AN ABSTRACT OF THE THESIS OF

Benjamin R. Flint for the degree of Master of Science in Forest Engineering presented on October 24, 2013.

Title: Analysis and Operational Considerations of Biomass Extraction on Steep Terrain in Western Oregon

Abstract approved:
Loren D. Kellogg

The development of bioenergy from biomass has dominated the minds of forest engineering researchers over the last decade. One of the main themes that has been generated from that research is that bioenergy from biomass has major operational hurdles to overcome before becoming economically feasible. More directly, the impact of the slope of the harvest area, the elevation of harvest sites and the ownership of the lands being harvested were, in this thesis, seen as major operational hurdles in western Oregon which would require further study. This thesis discusses two studies that were conducted to provide insight into the operational hurdles that are occurring in biomass development.

The first of these studies was an exploratory field study conducted in the area of small wood (<16” DBH) ground-based harvesting on steep terrain (>35%). The purpose of this study was to compare traditional (cable) and contemporary (ground-based) harvesting methods on steep terrain in an effort to determine the economic feasibility of the differing harvest
methods. To achieve the purpose of this study, a shift-level assessment was conducted on six different harvesting systems, all of which were conducting first-entry commercial thinning. The six different harvesting systems were a Koller K301 yarder with manual felling on steep terrain (>35%), a Koller K301 yarder with a Ponsse Ergo harvester (double-bogie) cutting and pre-bunching whole trees with no processing on steep terrain (>35%), a Koller K301 yarder with a Ponsse Ergo harvester (double-bogie) cutting with cut-to-length felling, processing and pre-bunching on steep terrain (>35%), a Ponsse Ergo harvester (double-bogie) cutting and processing for a Ponsse Buffalo King forwarder (double-bogie) on steep terrain (>35%) with an adverse haul to the landing, a Ponsse Ergo harvester (double-bogie) cutting and processing for a Ponsse Buffalo King forwarder (double-bogie) on steep terrain (>35%) with a favorable haul to the landing, and a Ponsse Ergo harvester (double-bogie) cutting and processing for a Ponsse Buffalo King forwarder on flat terrain (<35%).

To evaluate economic feasibility, the productivity and cost of each harvesting system was evaluated and compared. The results of the comparison of the six harvesting systems showed that the system with the lowest harvesting cost for first-entry commercial thinning on steep terrain was the harvester/forwarder combination; under all scenarios studied. However, this study also found that by processing and pre-bunching using the Ponsse Ergo harvester the productivity of the yarder was increased by 79% and the harvesting cost was reduced by 50%. Although the costs of the harvester/forwarder treatments were lower than the cost of the yarder treatments, there were still significant cost reductions and productivity increases when the harvester was paired with the cable yarder.
The Ponsse Ergo harvester was the focus of evaluation for operational aspects of ground based machinery on steep terrain. A detailed time study revealed that significant differences occurred in the average cycle time of the harvester when it was placed on steep terrain. Further analysis showed that the significant difference was not a product of increased slope but rather was the product of factors that were outside of the scope of this study. The harvester’s productivity was impacted by within unit and outside of unit drive times (the time spent driving between trees or driving between cutting areas and the time spent driving on the return trails for access to the next cutting road, respectively). Significant differences in the average within unit drive times was found at the extreme slope classes (65+%) for all treatment units with some treatments having impacts at slopes as low as 45%. However, the changes in average within unit drive times related to slope did not represent a large enough increase in drive times across the different slope classes within each treatment to be able to conclude that slope is the sole factor for decreased production on steep terrain. Thus, there are elements outside of the scope of this study which may have an unforeseen impact on drive times within the unit. Drive time outside of the unit accounted for a loss of an average of one hour per day of productive cutting, and had a significant impact on harvester productivity. Overall, a detailed analysis of the harvester data found that slope steepness had marginal impacts on the productivity of the harvester. This indicates that further analysis may be needed to identify the elements that were not included in the scope of this study that may impact the operability of the harvester on steep terrain.

The second study used to provide insight into the operational hurdles of biomass development was a biomass assessment conducted using Forest Inventory and Analysis (FIA) data provided by the U.S. Forest Service. This assessment focused on the operational factors
of land ownership, slope and elevation. This study works to assess the operational considerations of biomass harvesting at the landscape scale through a biomass assessment based on the ownership group (forest service, other federal, state & local and private), the elevation characteristics and the slope characteristics of timberlands in western Oregon. This assessment focused on comparing the biomass per acre (bone dry tons, BDTons) within a given unique feature to identify the trends or relationships that exist. With respect to ownership group, this study found that forest service lands had significantly more biomass per acre (BDTons) than all other ownership types and private lands had significantly less biomass per acre (BDTons) than all other ownership types. Other federal and state & local timberlands had no significant difference with respect to biomass per acre (BDTons). In order to make true comparisons within the elevation and slope categories, the impact of ownership group on these variables had to be accounted for to remove any possible bias. Thus, the categories of elevation and slope were looked at within each ownership group (forest service, other public and private) to provide a comparison with minimal bias. The study found that the amount of biomass per acre was not significantly different with changes in slope or elevation.

This thesis works to fill the gaps in the literature regarding the operational considerations of harvesting biomass on steep terrain in western Oregon. The results and conclusions will build to the body of literature already present on this topic.
Analysis and Operational Considerations of Biomass Extraction on Steep Terrain in Western Oregon

by
Benjamin R. Flint

A THESIS
Submitted to
Oregon State University

in partial fulfillment of the requirements for the degree of

Master of Science

Presented October 24, 2013
Commencement June 2014
Master of Science thesis of Benjamin R. Flint presented on October 24, 2013.

APPROVED:

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Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

______________________________
Benjamin R. Flint, Author
ACKNOWLEDGEMENTS

I would like to acknowledge the people who provided me with immense amounts of support and help throughout the process of preparing, conducting and writing this document. First, I would like to thank Dr. Loren D. Kellogg for his support, help and encouragement from the beginning to the end of this process. I would like to acknowledge the patience, understanding and encouragement that I have received from my wife, Jaime Flint. Also, I would like to acknowledge the support and guidance of Temesgen Hailemariam and Glen Murphy, both of whom provided me with support and guidance for my thesis and my future career. Lastly, I would like to mention that there are acknowledgement sections within the chapters themselves which outline the acknowledgements I have for those who supported and aided me in the development of that specific study.
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Chapter 1

An Introduction to the Analysis and Operational Considerations of Biomass Extraction on Steep Terrain in Western Oregon

Benjamin R. Flint

October 24, 2013
1.1 Overview

A world-wide increase in demand for low-cost energy sources is pushing for the production of woody biomass as a source of bio-energy. Despite this growing trend, much has been left unanswered regarding the ability of traditional harvesting systems to handle smaller and less valuable material sought by bio-energy markets. To further constrain the problem, smaller and less valuable material located on steep terrain (> 35% slope) gives rise to the need for aerial systems to feasibly remove this material from harvest units. Thus, having a low value product coupled with an expensive harvesting system leads to the infeasibility of harvesting woody biomass on steep terrain via traditional harvesting methods. With these constraints on the feasibility of biomass harvesting, this thesis will propose new harvesting techniques for the economic harvest of small wood on steep terrain and will also look at the potential for increased biomass availability within certain ownership groups or within differing topographic conditions based on the use of these techniques.

An in depth literature review was conducted to ascertain the currently used or researched methods for steep terrain small wood and/or biomass harvesting. Small wood for the purpose of this study was considered any stem that has a diameter at breast height of 16 inches or less. This literature review does not solely cover operations within the United States but rather goes beyond the confines of the U.S. and takes an international snapshot of the industry as a whole. By understanding the current state of the small wood harvesting industry, this study was able to develop and test new harvesting techniques that can have an immediate impact on the industry.
1.2 Literature Review

Over the last couple of decades there has been a growing trend within the United States toward the development and use of renewable energy. This trend has been personified by the ever popular “green movement” which hopes to achieve energy independence and sustainability, within the near future. A big part of achieving the green movement’s goals has been through the use of coarse woody debris (logging slash) for the generation of: electricity, heat and bio-fuels. Although the “green” movement has brought the concept of biomass harvesting to the forefront of the minds of forestry professionals, it is far from a “new” idea. Chappell and Beltz (1973) stated that “logging residues offer even greater opportunities for increasing wood supply if systems can be found to profitably handle the material.” Similarly, Dell and Green (1968) agreed that “…the most desirable method for disposing of logging waste is to use it.” These papers discuss not only the concept of utilizing logging slash as biomass but they also discuss the major issues with the idea, in terms of the physical and economic feasibility of the practice. Similar to the problems seen on today’s biomass harvesting sites, study sites in the past found that “costs of extra equipment and distance to markets are limiting factors” (Dell and Green, 1968)” in the profitability of harvesting biomass.

With similar issues of economic infeasibility holding modern logging operations and forest landowners back from jumping into biomass harvesting, one must wonder why the industry should even make an attempt to utilize this material. This is especially true since the idea has been around for so long without consistently taking hold. The major difference between the forest industry of today and the forestry industry of the past is that timber markets are near
historic lows, driving the need to utilize as much mass (or volume) of material from each acre as is possible in order to offset some of the major losses from the drops in timber value. Another major difference between today’s operations and operation in the past is the increases in the world’s crude oil prices. Many countries are now looking toward wood-based bio-fuels from the collection and harvesting of biomass material (Vuki and Visser, 2010) to offset higher fuel prices. Having extrinsic forces pushing the desire by forest land owners, governments and loggers to utilize biomass material for bio-energy will open the door for more economic and higher productivity biomass harvesting systems. Also, the political and social pressures placed on energy producers to develop sustained renewable energy are driving the development and implementation of woody biomass operations throughout the United States. For example, in 2003, Oregon’s governor had an action plan developed that called for widespread increases in the production of renewable energy across the state, especially with respect to wood-based operations (Oregon, 2003).

Although there is a general push, on all sides, to increase the role of biomass in the forest products arena, there are a lot of challenges both physically and economically that must be overcome before the practice will have widespread profitability. This problem was echoed by Rummer (2008) that "taking material from the stand adds cost, particularly if the material's form is difficult to collect such as residues or small diameter trees." Similarly, Rummer (2008) further argued that the high cost and physical limitations of biomass harvesting may prevent operations from occurring on all but the largest of landholders operations. One of the major physical and economic challenges facing biomass harvesting is the collection, processing and transportation of biomass that is derived from steep slopes. Since a large portion of the
harvestable timberland in the western United States is located on slopes greater than 35%, there is a need to develop effective and economical methods for conducting steep slope biomass operations. On traditional steep slope clear-cut operations, one of the ways used to eliminate the physical problems of biomass collection is to integrate chipping and/or grinding within an existing whole-tree cable logging system (Westbrooke et al., 2007). More specifically, Westbrook et al. (2007) found that “... a small chipper can be added to obtain additional chip production without adversely affecting round wood production”; thus, the study was able to generate extra material and revenue to their operation without impeding their traditional saw log and pulp production volumes. Similarly, Spinelli and Hartsough (2001) found that using chippers in conjunction with traditional harvesting systems where the chipper is centrally located, like on a landing, allows for increased production of biomass material and thus increased profit. The incorporation of a chipper or grinder at the landing within a conventional whole-tree yarding system is one potential way to achieve economic biomass production if only sawlog sized timber was coming off of the site, with only the tops, limbs and branches being utilized. When the harvest site includes small diameter timber and downed woody debris (as with a restoration thinning), the problem of biomass removal on steep slopes can be compounded significantly.

