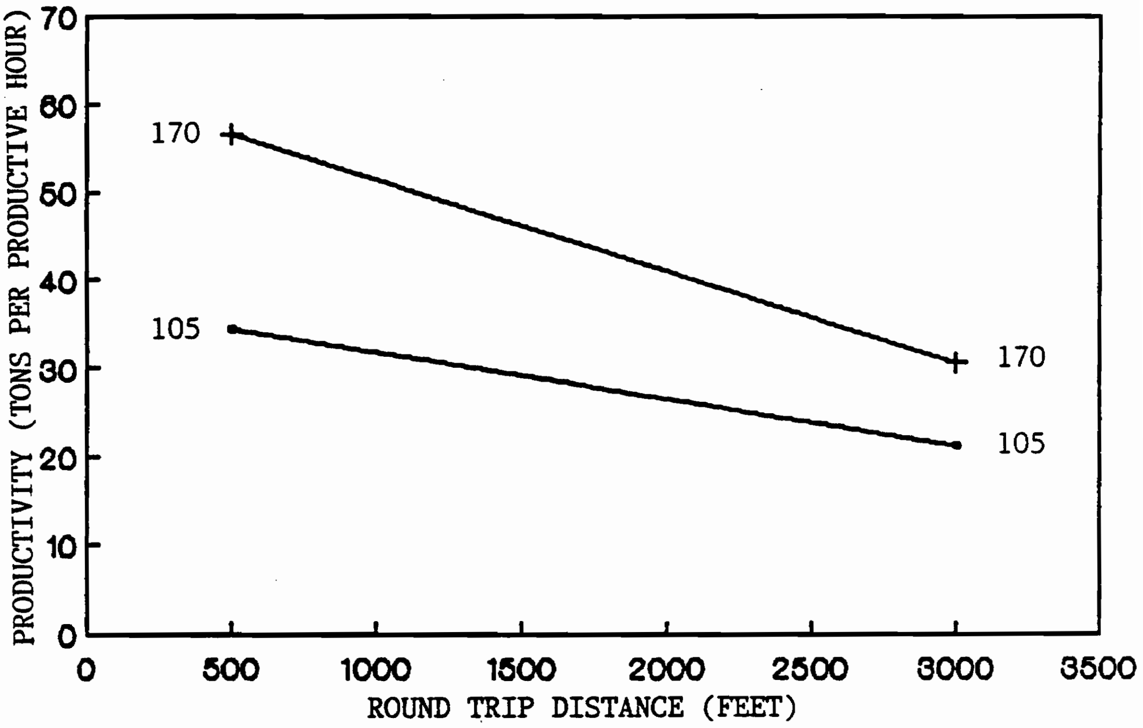

Figure 7. Graphical representation of productivity for the 105 and 170.

Impact of multiple bunch acquisition on productivity

During the time study, the 105 never acquired more than one bunch per turn while the 170 acquired multiple bunches 41 percent of the time. Of the 95 round trips observed on the 170 study, 56 were single bunch, 27 were double bunch, 11 were triple bunch and one involved four bunches.

A Kruskal-Wallis test indicated that there was no significant relationship between distance and the number of bunches acquired per turn. This indicates that the skidders were not trying to even out productivity by acquiring larger loads as distance from the landing increased.

To determine if skidding productivity was increased by multiple bunch acquisition, the Kruskal-Wallis test was used to determine if there were significant differences in productivity between one, two and three bunch turns. The results of this test indicated that there was no significant difference in productivity between single and multiple bunch acquisition. Even though average volume per multiple bunch turn was significantly greater, the extra volume obtained was offset by the increase in cycle time.

Utilization

During the production study, each skidder was equipped with a TRT service recorder to determine machine utilization. It was found that the 170 averaged 78 percent utilization, ranging from 51 to 87 percent, while the 105 averaged 80 percent utilization, ranging from 77 to 85 percent. It should be noted that these figures represent percentages of time that the skidders were in motion, and do not necessarily reflect the percentage of time that the skidders were productive. Because the skidders were occasionally involved with tasks other than skidding bunches to the landing, actual productive utilization will be slightly less than the above percentages.

Residual Stand Damage

Following each day's production data acquisition, corridors skidded that day were examined and all trees within six feet of either side of the corridor were inspected for damage. Each tree within this zone was classified as having no damage, minor damage, or major damage, depending on the amount of bark removed. Fifty square inches of exposed cambium was the threshold between minor and major damage. Also, tops and large branches broken off during harvesting and unremoved turn trees were considered to be damage. During the residual stand damage survey, corridor width was obtained by measuring the distance (feet) between leave trees at narrow points in the corridor.

Magnitude of residual stand damage

Of the 1134 trees examined on the 105 study site, 12 percent were classified as having major damage and 13 percent were classified as having minor damage. Of the 828 trees examined on the 170 study site, 15 percent fell into the major damage category and 12 percent were classified as having minor damage. Categorical data analysis concluded that there was no significant difference (alpha = .05) in minor damage by skidder size. However, the difference in major damage was found to be statistically significant at the alpha = .05 level.

Area surveyed for damage

During the residual stand damage survey, corridor width was obtained by measuring the distance (feet) between leave trees at narrow points in the corridor. In total, 103 corridor widths were measured in the 170 study site and 107 corridor widths were measured in the 105 study site. It was found that the average corridor widths in the 170 and 105 study sites were 11.5 feet and 11.9 feet, respectively. Although a two sample T-test and a Wilcoxon rank sum test concluded that corridor widths in the 105 study site were significantly wider (alpha = .05), the practical significance of a difference of .40 feet is questionable due to the method of measurement. In fact, the similarity in average corridor width indicates that the larger 170 did not require a wider corridor to operate during plantation thinning.

Corridors in the study areas were spaced approximately 70 feet apart, allowing about three corridors per square acre. Extending the six foot wide damage inspection zones on both sides of each corridor represents 0.17 acre surveyed for damage per acre. The results of a post-harvest inventory revealed that there were 204 trees per acre remaining between corridors on the 105 study site and 258 trees per acre remaining between corridors on the 170 study site. Multiplying the area per acre inspected for damage by the number of trees per acre remaining between corridors indicated that 44 trees per acre were examined on the 170 study site and 35 trees per acre were examined on the 105 study site.