One of the new technologies that have arisen within the biomass harvesting systems is the bundler. The bundling machines seen today consist of a bundling apparatus that is mounted on a forwarder in the location that would normally house the bunk. Although most bundling research has occurred on flat terrain with the bundler producing log sized bundles in the woods, the machine can be used at the landing in conjunction with a whole-tree yarding
steep slope operation. One of the greatest benefits of utilizing a bundler within biomass operations is that the bulk density of the logging slash can be increased; thus, improving the transportation economies of the harvesting system. Also, bundles can be handled and stored similar to logs, in that, traditional log handling systems can be used with bundles and the moisture of the bundle can be controlled to a greater detail than slash or even chips. In a study conducted in the Italian Alps by Spinelli and Magagnotti (2009), a bundler was used at the roadside in “steep mountainous terrain” through which the collection and transportation of slash was so productive that the practice proved to be economical, despite the high investment cost of the machine. Similarly, a study conducted in France by Cuchet et al (2004) showed that as long as the productivity of the bundler stayed around 15-24 bundles per hour that the production of material would outweigh the increase in cost. However, other studies like one that was conducted in Finland by Karha and Vartiamaki (2006) showed that bundlers were only economical if the hauling distances from the woods to the facility were fairly long. Negative effects have been seen in American studies that found the initial cost of the machine too high for the relatively low purchase prices seen in the United States for biomass material. Lastly, there has been some discussion of current research that is or will be conducted that will incorporate a far cheaper, stationary, bundler on a landing within the western United States. However, the stationary bundler research and ideas have not been published or peer-reviewed; thus, the physical or economic feasibility of the practice cannot be ascertained at this time.

The removal of small diameter trees and other downed material for traditional harvests and for fuel reduction operations on flat terrain (<35%) have been shown to be economically
feasible both using cable systems (Kellogg and Brown, 1995) and using ground based mechanized harvesting equipment (Bolding et al., 2009). Similar studies have found various biomass operations to be physically and economically feasible on slopes less than 35% (Nurmi, 2007; Hall et al., 2001). However, much of the economic feasibility and any net profitability can be negated when the effect of steep slopes (>35%) is taken into account (Skog et al., 2006). One of the biggest problems facing steep slope biomass operations is the slower speed and lower volumes produced when dealing with small diameter material. However, current research has been proposing new ways to conduct harvesting operations that would allow for some level of economic feasibility when working with smaller timber for biomass on steep slopes. One study conducted by Heinimann et al (1998) in the Austrian Alps utilized a steep slope capable harvester (maximum 35-55% slope) to process (cut-to-length) and pre-bunch small diameter timber prior to a cable harvest using automatic carriage control. The previous study was able to increase yarding production by 25% (Heinimann et al., 1998); which, if applied to a whole-tree yarding set-up, this allows for greater chipper or grinder utilization since more material would be present on the site; thus, it would offset the higher cost of steep slope biomass harvesting. A similar yet striking different practice uses the principle dictated in the previous paper, that bunching before cable yarding will increase yarder productivity and essentially allow for biomass harvesting, and takes it one step further. One of the major limitations of the practice seen in Heinimann et al (1998) is that it is limited by the ability of the harvester to work on slopes greater than 55%, this limited range of slope operability was resolved in a study conducted in New Zealand by Amishev and Evanson (2010), when they tethered an excavator and a harvester together to create decks
at slopes greater than would have been realized otherwise. Using a bulldozer and with a winch, Amishev and Evanson (2010) were able to tether their machines to create decks in the field that would allow for efficient and effective cable yarding of whole trees. The findings showed that there was an increase in productivity of 33% per cycle when tethering was used to harvest and bunch stems prior to cable yarding. Although other studies discussed the concept and applicability of tethering, this review was unable to find other field studies that applied the principle. However, the concept of tethering harvesting equipment and excavators is one that should be explored more in depth. It is a low cost (no new machinery) solution to improve productivity and economic feasibility, especially with respect to biomass.

Before leaving the discussion on the use of cable systems for yarding whole trees for biomass, the use of cable thinning and new carriage designs must be addressed. Cable thinning is not a new practice, Hochrein and Kellogg (1988) and many other articles have demonstrated the efficient and effective ways in which cable thinning can be used, especially using a small yarder. Specifically, cable thinning has immense value when biomass operations are being conducted as either fuel reduction or forest restoration thinning; similar to what was discussed in Kellogg and Brown, (1995). These operations do not require large yarders or even a medium size yarder but rather they would only need a small yarder or even a yoader. Trailer mounted yarders such as a Koller K300 (Hochrein and Kellogg (1988)) and various types of yoaders would be highly applicable for small scale biomass cable thinning. Lastly, both within the context of cable thinning and cable clear-cut harvesting, new ways of yarding with the cable system itself may lead to increased efficiencies and improved yarder yield when dealing with small-diameter timber and biomass. A conceptual cable harvesting system
designed and validated by Yoshimura and Hartsough (2010) uses a two carriage set-up through which an initial carriage or device would be sent out before the actual carriage to conduct lateral yarding in an area lower down than where the carriage is pulling logs to the landing. The design by Yoshimura and Hartsough (2010) would allow for manual felling to occur on the steep slopes with lateral yarding creating decks, which increases productivity especially when yarding smaller diameter timber in a fuel reduction thinning. Also, using a system that allows for independent lateral yarding creates the opportunity to productively collect widely spread material or stems, and could have positive economic impacts with regards to biomass harvesting.

Cable based systems will serve as an integral part of any steep slope biomass system. Although the use and extent of the cable systems might differ based on site and harvest requirements, the overall need for cable based systems in biomass harvesting is recognized. Cable based systems should be the backbone of any steep slope biomass program, but are not the only systems that can be implemented to achieve economical steep slope harvesting.

Helicopter logging has been used extensively in forest harvesting; to achieve both high production rates and access to isolated and hard to reach timber. In the last decade helicopters have begun to be utilized in more unconventional ways, in that, they are being used more and more for restoration thinning and small diameter timber harvesting. The study conducted by Christian and Brackley (2007) outlines the change in helicopter utilization when they looked at the costs and production rates of using helicopters to thin both large and small timber at variable canopy retention rates. Although Christian and Brackley (2007) found that there was a slight decrease in production as the percentage retention increased,
overall the change in cost ($/mbf) was minimal and would support using helicopter systems for a wide range of silvicultural applications. Having the ability to utilize helicopters for steep slope biomass operations would allow for fuel reduction and restoration operations to occur on isolated stands, and may achieve two goals at the same time. Similar to what was discussed above with cable logging and the use of harvesting equipment to pre-bunch decks of smaller timber to improve production, the following study used the same principle with helicopter logging and shows promise to be a way to improve efficiencies with helicopter biomass harvesting. The paper by Dykstra et al (1978) argues that by utilizing mechanical felling and bunching prior to helicopter yarding, the logging costs could be almost half of what can be achieved using conventional cable yarding systems. Although this paper is somewhat dated, it gets at a great point that the improved productivity and weight maximization for the helicopter will work to offset the higher cost of yarding low value pulp or biomass material. The largest benefit that can be derived from utilizing helicopters within biomass operations would be with fuel reduction and restoration thinning efforts that are needed on isolated, steep ground; similar to conditions in the eastern Cascade Mountains of Oregon. Although only briefly covered here, the importance of conducting fuel reduction and forest restoration thinning within the western United States is of great importance to minimize the risk of catastrophic wild fire or insect outbreak. It is estimated that there are 29 million acres of severely at risk timberlands that need to have fuel reduction treatments that would generate roughly 576 million bone dry tons of biomass material for the bio-energy sector (Vissage et al., 2003). Although not directly discussed in that paper, is the fact that there are areas within the 29 million acres derived by Vissage et al (2003) as high fire risk are
located on isolated and steep terrain. Thus, utilization of helicopters for fuel reduction and restoration type biomass harvesting would be greatly beneficial not only for the forest land owners but for the general public as well. Despite conventional wisdom, helicopter logging is not the last aerial system that can and is being used for use in steep slope biomass operations; an old practice has begun anew in the following study.

The utilization of aerial balloons to harvest timber was a practice that was most common in the middle of the 20th century. The use of this system began to decline in the mid-nineties and presently is not used in North America. However, a study by Hagner (2008) in Sweden shows that the practice is coming back into favor for steep slope thinning, fuel reduction and restoration operations in and around “sensitive” sites. Using the technique of harvesting the trees standing, the balloon system would allow for low impact whole tree yarding that could include the utilization of limbs, tops and bucked material as biomass with processing at the landing (Hagner, 2008). Although this study did not address the actual economic feasibility of the practice, especially with regard to biomass harvesting, it did provide a background through which many forest managers and/or researchers in Sweden can begin developing economic studies and operations. Balloon logging, like helicopter logging, would be beneficial in certain realms of biomass harvesting on steep slopes. Similar to helicopter logging, balloon logging would allow for logging in remote areas, especially within high retention thinning operations. However, the amount of biomass that could be generated from balloon operations as outlined by Hagner (2008) could be proven to be insufficient for profitable biomass operations. However, without further research, the potential for balloon logging within steep slope biomass harvesting is yet to be seen and needs further investigation. For
more information on the logistics, production rates and cost structures for balloon logging, the following articles can be referenced: (Peters, 1973) and (Megahan and Kidd, 1972). To this point, the use of aerial and some ground based operations on steep slopes have been discussed as methods of primary transport from the stump to the landing. However, as outlined in a paper by Sessions et al. (2010) there are some serious concerns regarding the ability of large grinders and conventional chips vans to access landings at the top of steep slopes given the current transportation infrastructure in the Western United States.

The issues that concern steep slope biomass harvesting with respect to roads revolve around the inability of some grinders, chippers and conventional chip vans to access landings that were designed to be accessed by stinger-steered log trucks. In the paper by Sessions et al (2010), they discuss how there are three major limitations of current road structures that inhibit biomass equipment and trucks from reaching western landings. The three major limitations are road width, curve geometry and grade-ability; of which, the two that have the largest impact on the physical capacity to conduct a biomass operation are curve geometry and grade-ability. Since most forest roads in the western U.S. were designed for stinger steered log trucks, the grades of the roads and the curve widening to compensate for off-tracking are too steep or insufficient, respectively, for chip vans to utilize the road structure. Lastly, the width of the road coupled with problems concerning the curve geometry may prevent large scale grinders or chippers from even making it to the landings for biomass processing. Thus, there has been a stream of current research which revolves around addressing these issues by utilizing either a centralized chipping yard or a centralized transfer yard for the biomass material or chips/hog fuel.
The use of a centralized grinding or chipping location has been researched extensively both within the United States and abroad. A study in Austria conducted by Gronalt and Rauch (2007) found that the most efficient and effective way of harvesting logging residues and more generally “forest biomass” was to transport the slash and small trees to a network of centralized chipping/grinding locations that were strategically placed throughout the forest operations network. Similarly, a study in Sweden conducted by Gustavsson et al (2011) found that chipping at a centralized location is more economic than chipping at the roadside with the given harvesting system. However, although these studies show how centralized chipping/grinding can be beneficial economically to a biomass operation, they do not show how the non-uniform slash material can be transported economically from the landing to a centralized location in the western United States. The issue of how to transport slash from the landing to a centralized location has been addressed in at least two publications. A study by Han et al (2010) found that there could be considerable economic gains to utilize roll-off trucking systems, in so far as the distance from the landing to the centralized yard was relatively short. Similar studies are currently being conducted to look at a multitude of other types of trucking and transportation of logging slash from a landing to a centralized location. Many of these studies however have yet to be peer-reviewed; thus, the application of such systems is yet to be determined as physically or economically feasible. Lastly, as mentioned in the article by Sessions et al (2010), there are advances in chip van technology, such as: rear-turning axles, sliding axles, etc., that can either reduce or eliminate some of the road issues faced by steep slope road systems and allow access to the material on the landings.
In summary, there is a strong need to develop biomass harvesting systems that are economically and physically feasible for operating on steep slopes. A proportion of the available biomass and fuel reduction material in the western United States lies on steep (>35%) slopes. Thus, new ways of harvesting (like pre-bunching, tethering, helicopter yarding and bunching and lateral cable yarding carriages) should be explored more thoroughly for their applicability on biomass operations. Also, the integration of chipping and grinding operations within existing traditional whole-tree harvesting systems may prove to be the easiest and most cost effective method of biomass collection. Lastly, the use of centralized chipping/grinding or centralized collection facilities may allow for an improvement of both production and transportation economy, if the research currently being conducted pans out. Overall, the future is bright for steep slope biomass operations both in the western United States and the world.

1.3 Thesis Synthesis

Given the information derived from the international literature review and from discussions with local landowners and contractors, this study was able to propose and test new harvesting techniques that could have an immediate impact on the industry. Also, it was decided that focusing solely on the development of new harvesting systems would not provide a large enough scope for this study. Thus, a biomass assessment was conducted on top of the harvesting study to provide a look into the future potential of biomass availability in the region. With two main focuses put forward for this study, the need was apparent for two separate thesis chapters in order to prevent confusion and to maximize the study’s impact. The following paragraphs provide an overview of the two separate thesis chapters.
The new harvesting techniques being proposed within this thesis will be discussed in full within the second chapter of this document. The second chapter details the results and conclusions of a field study conducted in the summer of 2011. The field study combined traditional harvesting systems with new harvesting systems to attempt to determine the most economically feasible way of removing small, low value timber from steep slopes. The new harvesting techniques that were studied revolved around cutting edge harvesting equipment that is capable of conducting ground based operations on steep terrain. The traditional harvesting systems focused on cable systems that typify the methods that are used to operate on both steep terrain and small timber. By combining and comparing the traditional with the new harvesting techniques, the study was able to determine the most economical pathway for the development of small wood harvesting in the future. Although "small wood" is not fully considered biomass currently, if biomass markets were to mature to a state where the use of small wood for energy was possible, then the foundation has already been developed for productive harvesting to occur.

The biomass assessment will be discussed in detail within the third chapter of this thesis. Many would hear the terms "biomass assessment" and think "that is not a new concept or idea" and they would be correct. The biomass assessment conducted within this thesis, although not totally a new concept has a new area of focus based on the potential operability of biomass harvesting. Most biomass assessments simply wish to make an accurate assessment of the total quantities of biomass that are available. Although that approach is needed, it fails to identify the key questions posed by the industry toward operability. Thus, this biomass assessment makes multiple assessments based on factors that
could have considerable impacts on the ability of harvest managers to actually develop and utilize the biomass material. The assessment was made based on factors including: ownership group, slope class and elevation. These three factors can have considerable impacts on the operability of biomass operations as a whole. Different ownership groups will have different land use objectives that can either support or oppose further biomass development. Differing slope classes can hold the potential to prevent harvesting of biomass altogether because of the increased cost associated with steep terrain harvesting. Although elevation doesn't, at first, seem to have a direct impact on biomass utilization, when looked at the macro-level, it is found to have a very profound impact. Higher elevation areas tend to be farther away from potential markets, have more dated and steep road networks and tend to be locked into very specific ownership groups. Thus, this is a biomass assessment that is focused on the potential for the development of biomass utilization.

These two studies, although presented within this thesis as independent chapters, are far from being unrelated. Both studies have the potential to impact the actions or conclusions from the other study. Having two studies that are intrinsically linked will provide both studies more synthesis and meaning than if the two studies were conducted separately.
1.4 Literature Cited

Chapter 2

First Entry Commercial Thinning: A Comparison of Traditional and Contemporary Harvesting Methods on Steep Slopes in the Coast Range of Oregon.

Benjamin Flint

October 24, 2013
2.0 Abstract

The practice of first-entry commercial thinning, without prior pre-commercial thinning, has recently emerged as a beneficial method to thin young stands in the coast range of Oregon. However, since the practice of first-entry commercial thinning is relatively new, little is known about the economic feasibility of the techniques utilized within steeper terrain harvest units. This exploratory study utilized a detailed time study and a shift-level assessment to compare six different harvesting systems to identify the economic feasibility of each harvesting method and to analyze the changes in the operational nature of ground based equipment when utilized on steep terrain. The six different harvesting systems were a Koller K301 yarder with manual felling on steep terrain (>35%), a Koller K301 yarder with a Ponsse Ergo harvester (double-bogie) cutting and pre-bunching whole trees with no processing on steep terrain (>35%), a Koller K301 yarder with a Ponsse Ergo harvester (double-bogie) cutting with cut-to-length felling, processing and pre-bunching on steep terrain (>35%), a Ponsse Ergo harvester (double-bogie) cutting and processing for a Ponsse Buffalo King forwarder (double-bogie) on steep terrain (>35%) with an adverse haul to the landing, a Ponsse Ergo harvester (double-bogie) cutting and processing for a Ponsse Buffalo King forwarder (double-bogie) on steep terrain (>35%) with a favorable haul to the landing, and a Ponsse Ergo harvester (double-bogie) cutting and processing for a Ponsse Buffalo King forwarder on flat terrain (<35%). To evaluate economic feasibility, the productivity and cost of each harvesting system was evaluated and compared. The results of the comparison of the six harvesting systems showed that the system with the lowest harvesting cost for first-entry commercial thinning on steep terrain was the harvester/forwarder combination; under all
scenarios studied. However, this study also found that by processing and pre-bunching using the Ponsse Ergo harvester the productivity of the yarder was increased by 79% and the harvesting cost was reduced by 50%. Although the costs of the harvester/forwarder treatments were lower than the cost of the yarder treatments, there were still significant cost reductions and productivity increases when the harvester was paired with the cable yarder.

The Ponsse Ergo harvester was the focus of evaluation for operational aspects of ground based machinery on steep terrain. A detailed time study revealed that significant differences occurred in the average cycle time of the harvester when it was placed on steep terrain. Further analysis showed that the significant difference was not a product of increased slope but rather was the product of factors that were outside of the scope of this study. The harvester’s productivity was impacted by within unit and outside of unit drive times (the time spent driving between trees or driving between cutting areas and the time spent driving on the return trails for access to the next cutting road, respectively). Significant differences in the average within unit drive times was found at the extreme slope classes (65+%) for all treatment units with some treatments having impacts at slopes as low as 45%. However, the changes in average within unit drive times related to slope did not represent a large enough increase in drive times across the different slope classes within each treatment to be able to conclude that slope is the sole factor for decreased production on steep terrain. Thus, there are elements outside of the scope of this study which may have an unforeseen impact on drive times within the unit. Drive time outside of the unit accounted for a loss of an average of one hour per day of productive cutting, and had a significant impact on harvester
productivity. Overall, a detailed analysis of the harvester data found that slope steepness had marginal impacts on the productivity of the harvester. This indicates that further analysis may be needed to identify the elements that were not included in the scope of this study that may impact the operability of the harvester on steep terrain.

Through the results of this study, land managers will be better prepared to make informed decisions for economical first-entry commercial thinning on their land base, utilizing innovative steep slope harvesting systems.
2.0.1 Acknowledgements

I would like to acknowledge the persons without whom this study and its analysis may never have come to fruition. Dr. Loren D. Kellogg provided me not only with direction but with immense guidance in the planning, analysis and conclusion determination. Similarly, without the help, guidance and patience of the land managers at Starker Forests Inc. and the planners and operators of Miller Timber Inc. this study may never have occurred. Also, I would like to thank Jeffery Wimer and Dr. John Sessions for their support and advice in the planning and execution of the field study. The analysis of the field data was also aided by the insight of Dr. Glen Murphy. Lastly, special thanks would like to be given to Thomas Lord who aided in the collection of the field data and Jennie Cornell for editing and revising this publication.
2.1 Introduction

With growing concerns related to energy independence, many researchers and professionals have turned their eye toward the forest in an effort to produce an energy commodity that is both carbon-neutral and domestically available. The commodity that is the focus of this interest is woody biomass. Although the term woody biomass can be defined as any biological matter present on the landscape, for the purpose of this study, a more current definition of woody biomass was utilized. Woody biomass is currently defined as any wood based material that is currently not used during the generation of existing forest products but which can be sold or utilized in bio-energy markets. Woody biomass is derived from limbs, tops, stumps and bucked material that traditionally was piled and burned during site preparation or was left on site. The reason woody biomass has become a source for bio-energy production is that it can be used within existing infrastructure for the generation of both heat and electricity.

Despite this focus on the current definition of "woody biomass", there is a strong possibility that as bio-energy markets begin to mature, the definition of woody biomass will expand to encompass small wood (energy wood) in addition to the materials already considered. Small wood describes small diameter trees and logs that are derived from pre-commercial and first-entry commercial thinning operations. Currently, small wood is utilized as either pulp wood or for chip-n-saw. However, as energy markets mature, there is a potential for a growing competition between pulp and chip-n-saw markets with bio-energy markets for small wood resources. Thus, with the potential for bio-energy markets to expand into the small wood sector, the efficiencies and relative productivity of traditional and new harvesting
techniques must be assessed to determine economically feasible methods to remove and utilize small wood biomass.