Trees damaged per acre

Multiplying the damage percent by the number of trees inspected per acre resulted in the information presented in Table 9. Since there was no significant difference in minor damage by skidder size it can be concluded that the incidence of minor damage is independent of machine size. However, the larger skidder (170) caused significantly more major damage than did the 105. The 170 caused major damage to an average of 6.6 trees per acre while the 105 caused major damage to an average of 4.2 trees per acre. Excluding unremoved turn trees from this estimate indicated that the 105 caused minor damage to 3.8 trees per acre and major damage to 3.3 trees per acre, while the 170 caused minor damage to 5.3 trees per acre and major damage to 6.2 trees per acre. It could be argued that the mortality or potential reduction in growth of an additional 2.4 trees damaged per acre is more than offset by a 44 percent increase in productivity when using the 170. It is important to note that the 170 may have caused more major damage than did the 105 simply because there were more trees per acre in the 170 study site. Foresters employed by the industrial landowner considered that the levels of residual stand damage found on both study sites were well within acceptable limits.

Soil Compaction

During December of 1988, soil compaction data were collected from 101 locations in the 105 study site and 95 locations in the 170 study site. Changes in soil density were evaluated at the zero to six inch depth using a cone penetrometer. The differences between compacted and non-compacted readings at each location were used to test the hypothesis that soil compaction differs with skidder type.

Results of cone penetrometer measurements

The soils found on the 105 study site and the 170 study site are classified as Dunbar fine sandy loam and Eulonia loamy fine sand, respectively. While not in the same family, these soils are described as having similar characteristics (USDA, 1982 and 1931). Both soils consist of fine sandy loam surfaces over clayey subsoils and are considered to be old, highly leached and somewhat poorly drained. Also, since both of the study sites are Loblolly pine plantations, both soils support the same type of understory and overstory vegetation. The Dunbar fine sandy loam is the deeper, older and less wet of the soils described. Based on the overall similarity of texture, vegetation and drainage, these soils would be expected to respond to compaction in a similar manner (Burger, 1988).

Table 9. Trees per acre damaged during skidding by 105 and 170.

	105	170
Minor Damage	4.5	5.3
Major Damage†	4.2	6.6
Total Damage	8.7	11.9

† Indicates significantly different at alpha = .05 through use of categorical data analysis.

Summary statistics of differences in soil density are presented in Table 10. A two sample T-test and a Wilcoxon rank sum test concluded that corridors in the 105 study site were significantly (alpha = .05) more compacted than corridors in the 170 study site.

Of interest is why a smaller, lighter machine skidding a lighter average load would cause more compaction than a larger heavier machine skidding a heavier average load. To explain this seemingly contradictory conclusion, additional, but limited analysis was performed concerning soil type, soil moisture, litter layer, dynamic load, tire size and number of passes.

Soil moisture

Soil moisture samples were not collected during the time study. Because of this, soil moisture data at the time of compaction is not available. However, soil moisture samples were collected approximately three weeks later and were analyzed to provide percent moisture content on a dry weight basis. Based on ten samples, it was found that the average soil moisture content was 17.08 percent in the 105 study site and 17.61 percent in the 105 study site. The similarity of the soils' moisture contents on a given day reinforces the validity of the cone penetrometer measurements.

Litter depth

Approximate litter depth was recorded at each compaction test site during the compaction study. After skidding, the average corridor litter depth was 1.8 inches on the 105 study site and 1.4 inches on the 170 study site.

Table 10. Differences in soil density between compacted and non-compacted areas in the 105 and 170 study sites.

	Pounds per square inch	
	105	170
Mean‡	93.7	67.1
Median†	93.5	60.5
Standard deviation	64.2	52.9
Minimum	-46.5	-27.5
Maximum	259	203

† Indicates significantly different at alpha = .05 using a Wilcoxon rank sum test.

‡ Indicates significantly different at alpha = .05 using a T-test.

Dynamic loads

Since differences in ground pressure influence soil compaction, dynamic loads were calculated for both machines. Average turn weights from the production study and machine weights for each skidder as equipped during the study were used for these calculations. A 55 percent (front axle) and 45 percent (rear axle) weight distribution was assumed for both machines (Davis, 1988). Other assumptions as well as the calculations used to determine dynamic loads are presented in Appendix C. Dynamic load was calculated to be 12,218 pounds on the rear axle and 8321 pounds on the front axle of the 105 and 17,118 pounds on the rear axle and 10,307 pounds on the front axle of the 170.

The "foot print", or ground surface contact, of the 105 skidder tire (Champion Spade Grip 28-L-26) was estimated to be 300, 850 and 920 square inches for zero, two and three inch penetration, respectively (Parker, 1988). Ground pressures for this machine with the calculated dynamic load and the above footprints are presented in Table 11.

The "footprint" of the tire mounted on the 170 (Firestone Flotation 23 DT Logger 67 x 34) was estimated to be 630, 980 and 1090 square inches for zero, two and three inch penetration, respectively (Parker, 1988). Ground pressures for the 170 given the calculated dynamic loads and estimated footprints are presented in Table 12. Inspection of Tables 11 and 12 show that the Franklin 170 exerted a greater ground pressure that the 105 for every axle and penetration combination except for the zero penetration category.

Effect of number of passes on compaction

In this study, data was not collected that would specifically relate compaction measurements with the number of passes. However, the results of the time study provide some information on

Table 11. Ground pressure (pounds per square inch) exerted by 105.

	Front Tires	Rear Tires
Zero penetration	8.2	13.6
Two-inch penetration	5.3	8.7
Three-inch penetration	4.7	7.9

Table 12. Ground pressure (pounds per square inch) exerted by 170.