Due to the relatively low value of small wood in first entry thinning and the relatively high cost of cable logging systems, small wood harvesting has been predominantly constrained to ground based operations on flat terrain (<35% slope). Small wood harvesting has been limited to flat terrain because traditional ground based harvesting equipment (i.e. Rubber Tired and Tracked Skidders) is only effectively utilized on slopes of less than 35%. Given this limitation, economical small wood harvesting operations in forest regions that are typified by steeper terrain, such as the Coast Range in Western Oregon have been scarce.

Timber land managers face many decisions regarding the health and growth of their respective stands. Traditionally, once a stand had been planted, the next progression of management would be to pre-commercially thin in an attempt to add significant amounts of radial growth in the early stages of stand development. However, pre-commercial thinning can be a rather expensive endeavor which provides only the potential for improved net volume return and the potential for increased future profits. Given the current timber market, land managers are making strides to both reduce overall harvesting costs and increase the net volume return from their respective land bases. One of the ways in which land managers can achieve these goals is to forego pre-commercial thinning and instead conduct a first-entry commercial thinning of small, low-value timber. By transitioning their management in this fashion, land managers are able to eliminate the cost of pre-commercial thinning but at the same time retain the growth potential of their stands. This approach works well with mechanized harvesting systems, because of their higher production rates
and relative low cost. But this approach has found considerable obstacles in the coast range of Oregon where land managers are faced with terrain that has traditionally been reserved for high cost cable thinning systems. Thus, there was a strong desire from local land managers to conduct a research study into the economic feasibility of harvesting small, low-value timber on steeper slopes.

This exploratory study was the outcome of the desire of local land managers to find the most economical way to conduct first entry commercial thinning on steep slope (>35%) harvesting units in the coast range of Oregon. Although the initial question of what is the most economical harvesting system for these conditions was the focal point of this study, there was an opportunity to delve deeper and look at the mechanisms which cause differences in economic feasibility. Thus, a two tiered approach was designed whereby at the macro-level the various harvest system configurations were tested and compared to provide an answer to the question of economic feasibility. While at the micro-level the harvester could be assessed in greater detail to determine why the changes in productivity were occurring. With these two-tiers in mind, the study focused first on the harvester and the micro-level study and then on the macro-level economic feasibility of the differing harvesting systems.

2.1.1 Literature Review

The drive to reduce the cost of harvesting operations on productive timberlands is not a contemporary phenomenon but rather has become a central pillar of the evolution of forest operations throughout the modern history of the industry. In the late 1970's and throughout the 1980's the timber industry was faced with the reality of a shrinking supply of old-growth
timber and an increasing supply of young second- and third-growth timber. This prompted early studies such as Aulerich and Kellogg (1977), Schuh and Kellogg (1988) and Hochrein and Kellogg (1988) to begin looking at ways for cost effective management of a young timber resource. Schuh and Kellogg (1988) evaluated the changes that were occurring in western forest operations related to the increased mechanization of harvesting operations. Despite the increase that was noted, there were two factors that proved to be prohibitive to wide-scale adoption of ground-based mechanized harvesting operations; these factors were the increased amount of down-time due to break downs and the loss of productivity on steeper terrain (Schuh and Kellogg, 1988). Even in the early days of mechanized harvesting in the western United States, the impact of slope on productivity was found to be a deterrent to the use of ground-based mechanized systems. As a result of the initial findings of the negative impact of terrain on ground-based mechanization productivity and cost, the focus for research was shifted toward ways in which traditional cable yarding techniques could be modified or hybridized in order to improve the economics of steep slope extraction of smaller, less valuable timber. Hybridization in forest operations is the joining of two or more traditionally separate harvesting systems into a single cohesive harvesting technique, such as combining a feller-buncher with a cable yarder. The study by Hochrein and Kellogg (1988) analyzed the benefits of practices such as pre-bunching and the utilization of small, mobile and inexpensive cable yarders to improve the economics of young timber harvesting. From a baseline set by the previously discussed studies, researchers began to look into ways in which modifications can be made to traditional cable harvesting systems to provide more
cost effective means of extracting smaller, less valuable timber from western timberlands on steep slopes.

Through the evolution of the industry, researchers in the 1990's pressed on with research to derive the most cost effective method for extracting smaller timber. A study by Kellogg and Brown (1995) took an innovative approach by combining ground-based mechanized equipment with cable logging techniques. The central finding of the combination of the ground-based mechanized equipment and the cable harvesting systems was that the combination was economically feasible, and opened the door for further research and analysis of the hybridization of techniques (Kellogg and Brown, 1995). Other studies occurring around the same timeframe utilized the mechanized harvesting systems or new cable system configurations to transition previously uneconomical thinning operations into economical ventures. A study by Hartsough et al. (1997) compared whole-tree, cut-to-length and hybridized whole-tree and cut-to-length ground based operations while thinning ponderosa pine in mixed conifer stands. The importance of this study was that the hybridized system was the most economically feasible method in plantations and those cut-to-length systems were able to improve productivity on steep and broken terrain (Hartsough et al., 1997). The increased mechanization and hybridization of the forest operations sector during the 1990's included the traditional thinning of younger saw-log sized stands and the first-entry commercial thinning of young stands. A study conducted in Tasmania provided an economical background for the elimination of pre-commercial thinning and the inclusion of commercial thinning in eucalypt regeneration (Cunningham, 1997). The study by Cunningham (1997) found that cable operations in young stand thinning were commercially
viable and were a practice to be encouraged to increase eucalypt production in the region. The breakthroughs made in these early studies helped guide the evolution of the industry toward the practice of utilizing mechanized equipment with cable systems and toward the development of first-entry commercial thinning, despite the widespread practice of pre-commercial thinning at the time. However, in a very short time-frame there were drastic changes in technology and market conditions that lead to another advancement in the evolution of harvesting operations.

The progression of utilizing mechanized and cable harvesting systems on steep terrain was continued through a study conducted by Heinimann et al. (1998). A cable yarder was found to have an increase in productivity of 25%, when combined with a harvester conducting cut-to-length falling and bunching on steep terrain. The study also found that the same increase in productivity could be realized by adding an additional choker setter in the brush. Thus, the added cost of the harvester to the system was outweighed by the less expensive prospect of adding an extra laborer (Heinimann et al., 1998). Although the results of the study did not advocate hybridization methods, the idea that productivity could be increased through hybridization, although not economical at the time, has led to additional and recent studies on the subject.

Hybridization of harvest methods and techniques has contributed to the evolution of the logging industry and has emerged with a renewed focus and interest in contemporary forest operations research. Contemporary research utilizes the old techniques in new ways while at the same time incorporating the concept of hybridization to attempt to have ever higher gains in productivity. A study by Acuna and Kellogg (2009) looked at differing hybridizations
of mechanized harvesting techniques over a range of ground slopes, all less than 40%, in eucalyptus thinnings. The study looked at combinations of a feller-buncher with two processors and compared to a harvester-forwarder to conduct full cut-to-length felling and processing followed by forwarding to a central landing (Acuna and Kellogg (2009)). The conclusion from the study was that the harvester-forwarder combination was more economical, despite being less productive, than the feller buncher-two processor-forwarder combination. Also, the economic differential was more profound as slopes increased, meaning that the harvester-forwarder combination became more cost effective on steeper slopes (Acuna and Kellogg (2009)). A similar study, in terms of harvesters operating on steep terrain, paired ground-based mechanized equipment with cable yarding systems through the practice of tethering (Amishev and Evanson, 2010). The ground-based equipment that was utilized in this study was a feller-buncher and two shovels that were tethered to cats near the landing (Amishev and Evanson, 2010). The feller buncher cut and decked stems that were further pre-bunched and partially shovel logged to a skyline cable road (Amishev and Evanson, 2010). Through the combination of ground-based mechanized operations and cable yarding systems, the study found that there was an increase of 33% in the trees hauled per cycle for the cable yarder when compared to unbunched traditional cable yarding (Amishev and Evanson, 2010). Building from the previous study, a study by Acuna et al. (2011) was conducted using the same concept of conducting bunching operations on steep terrain, but instead of using multiple machines, a single self-leveling feller-buncher was utilized. The pairing of a single feller-buncher with a cable yarder on steep terrain was able to obtain productivity gains of 20% to 27% depending on yarding distance (Acuna et al., 2011). Thus,
by reducing the number of mechanized machines on the ground, the total cost of the harvesting system was reduced while still achieving gains in productivity (Acuna et al., 2011). Contemporary forest operations harvesting studies have one major thing in common: they bring the idea of hybridization back, through the use of new technology and practices to improve efficiency and productivity.

The study being reported within this document builds on the concept of hybridization, and provides new insights for future forest operations on steep slopes in timber stands of marginal economic value. However, one aspect of this study that is not represented in the literature is a comprehensive assessment of the various hybridizations and techniques presented within the literature. This study builds on the idea introduced by Cunningham (1997) with the utilization of cable systems and ground-based mechanized equipment for first-entry commercial thinning. However, unlike Cunningham (1997), the operations are all conducted on steep terrain (slopes >35%). Similarly, this study takes the concept of pre-bunching put forth initially by Aulerich and Kellogg (1977) and expanded by others (Hochrein and Kellogg (1988); Kellogg and Brown, 1995; Heinimann et al., 1998; Acuna and Kellogg, 2009; Amishev and Evanson, 2010 and Acuna et al., 2011) and adds a new dimension with operations being conducted on steep terrain and within various terrain and operational aspects in relation to the cable yarder itself. Furthermore, this study evaluates operations beyond the threshold of the traditional operational range of ground-based equipment, especially with respect to forwarders. This study merges concepts together to provide for a more comprehensive review of economic feasibility of contemporary ideas for harvesting.
systems when compared to traditional harvesting practices. The drive for lower costs and greater productivity is the backbone of forest operations research.

2.1.2 Purpose and Objectives

Since first-entry commercial thinning, without prior pre-commercial thinning, is a relatively new practice, there has only been limited research into the most efficient and economical methods and techniques for removing small, low value material from young stands on steep slopes. This deficit in the current scientific knowledge lead to this study being developed in order to provide a starting point for the development of methods and techniques that meet land management objectives at the lowest possible cost. Thus, the purpose of this study is to provide information to land managers on economically feasible methods and techniques to conduct first-entry commercial thinning in small, young stands on steep slopes. The objectives of this study focused on developing an understanding of the operational feasibility and economics of new hybridization of harvesting techniques. The specific objectives of this study were as follows:

- Determine the productivity and cost functions and values for six different logging system configurations.

- Using the productivity and cost functions and values, determine the range of harvesting costs for six logging system configurations on steep slopes (>35%).

- Define the differences between harvesting equipment operations on flat and steep terrain.
This research is based on an exploratory case study of specific pieces of harvesting equipment conducting operations on specific slopes and with specific methodologies and techniques. Any extrapolation outside of the condition and equipment parameters in this case study may be erroneous. The operations conducted within this case study were done by experienced (10+ years in their respective machines) and talented machine operators. The operators from Miller Timber Inc. of Philomath, OR are well trained in both the operation of their given machine and in the safety regulations that restrict their machines’ use (OROSHA, 2008).

2.2 Study Area

The study area is located on Starker Forest Inc. timberland in Benton County, Oregon within Sections 3 and 4, T.11S., R.07W., W.M. The total harvest area is a combination of two thinning units (Devitt Ridge Thinning (79 acres) and Devitt Ridge Extension Thinning (91 acres)) which totals 170 acres. From the 170 acre harvest area, six study units were selected based on: topographic conditions, applicability to proposed harvesting techniques, and operational constraints. The six study units totaled 22.18 acres. The terrain throughout the units was broken or uneven in slope with portions being either flat (0-35% slope) or moderately steep (50-70%) with multiple benches and drainages throughout the area. The trees on the site were primarily 28 year old Douglas-fir (*Pseudotsuga menziesii*) with a low proportion of red alder (*Alnus rubra*) and true fir (*Abies spp.*). Before and after the study operations were conducted, sample plots were taken of the treatment units to describe the pre- and post-operations stand characteristics. The pre- and post-operations stand characteristics are summarized in Table 1.
Table 1. The pre- and post-operations values for trees per acre and average diameter at breast height for all treatment units, including treatment unit acreage.

<table>
<thead>
<tr>
<th>Treatment Unit</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>All units</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPA pre</td>
<td>253</td>
<td>268</td>
<td>276</td>
<td>280</td>
<td>312</td>
<td>272</td>
<td>277</td>
</tr>
<tr>
<td>TPA post</td>
<td>145</td>
<td>145</td>
<td>168</td>
<td>165</td>
<td>160</td>
<td>170</td>
<td>159</td>
</tr>
<tr>
<td>Avg. DBH pre</td>
<td>10.6</td>
<td>11.3</td>
<td>13.0</td>
<td>11.2</td>
<td>12.9</td>
<td>11.7</td>
<td>11.8</td>
</tr>
<tr>
<td>Avg. DBH post</td>
<td>11.4</td>
<td>12.3</td>
<td>11.9</td>
<td>11.8</td>
<td>12.2</td>
<td>11.9</td>
<td>11.9</td>
</tr>
<tr>
<td>Acreage</td>
<td>2.75</td>
<td>1.8</td>
<td>3.63</td>
<td>2.87</td>
<td>4.08</td>
<td>7.05</td>
<td>22.18</td>
</tr>
</tbody>
</table>

Each of the six study units corresponds to six different treatment types that were used to compare various combinations of traditional harvesting techniques and new hybridized harvesting techniques on varying slope conditions.

2.2.1 Study Units and Treatment Types

The six different treatments conducted within this study were unique to each unit, and were compared based on similar factors such as: yarding configuration, felling configuration or slope conditions. Each treatment consists of one of two yarding configurations involving either a Koller K301 yader (Figure 1) or a Ponsse Buffalo King (double bogie) forwarder (Figure 2). The yarding configuration was then combined with either a Ponsse Ergo (double bogie) Harvester (with or without ghost roads, Figure 3) or manual felling (Figure 4). Three of the five treatments were conducted using the Koller K301 yader and the other three study units utilized the Ponsse forwarder for yarding. The three Koller K301 units were on “steep slopes” (50-65%) and were differentiated either by: felling type (whole-tree or cut-to-length), felling mechanism (manual or Ponsse harvester) and/or number of ghost roads (single or double). The two forwarder sides were differentiated either by the slope of the treatment
area or the type of yarding being conducted (adverse or favorable) whereby all felling operations were cut-to-length via the harvester without ghost roads. The six treatment units and their respective acreage and harvesting system are summarized in Table 2.

Table 2. A summary of the: yarding mechanism, felling mechanism, felling type (PB = Pre-bunching, CTL=Cut-to-Length, GR= ghost roads and number of ghost roads) and slope for the five treatment configurations.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Size (ac)</th>
<th>Road Spacing (ft.)</th>
<th>Yarding</th>
<th>Felling</th>
<th>Processing</th>
<th>GR</th>
<th>Slope (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.75</td>
<td>100</td>
<td>Koller 301</td>
<td>Manual</td>
<td>Whole-tree</td>
<td>None</td>
<td>50-65</td>
</tr>
<tr>
<td>2</td>
<td>1.80</td>
<td>100</td>
<td>Koller 301</td>
<td>Harvester</td>
<td>Whole-tree, PB</td>
<td>Yes, 1</td>
<td>50-65</td>
</tr>
<tr>
<td>3</td>
<td>3.63</td>
<td>150</td>
<td>Koller 301</td>
<td>Harvester</td>
<td>CTL, PB</td>
<td>Yes, 2</td>
<td>50-65</td>
</tr>
<tr>
<td>4</td>
<td>2.87</td>
<td>50</td>
<td>Forwarder (adv. haul)</td>
<td>Harvester</td>
<td>CTL</td>
<td>None</td>
<td>50-75</td>
</tr>
<tr>
<td>5</td>
<td>4.08</td>
<td>50</td>
<td>Forwarder (fav. haul)</td>
<td>Harvester</td>
<td>CTL</td>
<td>None</td>
<td>45-65</td>
</tr>
<tr>
<td>6</td>
<td>7.05</td>
<td>60</td>
<td>Forwarder</td>
<td>Harvester</td>
<td>CTL</td>
<td>None</td>
<td>&lt; 35</td>
</tr>
</tbody>
</table>

Ghost roads were corridors that the harvester traveled on to cut stems but where yarding operations were not conducted. Ghost roads were used to increase the spacing between cable yarding corridors. The use of a single ghost road provided a corridor spacing of 100 feet; which was the corridor spacing utilized by the contractor under standard operating procedures; additional ghost roads provided extra spacing between cable yarding corridors that was above the standard operating procedure. The standard operating procedure for this contractor was used in the determination of the two control treatment units. Under standard
operating procedures, cable yarding terrain (>35%) consists of a harvesting system with manual felling, tree-length processing, Koller K301 yarding with a corridor spacing of 100'. Conversely, on ground-based harvesting ground (<35%), the standard operating procedure was the harvester felling and processing stems with the forwarder yarding to a roadside landing. Thus, a control unit was set up for both the cable yarding and the forwarding based on the standard operating procedure of the contractor utilized in this study.

The minimum acreage for the cable yarding treatment units was determined based on a small pilot study that was conducted with the K301 yader on a different site. The results of that pilot study determined that there must be a minimum of 86 turns per K301 yader treatment. The purpose of the minimum turn number was to provide a large enough sample size for statistical analysis at the 95% confidence level. In meeting with the contractor, it was estimated that there were approximately 80 turns pulled per acre, on average. Thus, it was decided that the minimum acreage for the treatment units would be 1.5 acres.
Figure 1. Koller K301 tractor mounted yarder; photo is courtesy of Miller Timber Inc.
Figure 2. The Ponsse Buffalo King Forwarder operating on 60% slopes, photo is courtesy of Dr. John Sessions.
Figure 3. The Ponsse Ergo harvester entering study unit 3
**Study Unit and Treatment 1** consisted of whole-tree manual felling combined with the Koller K301 yarding. Treatment Unit 1 was used to provide a baseline or control for changes in the yarder's productivity. Manual felling of stems coupled with a cable road spacing of 100 feet was used to approximate the standard operating procedure for the yarder. Stems were felled as whole-trees if they were within the cable corridor and were felled with the first log bucked to a length of 32 feet if the stem was outside of the cable corridor. Treatment unit 1 was 2.75 acres in size and had moderate slopes (40-55%) with an average slope of 46%. The landings were road-side and continuous, with a new landing for each corridor. Treatment Unit 1 served as the control for the comparisons made between the three yarder treatments.

**Study Unit and Treatment 2** utilized the Koller K301 for yarding after felling conducted by the Ponsse harvester. Stems were cut whole-tree and pre-bunched decks were generated either on or near the yarding corridor. In order to allow for consistent 100’ road spacing, a single ghost road was used at 50 feet between each corridor. Felling on the ghost road consisted of ejecting full length stems butt first on the side of the road that the stem was cut (i.e. if the stem was to the right of the ghost road it was ejected butt first toward the corridor that is to the right of the ghost road). The treatment was 1.8 acres in size and was conducted on steeper slopes (50-65%), with an average of 48%. The average slope was lowered by short sections of flatter terrain that was less than 35% at the base of the study unit. The landings were road-side and continuous, with a new landing for each corridor.

**Study Unit and Treatment 3** utilized the Koller K301 for yarding after cut-to-length felling and processing and the creation of pre-bunched decks with the Ponsse harvester. To provide improved differentiation between Treatment 2 and Treatment 3, Treatment 3 had a wider
cable road spacing of 150 feet consisting of two ghost roads every 50 feet between yarding corridors. Felling on the ghost roads consisted of ejecting processed (cut-to-length) logs butt first on the side of the trail that the stem was cut. The treatment was 3.63 acres in size and was conducted on primarily steeper slopes (50-65%), with an average of 52%. This average was lowered by two benches occurring on the mid-slope of the unit. The landings were road-side and continuous, with a new landing for each corridor.

**Study Unit and Treatment 4** utilized the Ponsse forwarder and the Ponsse harvester with cut-to-length felling. In order to provide differentiation between Treatment 4 and Treatment 5, Treatment 4 utilized the forwarder to conduct adverse hauling to the landing. Adverse hauling, as defined in this study, was when the loaded forwarder climbed up a grade (approx. 30-45%) to reach the landing, as can be seen in Figure 4 below. The treatment was 2.87 acres in size and was conducted on primarily steeper slopes (55-70%) with an average of 64% and a spacing of 50 feet between corridors. No ghost roads were used within this study unit. The landings were road-side and were placed at centrally located points for ease of log truck loading.
Figure 4. The travel path of the forwarder through study unit and treatment unit 4 with adverse hauling.

Study Unit and Treatment 5 utilized the Ponsse forwarder for yarding and the Ponsse harvester for cut-to-length felling. In order to provide differentiation between Treatment 4 and Treatment 5, Treatment 5 utilized the forwarder to conduct favorable hauling to the landing. Favorable hauling, as defined in this study, was when the forwarder traveled loaded on either downhill or flat grades to reach the landing, as can be seen in Figure 5 below. The treatment was 4.08 acres in size and was conducted on primarily steeper slopes (40-65%), with an average of 52% and a spacing of 50 feet between corridors. No ghost roads were used within this study unit. The landings were road-side and were placed at centrally located points for ease of log truck loading.
Figure 5. The travel path of the forwarder through study unit and treatment 5 with favorable hauling.