	Front Tires	Rear Tires
Zero penetration	13.8	20.4
Two-inch penetration	4.9	7.2
Three-inch penetration	4.5	6.6

this subject. Of the 95 round trips observed during the 170 study, 56 were single bunch acquisition, 27 were double bunch acquisition, 11 were triple bunch acquisition and one was four bunch acquisition. Of the 132 round trips observed during the 105 study all were single bunch acquisition. This means that the 105 made 132 round trips to pick up 132 bunches while the 170 made 95 round trips to pick up 147 bunches. Accordingly, if the 170 had made 132 round trips it would have acquired, on average, 204 bunches. To pick up 204 bunches, the 105 would have to make 204 round trips or 54 percent more passes while loaded. Expressed on an average weight per turn basis, the 170 would require 45 percent fewer trips to move the same total weight of wood.

Thus, it could be argued that the increased number of trips required by the 105 to skid an equal number of bunches or an equal weight of wood more than offset the greater ground pressure exerted by the 170. This may help to explain why corridors in the 105 study site were found to be significantly more compacted.

Cost Analysis

The production data collected during the field studies were combined with acquired cost estimates to arrive at total weekly costs and costs per ton of production for both machines. A discounted cash flow analysis was performed to determine the effect of using a 170 rather than a 105 grapple skidder on system net present value.

Weekly owning and operating costs

Total weekly cost was considered to be the sum of fixed and operating costs. Fixed costs consisted of equipment payments, insurance, and taxes. Eighty percent of the skidder purchase price financed at 13.97 percent A.P.R. for 36 months was used to determine the equipment payment. Taxes were calculated at 2.8 percent per year on one-half of the skidders market value. Fire, theft and vandalism insurance was assumed to be 1.2 percent per year of the skidders market value. Operating costs consisted of maintenance and repair, operator wages and supply consumption. Maintenance and repair costs were estimated to be 75 percent of normal depreciation, calculated on a straight line basis for five-year equipment life. To simplify the analysis, operators were assumed to be paid $8.00 per hour (plus 40 percent fringe benefits) even though they were actually paid by the load. Supply costs were based on a 50 hour work week, 80 percent utilization and hourly consumption rates.

Based on the above, and given the assumptions presented in Appendix D, it was determined that the total estimated weekly cost for the 105 was $1320.00, of which $496.00 was fixed cost and $824.00 was operating cost. Total cost for the 170 was estimated to be $1505.00 per week, of which $617.00 was fixed and $888.00 was operating cost.

Cost per ton

Cost per ton is the result of dividing total weekly cost by weekly skidding productivity, and is based on harmonic mean production rates, 80 percent utilization and a 50 hour week. It was estimated that the 105 costs $1.27 per ton of wood skidded and that the 170 costs $1.00 per ton of wood skidded. Even though the 170 was found to be more expensive to own and operate than the 105, the 44 percent increase in skidding productivity associated with the 170 resulted in a lower skidding cost per ton.

Cash flow analysis

During the production study, it was noted that the 170 generally skidded the output of two feller-bunchers. This suggests that a system using a 170 to skid may need two feller-bunchers to fully utilize potential skidding productivity. Realizing that a system using two feller-bunchers might result in a higher cost of production, a simplified cash flow analysis was performed to determine the effect on system net present value of changing from a system using a 105 and one feller-buncher to a system using a 170 and two feller-bunchers.

For this calculation, it was assumed that elements of both systems would remain the same except for costs associated with skidding, costs associated with using one as compared to two feller-bunchers, and revenues based on differing skidder productivity. Because of this, all costs except for those associated with skidders and feller bunchers were excluded from the analysis. This exclusion is reasonable in a comparative setting since the difference, rather than the absolute values, of net present value is of interest.

The discounted cash flow analysis for both systems is presented in Appendix E. The analysis includes down payments, personal property taxes, insurance, operating costs, salvage values, observed skidder productivity and an arbitrarily chosen revenue of $10.00 per ton of production output, and is calculated based on new machine start-ups and a five-year life. System overhead and trucking costs are not included in this analysis.

The results of this discounted cash flow analysis shows a higher net present value for the system employing the 170 and two feller-bunchers. This suggests, under the assumptions made, that this system could be a better choice from a financial standpoint.

Computer Simulation

To determine the effect of tree size on grapple skidder productivity, six simulations were performed using the Generalized Machine Simulator (Stuart and Farrar, 1983) with two different harvesting systems and three different forest models. The following results are based on a deterministic computer simulation of harvesting activities under a specific set of assumptions, and represent productivity based on 100 percent utilization. The purpose of this set of simulations was to demonstrate the relative impact of tree size on the productivity of a large and a small grapple skidder.

Description of harvesting systems simulated

System A was created to illustrate the impact of tree size on the productivity of a small grapple skidder. This systems consisted of a Franklin 170 feller-buncher equipped with a 15 inch Morbark shear, a Franklin 105 grapple skidder with a 74 inch grapple, and a delimbing gate.

System B was created to illustrate the impact of tree size on a large grapple skidder. This system consisted of a Franklin 170 feller-buncher equipped with a 15 inch Morbark shear, a Franklin 170 grapple skidder with a 90 inch grapple, and a delimbing gate.

The grapple skidder time and production data collected during the field studies and previously published feller-buncher production studies (Lanford and Sirois, 1983) were used as inputs for the simulation. Elemental timing information and operating parameters used as inputs for the 170 feller-buncher, the 105 grapple skidder, and the 170 grapple skidder are presented in Tables 13, 14, and 15, respectively. Each system performed corridor thinning in a manner consistent with that observed during the field studies, and used 12 foot wide corridors spaced on sixty foot centers.

Table 13. Elemental timing information and operating parameters used as inputs in the simulation for Franklin 170 feller-buncher.