Study Unit and Treatment 6 utilized the Ponsse forwarder for yarding and the Ponsse harvester for cut-to-length felling. The treatment was 7.05 acres in size and was conducted on primarily flatter (< 35%) slopes, with an average slope of 5%. Since this study unit had flat terrain (<35%) a road spacing of 60’ without ghost roads was utilized. The landings were road-side at centrally located points for ease of log truck loading. This study unit served as the control for the productivity and cost comparisons made between the three forwarder treatments and can be typified as the standard operating procedure for the contractor used in this study.

2.3 Research Methodology

The research methodology that was used to develop the harvesting productivity assessment for each of the six treatments was adopted from the procedures originally outlined by Olsen and Kellogg (1983) and those utilized in several other publications: Kellogg et. al (1999),
Acuna and Kellogg (2009), Bolding et. al (2009) and Olsen et. al (1998). The primary methods to determine productivity were followed in two different analyses: the detailed time-study and the shift level time study. The detailed time study was applied to the harvester to provide an in-depth analysis of the differentiation and changes that occur to the operational capability of the harvester on steep terrain. The shift level assessment was used both with the harvester and with the six treatments to provide a macro-level assessment of the productivity of each treatment. The differentiation or tiered time-study approach between the micro-level (detailed time-study) and macro-level (shift-level assessment) was used to provide a wider scope to the study to allow a greater number of treatment types within the given study time-frame and still provide some detailed analysis of the operational changes that occur on steep terrain. The specific methodologies for each tier of detail are discussed separately, as the two methodologies were independent of one another during the analysis of the collected data.

The productivity assessment was only half of the study, in that, in order to make true comparisons between treatment units and between harvesting systems, cost determinations were added to the productivity assessment. The cost determinations were made using the machine-rate method, which details the fixed and variable costs for each piece of equipment and more importantly each treatment unit.

**2.3.1 Harvester (Detailed Time-Study)**

The harvester was chosen as the focal point of the detailed time study because changes in the productivity of the harvester could have the greatest impact on the overall feasibility of
any of the study treatments. Also, since this study is exploratory in nature, it was believed that noted changes in the productivity of the harvester would have the greatest influence on management choices for harvesting methods.

The detailed time study focused on two distinct aspects of the harvester’s operational nature, the average cutting cycle and the average within unit drive time between cutting areas. The average cutting cycle represented all of the different elements that combined to represent the selection, cutting and processing of an individual stem and the average drive time represented the amount of time required to drive between the individual trees or between cutting patches. Thus, by analyzing these two functions, an understanding was developed of what changes occurred when the harvester was operating on steep terrain versus flat terrain.

The detailed time study used the measurement or timing of specific operational elements. The process of cutting a stem was broken into discrete and identifiable steps, each of which was timed and recorded to provide data to analyze for potential productivity changes. Each of these discrete identifiable steps combined to form the "cycle time" for a machine. In the case of the harvester, a complete cycle includes driving to a tree, felling, processing and driving to the next tree, with each identifiable step in between being broken down into a discrete element. For this study the machine cycle for the Ponsse harvester was broken into nine discrete elements. The following list details the nine discrete elements that were used and includes their definition within the limits if this study:
Tree Selection and Boom Swing: describes the time required for the machine operator to look into the canopy, select a tree for removal and swing the boom to the stem to be cut. (Began after the machine stopped driving and ended when the cutting head latched onto a stem).

Head Positioning and Cutting: describes the time required for the machine operator to position the head on the stem in the correct orientation and the time that was required to cut the stem. (Began when the cutting head latched onto a stem and ended when the stem was fully separated from the stump).

Processing (CTL): describes the time required to move the tree from the stump to a suitable location for processing and also included the time required to completely process the stem into the subsequent log segments. This element was only used within cutting cycles that involved full cut-to-length harvesting. (Began once the stem had been completely separated from the stump and ended once the machine began moving toward a new stem (either the boom or the whole machine)).

Productive Decking (whole-tree): describes the time required to move a cut whole-tree stem and place it into a suitable deck for yarding. This element was only used within cutting cycles that involved whole-tree harvesting. (Began when the stem was separated from the stump and ended once the machine began moving toward a new stem (either the boom or the whole machine)).

Non-productive Decking: described the time required, outside of general productivity, to place stray logs into a deck or to move logs from one decking location to another because of complications within the operation itself. This
element represented a single type of cutting delay within the operation. (Began when the machine stopped a given part of the cycle to reposition a log or a deck due to log or deck movement and ended when the machine began the cutting cycle again).

- **Drive to tree/drive within unit:** described the time required for the machine to drive from the previously cut stem to the next stem or area for cutting (began when the operator started driving the machine and ended once the machine stopped).

- **Clearing/slash movement:** described the time required to cut down or move small shrubs or trees that were in the path of the harvester or when piles of slash generated from processing were moved for operational purposes (operational delay, began when the boom would swing over to the brush or slash pile and would end either when the boom began moving toward stems or when the machine would begin driving).

- **Delay:** described general delay times that are shorter than 10 minutes in length. This element included: chain changes, wiping windows, personal breaks, small machine maintenance and any small scale (<10 min.) delays in productivity. (Began when the machine would stop any element of the cutting cycle and ended once the machine began operating again).

- **Non-timed segment:** was used when the study required a stop in timing that was not related to the operation being observed. Usually, non-timed segments represented time that was required for breaks in the study itself rather than breaks or delays in the operation being observed.
The data collection for the detailed time study was conducted using video analysis via the program Timer Pro Professional (Timer, 2011). The need for video analysis arose from the very fast transitions between elements that occur within the harvester's cutting cycle. A researcher rode in the cab of the harvester and video record the operation throughout the length of each treatment. Once the video was collected, it was then digitized into a usable format and analyzed using the computer program Timer Pro Professional; the video feed could be slowed down and the actual "detailed time-study" could be conducted. Once the computer aided detailed time-study was completed, the collected data was exported to Microsoft Excel to develop an analysis of the various treatment productivities and to evaluate how they compared to one another.

The detailed time study was conducted by comparing the differences in the operational nature of the harvester both between the individual treatments and within each unique treatment. Comparisons were made using R statistical software (R, 2010) to conduct one-way ANOVA analysis and pair-wise T-tests between the average cycle time and the average drive time of the four steep terrain harvester treatment units and the average cycle time and average drive time for the flat terrain harvester treatment unit 6 (control). Due to confounding variables related to slope conditions and cutting style, the comparisons made between treatment units could not be used to validate perceived changes in harvester productivity on steep terrain. As an alternative analysis, a more detailed approach was taken; whereby, an analysis of the changes in the average cycle time and average drive time between the different slope classes within the each of the three most unique treatment units was utilized. The three analyzed unique treatments were in treatment unit 2 (harvester
whole-tree felling for the yarder on steep terrain), treatment unit 3 (harvester cut-to-length felling for the yarder on steep terrain) and treatment unit 4 (harvester cut-to-length felling for the Forwarder on steep terrain). Within each unique treatment unit, a one way analysis of variance (ANOVA) and pairwise T-tests (both two-sided and one-sided (alternative greater)) were conducted to compare the change in both the average cycle time and average drive time between each slope class within each treatment. By creating a two-tiered detailed analysis, inferences were made for the change in the productivity of the harvester as it operated on steep terrain while still providing an overall view of the difference in the productivity between treatment units.

The use of on the ground observation was used to note changes in cutting style that were not evident within the data that was collected. The observations represent aspects or types of changes in the productivity or movement of the harvester on steep terrain that were not specifically outlined within the data.

Shift level analysis was used to provide macro-level data to determine daily productivity and operability assessments for the harvesting system. The shift level assessment was used to develop overall productivity assessments for each of the six differing harvesting systems used in each of the six treatment units, and it provided an overall view of the changes that arose in the harvester’s operability on steep terrain. The shift level study form used for the analysis of the harvester is in Appendix I.
2.3.2 Harvest System (shift-level assessment)

The shift-level assessment provided the information for the development of macro-level (treatment unit) productivity assessments. The shift level assessment was conducted by noting and recording the various productivity factors that occur within a given day on a given treatment unit. The productivity factors were assessed individually by harvest system component (felling or yarding). Thus, there were four different sets of productivity factors analyzed representing the two felling methods (manual, harvester) and the two yarding methods (forwarder, yarer). The general productivity factors that were assessed for are listed below:

Manual felling:

- Start and stop time
- Number of timber fallers
- Number of stems cut
- Delays (>10 minutes): Operational (walk in/out of unit, hang-ups), Mechanical (chainsaw repair/maintenance, fuel & lube), Other (personal, etc.)

Harvester:

- Start and stop time
- Treatment unit
- On board computer production report (stems cut)
- Fuel consumption (to the nearest gallon)
- Delays (>10 minutes): Operational (wait time or travel between units), Mechanical (repair or maintenance, including scheduled daily maintenance, fuel & lube), Other (personal, etc.)

**Forwarder**

- Start and stop time
- Treatment unit
- Number of Bunks forwarded
- Number of trucks loaded and the duration of loading
- Delays (>10 minutes): Operational (wait time or travel between unit, etc.), Mechanical (maintenance/repair including scheduled daily maintenance), Other (personal, etc.)

**Yarder**

- Start and stop time
- Number of crew members
- Treatment unit
- Number of turns and number of pieces yarded
- Number of trucks loaded
- Processing time (if needed)
- Yarder fuel consumption
- Loader and/or processor fuel consumption
- Road and/or landing change time
• Delays (>10 minutes): Operational (rig-up or tear down, waiting for processor, etc.), Mechanical (equipment repair/maintenance, etc.), Other (personal, etc.)

An example of each of the shift level forms is included in Appendix I of this document. The forms were completed by either a researcher or an operator. Data Elements such as scheduled machine hours (SMH), productive machine hours (PMH), utilization rate (%UT) and overall productivity (i.e. number of stems cut, number of pieces yarded, etc.) were determined for use in the development of harvest system cost of each treatment unit.

The measure of productivity of the yarder was based on data such as pieces per turn, turns per hour and pieces per hour. However, unlike with the forwarder (number of bunks), there are additional aspects of the yarders’ operability that can impact the overall productivity. These factors include: cable road change time and frequency, net payload, number of crew members, number of chokers and the operational practice of presetting logs. Within this study, the number of crew members, the number of chokers and the use of presets were kept the same throughout all of the treatment units. Three people hooked logs and they consistently had three chokers set per turn and another set of three chokers was used for presetting logs. Thus, what was changed between treatment units was the number of skyline road changes required in the different units and the net payload that was being yarded to the landing.

With respect to the productivity value "number of pieces yarded", some transformations were required in order to provide a basis for comparison between the different felling methods (whole-tree, tree-length and cut-to-length) used in the cable yarding treatment
units (1, 2 and 3). Using data collected from the manual felling in treatment unit 1 (tree-length and whole-tree) and the data collected from the harvester in treatment unit 3 (cut-to-length), the recorded value of number of pieces yarded was adjusted by 1.31 for tree-length pieces and 1.50 for whole-tree pieces. The adjustment factors themselves were found by averaging the number of pieces processed per stem from treatment unit 3’s harvester cut report. The harvester’s cut report was generated from the optimization software within the harvester’s computer system. The report details the number of stems cut and subsequently the number of pieces bucked from each stem. Thus, adjustment factors were developed based on how many pieces on average were bucked from a single stem (whole-tree, treatment unit 2) and how many pieces, on average, were bucked after butt log had been removed (tree-length, treatment unit 1). Also, in treatment unit 1, the manual felling data was used to discern the total number of stems that were dropped as whole trees (those within the yarding corridor) and the total number of stems that were dropped as tree-length pieces (the rest of the treatment unit). Without adjusting the number of pieces yarded, there would be no basis of comparison between the three cable yarding treatment units. Thus, the adjustments allow for a basis of comparison based on the total number of pieces yarded after being processed.

Also, the shift-level data provided its own basis for comparison between units, through comparisons of the values of productivity or delays based on the individual treatments themselves. An example is the comparison of the number of turns per day or hour achieved in one treatment unit against the number of turns per day or hour in another treatment unit. Although this provides a general assessment of the differences between systems, it
does not provide a complete indication of which harvest system or treatment unit was the best option without also considering cost.

2.3.3 Costing (machine-rate method)

In order to evaluate the economic feasibility for each of the treatments within the study, a detailed methodology was developed to accurately project the costs of the harvest systems. This was accomplished through the machine rate method as laid out by W.D. Greene and B.L. Lanford (1999). The machine rate method is a process whereby the fixed costs, variable costs and labor costs are developed independently for each piece of equipment and then combined to ascertain a per hour cost for each treatment type. Once a per-hour cost is determined, the per-unit cost and overall treatment cost can then be ascertained using productivity values. To provide greater detail into how the machine rate method was applied for this study, each step of the costing process is discussed separately in Appendix II.

2.3.3.1 Independent Equipment Cost

The purchase price that was used within the cost analysis was based on the listed price for a new piece of equipment as provided by the contractor (Miller Timber Inc.). All other values were ascertained from industry standard prices and/or rates. Appendix III of this document lists all of the values utilized within this study for the development of individual equipment costs. Using the machine rate method the fixed costs, variable costs and Labor costs were developed to determine the total cost of each piece of equipment within the study. Also, since each operator had their own company pick-up truck, an industry average of $14.00 per
scheduled machine hour was included in the total cost of each operator’s piece of equipment to account for the pick-up truck.

The independent total cost was determined for each piece of equipment used within this study. These costs are indicative of both the information derived from the shift-level analysis and industry standard practices and/or rates. The independent total costs, after calculation, were then used within the development of the cost of each harvest system used in each treatment unit.

2.3.4 Harvest System Costing

This study used the combination of shift level productivity data with the machine rate method cost data to provide an overall cost for each harvesting system. Through the development of a total cost for each harvesting system, the treatment types were then compared based on a standardized unit of cost. The standardized unit of cost for the basis of comparison was, developed at the per unit level with the unit being a single truck load of logs. Although the truck load is not a typical unit from which to base costs, this approach provided the best method for comparisons because of the data that was collected. The data collected lead to the formulation of a cost per piece for each harvest method (felling, yarding) and harvesting system, with a piece representing a single log. Since the pieces (logs) were not homogenous in size, a conversion to volume or weight (MBF, CCF or ton) would be unrealistic of the data collected. However, the data did provide an average number of pieces per truck load, which lead to the determination that the best unit for comparison based on the data collected was the cost per load for each harvesting system.
When combining the productivity shift level data and the cost data for the six treatments there were two levels associated with the development of per-unit cost ($/load). The first was to view the per-unit cost ($/load) for each treatment by the individual harvesting method (i.e. felling and yarding) and the second was to bring everything together and develop per-unit ($/load) harvesting costs for the entire harvest system within each treatment unit. Approaching the cost analysis in this fashion led to a better understanding of the influences that the felling and/or yarding technique had on the cost of the harvesting mechanism individually without having to read between the lines with the full system cost analysis.

2.3.4.1 Individual Machine Cost

The total and per unit ($/piece) cost for each machine within a given treatment was developed to display how the cost of the equipment changes with different levels of productivity. These costs were developed from the shift level data using the hourly machine rate, the total number of hours, and total production, in either stems cut or pieces (logs) yarded. First the total cost of the machine in a given treatment was found by multiplying the total number of hours by the per hour machine rate. The cost was then divided by the total productivity (stems cut or pieces yarded) to determine a per-unit cost ($/load) for the machine in a given treatment unit.

Having a per-unit ($/piece) cost associated with each machine in each treatment type, provided a basis for comparison between the treatment units when a single machine was
the focus of analysis. However, the total harvest system cost of each treatment has more validity to determine the economic feasibility of different harvesting practices.

2.3.4.2 Harvest System Cost

Using the total cost developed for each machine in each treatment unit, the total cost for the harvest system in each treatment unit was found by combining each of the individual machine costs into a single cost representing the entire harvesting system for the treatment unit. An extra 18% was added on top of the total harvest system cost to account for overhead, risk and profit. Once the final total cost had been developed for each treatment type, the per unit cost was found by dividing the total cost by the number of pieces (logs) that were yarded (total production) for the treatment.

A cost per load was developed to give a consistent and identifiable basis for comparison. The cost per load was used as the primary basis for comparison between the different harvest treatment types. The number of pieces per load was found via the forwarder shift level data. An average was found based on the figure present within the forwarder shift level data and it was determined that there were 274 pieces on average within a single log truck load. Using the value of 274 pieces per load, the total cost was transformed from a cost per piece into a cost per load for each treatment unit.

2.4 Results

The first group of results presented is the results of the detailed time-study for the harvester. The second group of results includes the findings from the shift-level assessment and the economic analysis of the different treatment types.
2.4.1 Harvester

The results of the detailed analysis of the harvester are based on the analysis of trends and/or changes that occurred in the operational nature of the harvester when placed on steep terrain in contrast to working on gentle-sloping terrain. The shift-level data from the harvester provided a general insight into the differences in productivity between units. The results of the shift-level assessment conducted on the harvester are summarized in Table 3.

Table 3. The shift level study results for the productivity of the harvester in each treatment unit with a comparison of steep terrain units (2, 3, 4 and 5) to the control flat terrain treatment unit 6.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Productive hrs.</th>
<th>Stems Cut</th>
<th>Stems/hr.</th>
<th>% Change from Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 (control)</td>
<td>16.5</td>
<td>1030</td>
<td>62</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>9.5</td>
<td>326</td>
<td>34</td>
<td>-45%</td>
</tr>
<tr>
<td>3</td>
<td>16</td>
<td>897</td>
<td>56</td>
<td>-10%</td>
</tr>
<tr>
<td>4</td>
<td>11</td>
<td>437</td>
<td>40</td>
<td>-36%</td>
</tr>
<tr>
<td>5</td>
<td>22</td>
<td>865</td>
<td>39</td>
<td>-37%</td>
</tr>
</tbody>
</table>

From Table 3 it can be seen that the largest change in harvester productivity occurred in treatment unit 2; where there was a 45% reduction in the number of stems cut per hour. Conversely, treatment unit 3 had the smallest change in harvester productivity, with a 10% reduction in the number of stems cut per hour (Table 3). Although the shift-level data provided an assessment of the changes in productivity between the treatment units, the results could not be used to determine why the treatment units had different productivity levels. Thus, the detailed time study data was used to develop an understanding of the causality of the changes in productivity with respect to the control.
There was one primary observational result that was found from simply viewing the harvester operating on both flat and steep terrain. When the harvester was operating on flat (<35%) terrain, there was not a need to have designated skid trails to control the harvester’s movement through the stand. However, when the harvester was operating on steep (>35%) terrain, there was a need to have the harvester follow specific routes through the stand. The need related to the safety of operation, in that, the harvester roads were flagged prior to the operation to ensure that the hill slope and side slope did not exceed the operational limits of the machine. The difference in harvester road layout lead to the observational result detailed in Figures 6 and 7.

Flat terrain “wandering”

*Figure 6.* The observed harvester movement (red lines) and cutting style (blue circles) through a flat terrain harvest unit, this has been named” harvester wandering".
Steep Terrain “structured”

**Figure 7.** The observed harvester movement (red arrows) and cutting style (blue swaths) through a steep terrain harvest unit, this has been named "structured".

The results of the detailed time study were developed in two levels. The first stage focused on the comparison of the average cycle time and average drive time across all of the harvester treatment units. The second level delved deeper into the treatment units themselves, whereby an analysis was conducted to compare the cycle times and drive times against slope within the three unique treatment units. The three unique treatment units represent the three different felling methods used within the study. The two-level analysis provided an in depth look at the operational nature of the harvester when operating on steep (>35%) terrain.

The analysis of the change in the average cycle time began with the plotting of the average cycle time and a corresponding 95% confidence interval for each of the harvester treatment units. The plot of the average cycle time across the different treatment units is presented in Figure 8.
Figure 8. The average cycle times (sec.) and the corresponding 95% upper confidence limit and lower confidence limit for the five harvester treatment units.

From Figure 8 it can be seen that differences occurred in the average cycle time across the different harvester treatment units, with treatment units 2 and 6 (control) representing the lowest average cycle times and treatment units 3 and 4 representing the highest average cycle times. In order to determine if the differences related to treatment units (Figure 8) are significant, two-tailed and one-tailed pair-wise t-tests were conducted. The results of the pairwise t-tests are summarized in Table 4, Table 5 and Table 6.

Table 4. The two-sided pair-wise t-test p-values for the comparison of the average cycle time for five harvester treatment units.

<table>
<thead>
<tr>
<th>Treatment unit</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td></td>
<td>&lt;0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>&lt;0.001</td>
<td></td>
<td>0.646</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>&lt;0.001</td>
<td>0.031</td>
<td>0.102</td>
<td></td>
</tr>
<tr>
<td>6 (control)</td>
<td>0.096</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.04</td>
</tr>
</tbody>
</table>
There were significant differences between treatment unit 2 and all of the steep terrain harvest treatment units (3, 4, 5) with p-values all <0.001 (Table 4). Similarly, the flat terrain harvester unit's (treatment unit 6) average cycle time was significantly different from all of the other harvester treatment units (3, 4 and 5) average cycle times except for unit 2, with p-values of <0.001, <0.001 and 0.04, respectively (Table 4). Although knowing that differences occurred provides insight into the change in the harvester's operability, it is more important to develop an understanding of the direction of the differences, whether larger or smaller. To determine the direction of the differences, the one-tailed pair-wise t-test results are summarized in Table 5 and Table 6.