Elemental Timing Information (in minutes)

Travel Unloaded:
Time = 0.0022 (distance in feet)

Move to Tree or to Bunch:
Time = 0.21 (forest model 39) or
0.29 (forest model 51)

Positioning at Tree and Shearing:
Time = 0.23

Dispose:
Time = 0.034

Operating Parameters

Shear:	
Maximum diameter at ground line, pine	15 inches
Accumulation:	
Maximum volume	35 cubic feet
Maximum number of trees	7
Disposition:	
Maximum volume per bunch	
with 105 grapple skidder	131 cubic feet
with 170 grapple skidder	237 cubic feet
Maximum number of trees per bunch	
with 105 grapple skidder	16
with 170 grapple skidder	32
Maximum travel distance to bunch	
forest models 39 and 51	50 feet
forest model 22	100 feet

Table 14. Elemental timing information and operating parameters used as inputs in the simulation for Franklin 105 grapple skidder

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Elemental Timing Information (in minutes)

Travel Unloaded:
Time = 0.0022 (distance in feet)

Positioning and Acquiring:
Time = 0.81

Travel Loaded:
Time = 0.0022 (distance in feet)

Delimbing and Releasing:
Time = 1.25

Operating Parameters

Maximum volume per turn	131 cubic feet
Maximum number of trees per turn	16

Table 15. Elemental timing information and operating parameters used as inputs in the simulation for Franklin 170 grapple skidder

<u>Elemental Timing Information (in minutes)</u>

Travel Unloaded:
Time = 0.0022 (distance in feet)

Positioning and Acquiring:
Time = 1.61

Travel Loaded:
Time = 0.0022 (distance in feet)

Delimbing and Releasing:
Time = 0.94

<u>Operating Parameters</u>

Maximum volume per turn	237 cubic feet
Maximum number of trees per turn	32

Forest models employed

The effect of tree size on grapple skidder productivity was determined by thinning three different 18 acre forest models with the same harvesting system. The forest models chosen represent a range of average diameters, and have characteristics similar to those found in the study sites.

Forest Model 22 represents a 22 year old Loblolly pine plantation with a site index of 80 (base-age 50). This model contains 805 trees per acre of which 91.7 percent are Loblolly pine. The average tree prior to harvest was 4.8 inches in diameter with a total height of 41 feet. Basal area prior to harvest was 109 square feet per acre. To attain a residual basal area of approximately 75 square feet per acre, all trees between 4 inches and 5.5 inches in diameter were removed during thinning. The average tree harvested was 4.5 inches in diameter.

Forest Model 39 represents a 16 year old Loblolly pine plantation with a site index of 80 (base-age 50). This model contains 721 trees per acre of which 99.9 percent are Loblolly pine. The average tree prior to harvest was 6.3 inches in diameter with a total height of 46 feet. Basal area prior to harvest was 156 square feet per acre. To attain a residual basal area of approximately 75 square feet per acre, all trees between 4.0 inches and 6.8 inches in diameter were removed during thinning. The average tree harvested was 5.5 inches in diameter.

Forest Model 51 represents an 18 year old Loblolly pine plantation with a site index of 80 (base-age 50). This model contains 437 trees per acre of which 98.2 percent are Loblolly pine. The average tree prior to harvest was 7.7 inches in diameter with a total height of 50 feet. Basal area prior to harvest was 144 square feet per acre. To attain a residual basal area of approximately 75 square feet per acre, all trees between four inches and eight inches in diameter were removed during thinning. The average tree harvested was 6.6 inches in diameter.

The impact of tree size on productivity

The results of the simulation were consistent with the results of the field study in that the 170 was found to be an average of 43 percent more productive than the 105. The 170 outproduced the 105 by an average of 102 cubic feet per hour Fn forest Model 22, 330 cubic feet per hour in Forest Model 39 and 320 cubic feet per hour in Forest Model 51. Summary statistics for grapple skidder productivity in Forest Models 22, 39 and 51 are presented in Tables 16, 17, and 18, respectively.

Productivity in cubic feet per hour versus average tree diameter harvested is shown graphically in Figure 8. Productivity estimates obtained during the field study (and presented earlier in this section) are also included in this figure. Close inspection of Figure 8 shows that the lines which represent average productivity for the 170 and maximum productivity for the 105 are virtually the same. This is consistent with the results of the field study, and illustrates the magnitude of the 170's productivity advantage over the 105. As expected, skidding productivity was found to be directly related to average tree size harvested: both skidders were found to be the least productive when working with the smallest average tree diameter harvested, and most productive when working with the largest average tree diameter harvested. However, productivity rates for the 170 and 105 showed the least amount of difference when working with the smallest average diameter harvested (Figure 8). As the average diameter of trees harvested increased the difference in productivity between the 105 and 170 became more pronounced with the 170 showing a greater improvement in productivity than the 105. This suggests that the 170 may not offer as much of an absolute productivity advantage over the 105 when working in timber smaller than that observed in the study areas.

Table 16. Summary statistics for grapple skidder productivity while operating in Forest Model 22.

	105	170
Average diameter of tree harvested (inches)	4.5	4.5
Total volume skidded (cu. ft.)	2441	2441
Total number of bunches	109	100
Average number of trees per bunch	11	13
Average volume per bunch (cu. ft.)	22	24
Average bunches per hour	15	18
Minimum productivity (cu. ft. per hour)	207	375
Average productivity (cu. ft. per hour)	302	430
Maximum productivity (cu. ft. per hour)	468	546

Table 17. Summary statistics for grapple skidder productivity while operating in Forest Model 39.

	105	170
Average diameter of tree harvested (inches)	5.5	5.5
Total volume skidded (cu. ft.)	17322	17322
Total number of bunches	378	234
Average number of trees per bunch	13	21
Average volume per bunch (cu. ft.)	46	74
Average bunches per hour	14	13
Minimum productivity (cu. ft. per hour)	391	521
Average productivity (cu. ft. per hour)	626	957
Maximum productivity (cu. ft. per hour)	941	1470

Table 18. Summary statistics for grapple skidder productivity while operating in Forest Model 51

	105	170
Average diameter of tree harvested (inches)	6.6	6.6
Total volume skidded (cu. ft.)	2853	2853
Total number of bunches	258	216
Average number of trees per bunch	11	13
Average volume per bunch (cu. ft.)	50	60
Average bunches per hour	14	17
Minimum productivity (cu. ft. per hour)	481	773
Average productivity (cu. ft. per hour)	706	1026
Maximum productivity (cu. ft. per hour)	1041	1391

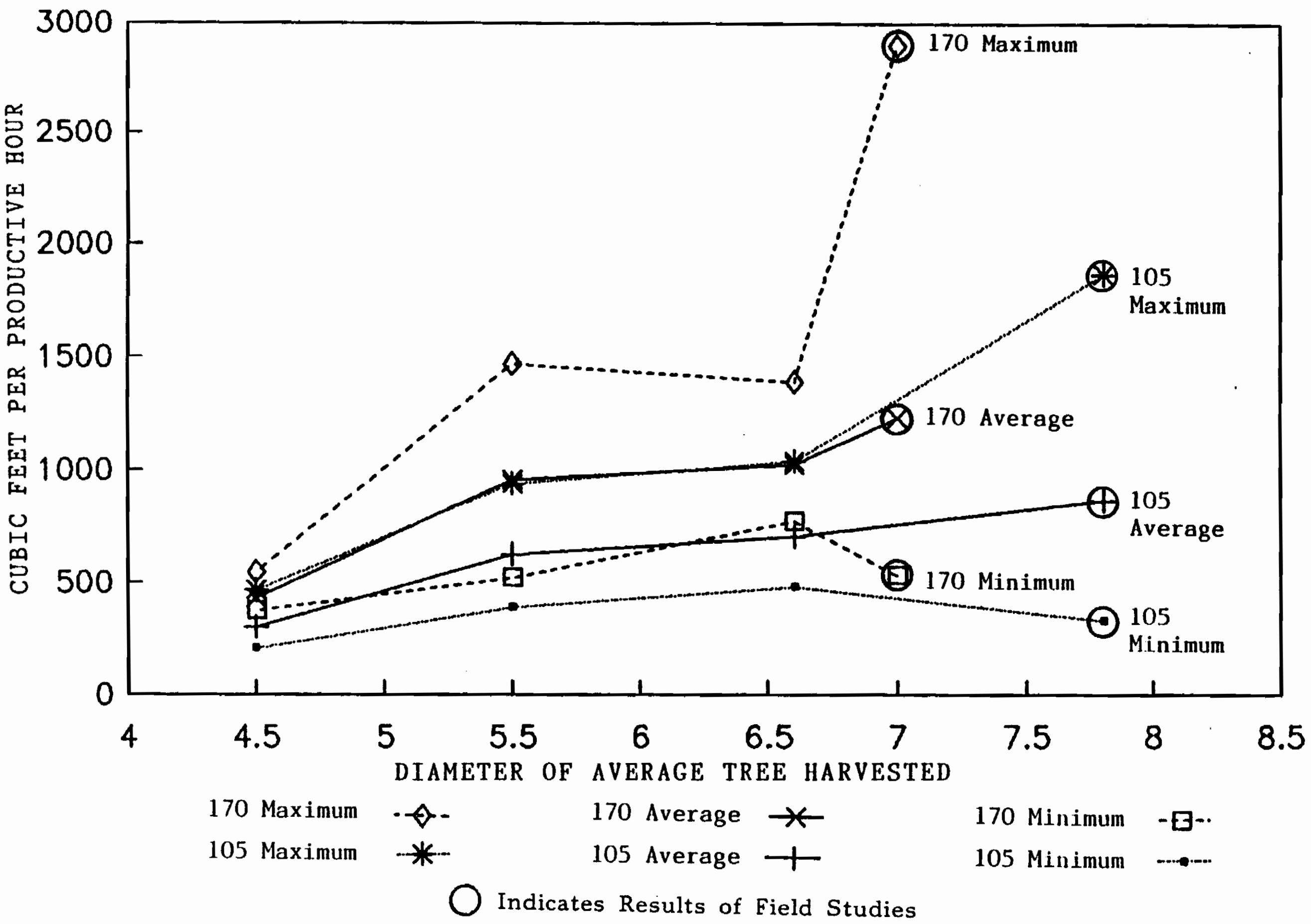

Figure 8. Productivity versus diameter of average tree harvested

SUMMARY AND CONCLUSION

The objective of this research was to compare the performance of a small grapple skidder (Franklin 105) with a large grapple skidder (Franklin 170) in a pine plantation thinning application. Comparisons included (1) time and productivity, (2) residual stand damage, (3) soil compaction, (4) cost, and (5) the impact of tree size on skidder productivity.

Time and production data were collected for 132 round trips for the Franklin 105 and 95 round trips for the Franklin 170 in similar Loblolly pine plantations. Round trip cycle times and weight of turns were combined to express productivity in tons per productive hour. It was determined that the Franklin 170 was an average of 44 percent more productive than was the 105. Since round trip cycle time was found to be significantly longer for the 170, this increase in productivity was attributed to the 170's greater load weight capacity. The maximum load skidded by the 105 was slightly less than the average load skidded by the 170.

To determine if skidding productivity was increased by multiple bunch acquisition, the productivity of multiple bunch turns were examined. During the time study, the 170 acquired multiple bunches 41 percent of the time, while the 105 never acquired more than one bunch per turn. It was found that there was no significant difference in productivity between single and multiple bunch acquisition. Even though the average volume per multiple bunch turn was significantly greater, the extra volume obtained was offset by the increase in cycle time.

To determine if the skidder operator was attempting to even-out productivity by acquiring larger loads as round trips distance increased, regression analysis was used to predict the weight of loads using distance as an independent variable. It was concluded that very little of the variability in load size was due to skidding distance. This supports the concept that grapple skidder operators have little choice concerning the load size that they carry, and that feller-buncher operators tend to construct piles in accordance with a fixed grapple size, regardless of the skidding distance. The use of grapple skidders has removed much of the distance and weight induced variability in skidder productivity.

Residual stand damage was measured, with fifty square inches of exposed cambium being the threshold between minor and major damage. It was found that there was no significant difference in minor damage by skidder size and that the 170 caused significantly more major damage than did the 105. Expressing the percentage of trees damaged on a trees per acre basis revealed that the 105 caused minor damage to 4.5 trees per acre and major damage to 4.2 trees per acre. The 170 caused minor damage to 5.3 trees per acre and major damage to 6.6 trees per acre. The average corridor width in the 170 and 105 study site was 11.5 feet and 11.9 feet, respectively. The similarity of average corridor width indicated that the larger 170 did not require a wider corridor to operate during thinning.

Changes in soil density were evaluated at the zero to six inch depth using a cone penetrometer. Results showed that corridors in the 105 study site were significantly more compacted than corridors in the 170 study site. This phenomena may be explained by the fact that the 170 required 45 percent fewer trips than the 105 to move the same total weight of wood. The increased number of trips required by the 105 may have offset the greater ground pressure exerted by the 170.

The production data collected during the field studies were combined with acquired cost estimates to arrive at costs per ton of production. It was estimated that the total cost per ton skidded was $1.27 for the 105 and $1.00 per ton for the 170.

Computer simulation was used to determine the impact of tree size on grapple skidder productivity. The results of this simulation suggested that the 170 is more sensitive to variation in tree size than the 105. The productivity advantage shown by the 170 may be decreased when operating with smaller average tree diameters.

Conclusion

It can be concluded that large grapple skidders similar to the 170 are capable of excellent performance in pine plantation corridor thinning applications. The large grapple skidder studied in this project was found to be (1) more productive, (2) associated with less soil compaction, (3) less expensive on a cost per ton of production basis, (4) more sensitive to variation in tree size and (5) associated with only slightly more residual stand damage than the small grapple skidder studied. Accordingly, logging contractors may be ill-advised to select smaller, less efficient skidders for corridor thinning applications.

Several questions were left only partially answered in this project and warrant further research. The time and production data, residual stand damage data and soil compaction data were collected in a production environment and not under controlled conditions. Because of this, it was impossible to determine how much of the variability in the data resulted from factors which were not measured or controlled. Also, the results of this study are anecdotal in nature and may apply only to the circumstances encountered when and where the data was obtained. This project could be extended to document the performance of large versus small harvesting equipment currently in use in the South under controlled conditions and differing circumstances.

Appendix A. Specifications for Franklin 105 Grapple Skidder

105 GRAPPLE SKIDDER M-28

ENGINE:

Manufacturer	Detroit Diesel
Model/Cyls.	3-53N50/3 cyls.
Max. HP	92 @ 2800 RPM (69 kw)
Flywheel HP	77 @ 2650 RPM (57 kw)
Governed RPM	2650 RPM
Max. Torque @ 1800 RPM	198 ft. lb. (27 kgm)
Bore & Stroke	3.975" x 4.5" (101mm x 114mm)
Displacement	159 cu. in (2.6 liters)

POWER TRAIN:

Transmission	Franklin P4-200, 4 speed powershift
Torque Converter	Rockford 10.2" (259mm)
Axles	Franklin F-185; Planetary, heavy duty
Differentials	No-spin, front & rear
Brakes-Service	Enclosed, multi-disc, wet brake
Parking	Enclosed, multi-disc, wet brake, automatic

OPERATIONAL

Frame Articulation Angle	±38
Frame Oscillation Angle	±15

TRAVEL SPEED (mph)

	1st	2nd	3rd	4th
Forward	0-3.36	0-5.56	0-9.15	0-15.13
Reverse	0-3.36	0-5.56		

HYDRAULIC SYSTEM

Hydraulic Quick Steering Steering Pump (gear type)	20.5 GPM @ 2650 RPM
Winch, Blade and Grapple Pump	24 GPM @ 2650 RPM

Hydraulic Reservoir Capacity 25 Gals.

Filtration: 10 Micron Return Line By-pass Filter and Suction Strainer

Steering Cylinder	Two Double Acting Cylinders with 3" x 16" Stroke & 1-1/2" Rod
Blade Cylinder	Two Double Acting Cylinders with 3" x 16" Stroke & 1-1/2" Rod
Grapple - (74" Openings)	
Lift Cylinders	Two Double Acting Cylinders with 3-1/2" x 16" Stroke & 1-1/2 Rod
Bucket Cylinders	Two Double Acting Cylinders with 4" x 12" Stroke & 2-1/2" Rod

STANDARD EQUIPMENT:

Two Stage Dry Air Cleaner
12 Volt Electrical System
Full Belly Pans & Hinged Bomb Bay Doors
ROPS and FOPS Cab
10 lb. Fire Extinguisher
Tapered Roller Bearings in Center Section
Tapered Roller Bearings in Grapple Head
Swing Retarders
Limb Deflectors
Wrapped Muffler
Cab Fan
Suspension Seat

WINCH:

Make	Franklin H-32
Max. Line Pull	27,000 (12,247 kg)
Line Speed	290 FPM (77m/min)
Drum Capacity	1/2"-320' (13mm-98m) 5/8"-210' (16mm-64m)

Single Lever Controlled, Hydraulically Activated

TIRES: 18.4 x 26 LS2 Steel Reinforced, Standard
Optional: 18.4 x 34, 23.1 x 26, 28L x 26, 67/34.00 x 26

WEIGHT:

With Standard Equipment	18,340 (8,321 kg)

OPTIONS: Lights, Heater, Enclosed Cab,
Cummins 4BT3.9 Engine, F-205 Axles

All Specifications Are Subject To Change

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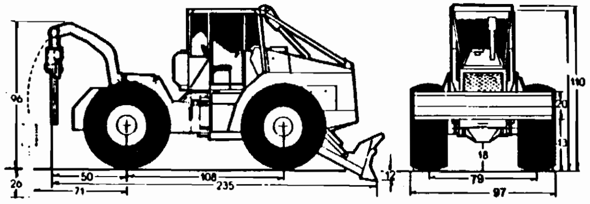

Appendix B. Specifications for Franklin 170 Grapple Skidder

170 PTM-31A GRAPPLE SKIDDER

ENGINE:
Manufacturer.............................. Detroit Diesel
Model/Cyle................................ 4-53TC60/4 cyl.
Max. HP.......................... 185 @ 2500 RPM (138 kw)
Flywheel HP..................... 160 @ 2500 RPM (119 kw)
Governed RPM.................................. 2500 RPM
Max. Torque @ 1800 RPM...............420 ft. lb. (58 kgm)
Bore & Stroke .... 3.975" x 4.5" (101mm x 114.3mm)
Displacement .... 212 cu. ins.(3.5 liter)

POWER TRAIN:
Transmission.......... Franklin P4-375, 4 speed powershift
Torque Converter..................... Rockford 12" (305mm)
Axles............... Franklin F-240; Planetary, heavy duty
Differentiple....................... No-spin, front & rear
Brakes-Service............ Enclosed, multi-disc, wet brake
Parking........ Enclosed, multi-disc, wet brake, Automatic

OPERATIONAL
Frame Articulation................................ ±38
Frame Oscillation Angle........................... ±15

TRAVEL SPEED (mph)

	1st	2nd	3rd	4th
Forward	0-3.02	0-4.96	0-8.16	0-13.5
Reverse	0-3.78	0-6.19		

HYDRAULIC SYSTEM

Hydraulic Quick Steering Steering Pump (gear type)	23 GPM @ 2500 RPM
Winch, Blade, Grapple Pump (gear type)	23 GPM @ 2500 RPM

Hydraulic Resevoir Capacity 35 Gals.
Filtration: 10 Micron Return Line By-pass Filter and Suction Strainer

Steering Cylinder	Two Double Acting Cylinders with 3-1/2" x 16" Stroke & 1-3/4 Rod
Blade Cylinder	Two Double Acting Cylinders with 3-1/2" x 12 Stroke & 1-3/4" Rod

GRAPPLE:

Lift Cylinders	Two Double Acting Cylinders with 4" x 24 Stroke & 2" Rod
Bucket Cylinders	(66") Two Double Acting Cylinders with 4" x 12" Stroke & 2-1/2" Rod (90") Two Double Acting Cylinders with 5" x 13-1/4 Stoke & 2-1/2" Rod

STANDARD EQUIPMENT:
Two Stage Dry Air Cleaner
12 Volt Electrical System
Full Belly Pans & Hinged Box Bay Doors
ROPS and FOPS Cab
20 lb. Fire Extinguisher
Tapered Roller Bearings in Center Section
Swing Out Grill Insert
Wrapped Muffler
Grapple - Tapered Roller Bearings
Easy Access Batteries
Heavy Duty Blade
Swing Retarders
Limb Deflectors
66 Inch Opening Grapple
Cab Fan
Suspension Seat

WINCH:
Make....................................... Franklin H-32
Max Line Pull (Bare Drum)......... 27,000 lbs. (12,247 kg)
Line Speed (Bare Drum).................. 290 FPM (77m/min)
Drum Capacity..................... 1/2"----530' (13mm-98m)
5/8"----320' (16mm-64m)

Single Lever Controlled, Hydraulically Activated

TIRES: 28L X 26 LS2 Steel Reinforced, Standard
Optional: 23.1 x 26, 67/34.00 x 26, *24.5 x 32, *30.5 x 32

*Requires Heavy Duty Axles

WEIGHT:
With Standard Equipment............ 25,160 (11,415 kg)

OPTIONS: Lights, Heater,90" Grapple Arms, Enclosed Cab,
Cummins 6BT5.9 or 6BT5.9 Aftercooled Engine

All Specifications Are Subject to Change

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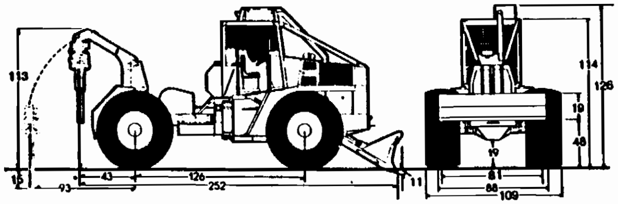
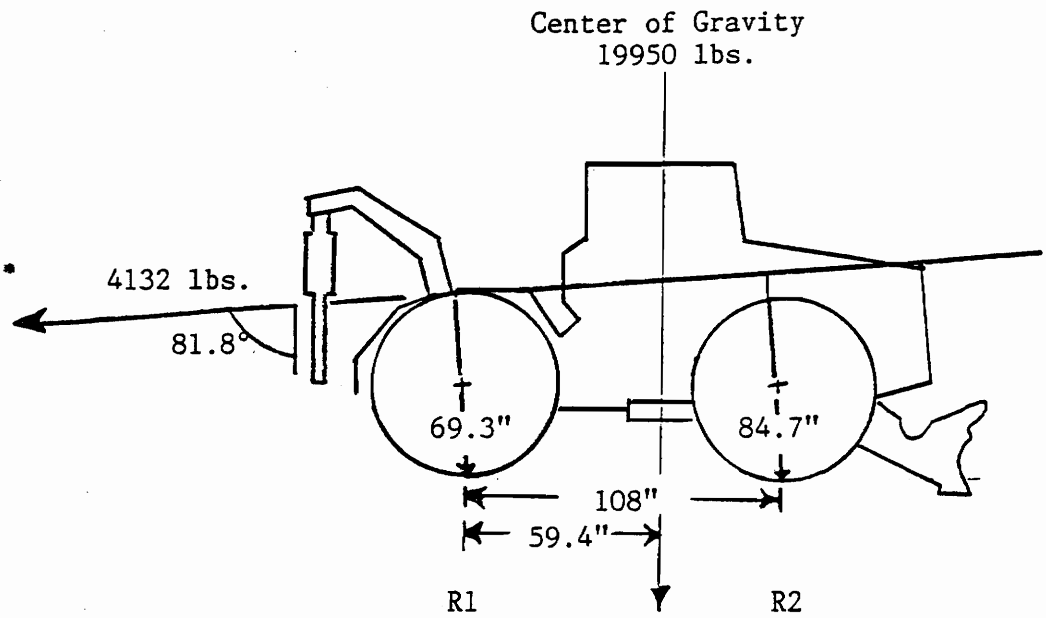


Appendix C. Ground Pressure Calculations

Assumptions concerning the load:

1. Total length- 49 feet for the 105, 50 feet for the 170.
2. Center of gravity- one-third of distance from butt end to top end.
3. One-quarter of the bunch length is dragging on the ground.
4. A constant weight distribution (as the boles taper, they also become more "limby").
5. Average load weight- 5075 pound for the 105, 8974 pounds for the 170.

Case 1: Axle weights for Franklin 105 grapple skidder.



Sum of Moments Around R2:

-4132(84.7)-19950(108-59.4)+R1(108)=0

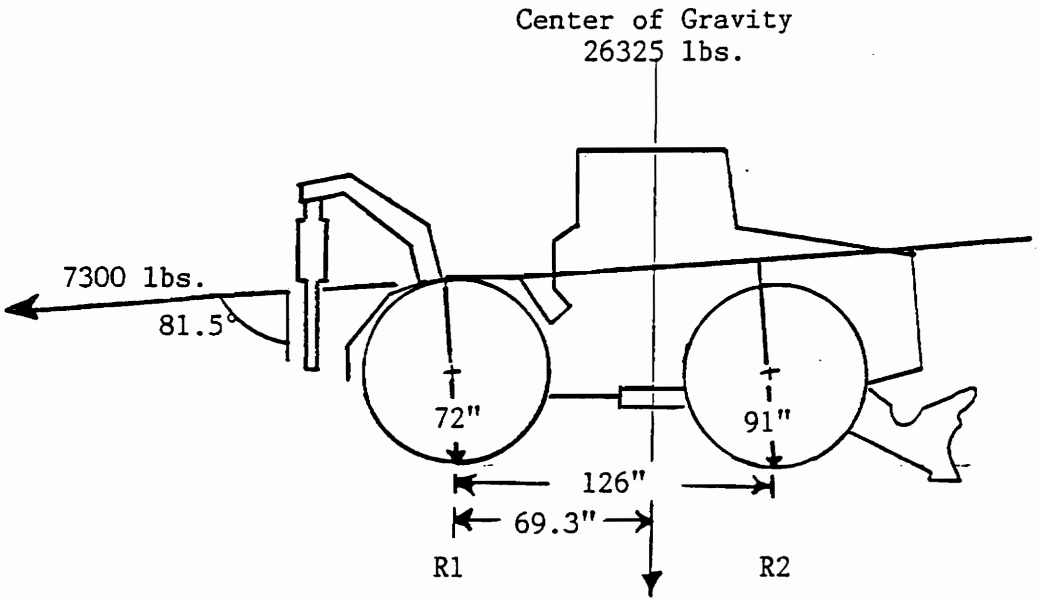
Dynamic Load on Rear Axle (R1)= 12218.1 lbs.

Sum of Moments Around R1:

-4132(69.3)+19950(59.4)-R2(108)=0

Dynamic Load on Front Axle (R2)= 8321.1 lbs.

Case 2: Axle weights for Franklin 170 grapple skidder.



Sum of Moments Around R2:

$-7300(91)-26325(56.7)+R1(126)= 0$

Dynamic Load on Rear Axle (R1)= 17118.5 lbs.

Sum of Moments Around R1:

$-7300(72)+26325(69.3)-R2(126)= 0$

Dynamic Load on Front Axle (R2)= 10307.3 lbs.

Appendix D. Assumptions used for Cost Analysis

Fixed Costs

1. Assumed Equipment Prices:

Franklin 170 Grapple Skidder............	$ 94,300
Franklin 105 Grapple Skidder............	$ 76,000
Franklin 105 Feller-buncher.............	$ 80,120

2. Equipment Financing:

   20 percent of purchase price as down payment, the remainder financed at 13.97 percent APR for 36 months.

3. Salvage Value:

   1.5 percent of purchase price per month based on a five year life.

4. Depreciation:

   Five year straight line.

5. Taxes:

   2.8 percent per year on one-half of market value.

6. Insurance:

   1.2 percent per year of market value.

Operating Costs.

1. Maintenance and Repair:

   75 percent of depreciation per year.

2. Operator Wages:

   $ 8.00 per hour plus 40 percent fringe benefits.

3. Supply Consumption:

   A- Fuel.

   Price..............................$ 0.36 per gallon.

   Cost (105)= (4.36 gallons per operating hour)($ 0.36 per gallon).

   Cost (170)= (5.23 gallons per operating hour)($ 0.36 per gallon).

   B- Engine Oil.

   Price..............................$ 3.72 per gallon.

   Cost (105)= (0.016 gallons per operating hour)($ 3.72 per gallon).

   Cost (170)= (0.032 gallons per operating hour)($ 3.72 per gallon).

   C- Hydraulic Oil.

   Price..............................$ 2.95 per gallon.

   Cost (105 and 170)= (0.004 gallons per operating hour) ($2.95 per gallon).

   D- Lubricant Cost.

   50 percent of engine oil cost.

Other Assumptions

1. 50 hour work weeks.
2. 45 weeks worked per year.
3. 80 percent utilization.
4. Revenue of $ 10.00 per ton of production output.

Appendix E. Discounted Cash Flow Analysis

The following calculations use the assumptions outlined in Appendix D and a 15 percent real interest rate.

Case 1. System using one Franklin 105 grapple skidder and one Franklin 105 feller-buncher.

ITEM	YEAR 0	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5
			<u>105 skidder</u>			
Downpayment.	15200					
Fixed Costs.		26571	26215	25861	557	203
Operating Costs.		37086	37086	37086	37086	37086
Salvage.						7600
			<u>105 feller-buncher</u>			
Downpayment.	16024					
Fixed Costs.		28012	27637	27262	583	218
Operating Costs.		37581	37581	37581	37581	37581
Salvage.						8064
Revenues		468000	468000	468000	468000	468000
Net	-31224	338750	339481	340210	392193	408576
Present Value (15%).	-31224	294565	256696	223694	224237	203134

Net Present Value (15 percent)= 1171102

Case 2. System using a Franklin 170 grapple skidder and two Franklin 105 feller-bunchers.

ITEM	YEAR 0	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5
			170 skidder			
Downpayment.	18860					
Fixed Costs.		32972	32525	32084	687	245
Operating Costs.		39943	39943	39943	39943	39943
Salvage.						9430
			105 feller-bunchers (2)			
Downpayment.	32048					
Fixed Costs.		56024	55274	54524	1166	436
Operating Costs.		75162	75162	75162	75162	75162
Salvage.						16128
Revenues		675000	675000	675000	675000	675000
Net	-50908	470899	472096	473287	558042	584772
Present Value (15%)	-50908	409477	356972	311195	319062	290735

Net Present Value (15 percent)= 1636532

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