**Table 5. The one-sided pair-wise t-test (alternative greater) p-values for the comparison of the average cycle time for five harvester treatment units.**

<table>
<thead>
<tr>
<th>Pair-wise T-test (One-sided, Alt. Greater)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment Unit</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6 (control)</td>
</tr>
</tbody>
</table>

**Table 6. The one-sided pair-wise t-test (alternative less) p-values for the comparison of the average cycle time for five harvester treatment units.**

<table>
<thead>
<tr>
<th>Pair-wise T-test (One-sided, Alt. Less)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment Unit</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6 (control)</td>
</tr>
</tbody>
</table>
From Table 5, the only significant differences that occurred revolve around treatment unit 2. All four of the other treatment units (3, 4, 5 and 6) were found to be significantly greater than treatment unit 2 with respect to the average cycle time of the unit, with p-values of <0.001, <0.001, <0.001 and .048, respectively (Table 5). Similarly in Table 6, it can be seen that treatment unit 6 had an average cycle time that was significantly lower than treatment units 3, 4 and 5 (p-value = <0.001, <0.001 and 0.021, respectively). Lastly, the average cycle time of unit 5 was significantly lower than that of treatment unit 3 (p-value = 0.01, Table 6).

The average cycle time does not portray all the changes in the productivity of the harvester as a result of changes in slope and felling method (different treatment units). The average drive time was also analyzed for changes and/or differences between treatment units. The average drive time represents the average amount of time spent driving to individual trees or groups of trees within the confines of the treatment unit. The average drive time and the corresponding 95% confidence interval of the average cycle time was plotted to show any macro-level trends and can be seen in Figure 9.
Figure 9. The average drive times (sec.) and the corresponding 95% upper confidence limit and lower confidence limit for the five harvester treatment units.

Figure 9 shows that there is an increase in the average drive time for all of the steep terrain harvester treatment units (2, 3, 4 and 5) when compared to the flat terrain treatment unit 6 (control). To determine if the differences in the average drive time between treatment units were significant, a one-way ANOVA analysis was conducted followed by subsequent two-tailed and one-tailed pairwise t-tests. The one-way ANOVA F-test resulted in a p-value of .0028. The one-way ANOVA, although it shows that there were significant differences in the average drive time between the treatment units, it does not detail which treatments units are significantly different or in what direction the difference was occurring. To determine the significant differences that occurred two-tailed and one-tailed pair-wise t-tests were used. The results of the two-tailed pair-wise t-tests are summarized in Table 7.
Table 7. The two-sided pair-wise t-test p-values for the comparison of the average drive time for five harvester treatment units.

<table>
<thead>
<tr>
<th>Pair-wise T-test (Two-sided)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment unit</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6 (control)</td>
</tr>
</tbody>
</table>

The significant differences in average drive time that occurred were with treatment unit 6 (flat terrain, control) against all other treatment units (2, 3, 4 and 5) with p-values = .002, <0.001, <0.001 and <0.001, respectively (Table 7). Although the two-tailed t-test displays which differences were occurring, it did not show in which direction the differences occurred. The one-tailed pair-wise t-test was used to determine the direction of difference between unit 6 and the other four harvester treatment units (Table 8).

Table 8. The one-sided pair-wise t-test (alternative less) p-values for the comparison of the average drive time for five harvester treatment units.

<table>
<thead>
<tr>
<th>Pair-wise T-test (One-sided, Alt. Less)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment Unit</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
</tbody>
</table>

The flat terrain harvester control unit (treatment unit 6) had an average drive time that was significantly lower than that of all four of the steep terrain harvester treatment units, with all p-values = <0.001 (Table 8). Despite the significance of the changes seen in the
comparisons between the differing treatment units, there was no statistical inference that could be made outside of the scope of this case study due to the presence of the confounding variables of slope and felling method. A more detailed assessment was completed within the treatment units to provide support for stronger inferences about the changes in the operational nature of the harvester related to slope and felling method. To achieve this, the three most unique steep slope units, units 2, 3 and 4 were analyzed based on average cycle time and the average drive time as they correlate to specific slope classes within each treatment unit. The general trend for the average cycle time by slope class across the three unique treatment units is summarized in Figure 10.

**Figure 10.** The average cycle times (sec.) by slope class (1 = 0 to 35%, 2 = 35 to 45%, 3 = 45 to 55%, 4 = 55 to 65% and 5 = 65 %+) for each treatment unit.

The trends illustrated in Figure 10, were not significantly different. The results of the one-way ANOVA F-test and the pairwise t-tests (two-sided and one-sided (alternative greater)) were used to evaluate the significance of the observed differences for each of the three
treatment units (Treatment Unit 2, 3 and 4). For Unit 2, the average cycle times were the same across the different slope classes (one-way ANOVA F-test p-value = .1143, all t-test p-values > .05). For unit 3, the average cycle time was not found to be significantly different between the differing slope classes (one-way ANOVA F-test p-value = .8345, all t-test p-values >.05). Similarly, for unit 4 no significant differences were found between the slope classes with respect to the average cycle time (one-way ANOVA F-test p-value = .091, all t-test p-values >.05). The importance of finding no significant differences in the average cycle time within the treatment units while finding significant differences in the average cycle time between the treatment units is covered in the discussion section.

The average drive time within each unit was tested at the different slope classes to evaluate how the ground slope impacted the drive times within each of the three unique harvest units (Figure 11).

![Figure 11](image.png)

**Figure 11.** The average drive times (sec.) by slope class (1 = 0 to 35%, 2 = 35 to 45%, 3 = 45 to 55%, 4 = 55 to 65% and 5 = 65 %+) for each treatment unit.
From Figure 11 it can be seen that there was a macro-level trend; whereby, the average drive time increased on slopes that were greater than or equal to 45%. However, the significance of this trend was determined through the comparison of means via the two-tailed and one-tailed pair-wise t-test. The t-tests were carried out for each of the three unique harvester treatment units (2, 3 and 4) with respect to the average drive time in relation to slope class. The results of the two-tailed pair-wise t-test conducted for unit 2 are summarized in Table 9.

**Table 9.** The two-sided pair-wise t-test p-values for the comparison of the average drive time against the five slope classes in treatment unit 2.

<table>
<thead>
<tr>
<th>Pair-wise T-test (Two-sided)</th>
<th>&lt;35</th>
<th>34 to 45</th>
<th>45 to 55</th>
<th>55 to 65</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope Class</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35 to 45</td>
<td>0.93</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45 to 55</td>
<td>0.22</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>55 to 65</td>
<td>0.86</td>
<td>0.77</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>65+</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.021</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

From Table 9, there is a significant difference between the average drive time when the harvester was operating on slopes greater than 65% (p-values <.05). However, what cannot be shown by the two-tailed results is the direction in which the difference is occurring. The directions of the differences were determined by the one-tailed pair-wise t-test (Table 10).
Table 10. The one-sided pair-wise t-test (alternative greater) p-values for the comparison of the average drive time against the five slope classes in treatment unit 2.

<table>
<thead>
<tr>
<th>Slope Class</th>
<th>&lt;35</th>
<th>34 to 45</th>
<th>45 to 55</th>
<th>55 to 65</th>
</tr>
</thead>
<tbody>
<tr>
<td>35 to 45</td>
<td>0.46</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45 to 55</td>
<td>0.11</td>
<td>0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>55 to 65</td>
<td>0.57</td>
<td>0.61</td>
<td>0.92</td>
<td></td>
</tr>
<tr>
<td>65 +</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.011</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

The average drive time when the harvester was on slopes in excess of 65% was longer than when the harvester was on other slope classes (p-values <.05, Table 10). Treatment unit 3 had similar trends as those seen in Unit 2; however, the differences are far more dynamic covering more than one slope class (Table 11).

Table 11. The two-sided pair-wise t-test p-values for the comparison of the average drive time against the five slope classes in treatment unit 3.

<table>
<thead>
<tr>
<th>Slope Class</th>
<th>&lt;35</th>
<th>34 to 45</th>
<th>45 to 55</th>
<th>55 to 65</th>
</tr>
</thead>
<tbody>
<tr>
<td>35 to 45</td>
<td>0.87</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45 to 55</td>
<td><strong>0.012</strong></td>
<td>0.056</td>
<td></td>
<td></td>
</tr>
<tr>
<td>55 to 65</td>
<td><strong>0.0013</strong></td>
<td><strong>0.019</strong></td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td>65 +</td>
<td><strong>&lt;0.001</strong></td>
<td><strong>0.0014</strong></td>
<td>0.101</td>
<td>0.121</td>
</tr>
</tbody>
</table>

In treatment unit 3, significant differences occurred on slopes between 0 and 45% (p-values <.05) and on slopes between 45% and 65+% (p-values >.05); however, within each slope class there was no significant difference (Table 11). The direction of difference was found through the one-tailed pair-wise t-test (Table 12).
Table 12. The one-sided pair-wise t-test (alternative greater) p-values for the comparison of the average drive time against the five slope classes in treatment unit 3.

<table>
<thead>
<tr>
<th>Pair-wise T-test (One-sided, Alt. Greater)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope Class</td>
</tr>
<tr>
<td>---------------</td>
</tr>
<tr>
<td>35 to 45</td>
</tr>
<tr>
<td>45 to 55</td>
</tr>
<tr>
<td>55 to 65</td>
</tr>
<tr>
<td>65 +</td>
</tr>
</tbody>
</table>

When the harvester operated on slopes in excess of 45%, there was a significant increase in the average drive time (p-values <.05, Table 12). However, once above 45% slopes there was no significant difference in the average drive time (p-values >.05, Table 12). Unit 4 had more similarities with unit 3 than with unit 2 with respect to the results of the t-tests (Table 13).

Table 13. The two-sided pair-wise t-test p-values for the comparison of the average drive time against the five slope classes in treatment unit 4.

<table>
<thead>
<tr>
<th>Pair-wise T-test (Two-sided)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope Class</td>
</tr>
<tr>
<td>---------------</td>
</tr>
<tr>
<td>35 to 45</td>
</tr>
<tr>
<td>45 to 55</td>
</tr>
<tr>
<td>55 to 65</td>
</tr>
<tr>
<td>65 +</td>
</tr>
</tbody>
</table>

Significant differences occurred in treatment unit 4 when the harvester was on slopes in excess of 55% (p-values <.05, Table 13). However, once slopes exceeded 55% there were no significant differences (p-values >0.05, Table 13). The direction of these differences was determined using the one-tailed pair-wise t-test (Table 14).
Table 14. The one-sided pair-wise t-test (alternative greater) p-values for the comparison of the average drive time against the five slope classes in treatment unit 4.

<table>
<thead>
<tr>
<th>Slope Class</th>
<th>&lt;35</th>
<th>34 to 45</th>
<th>45 to 55</th>
<th>55 to 65</th>
<th>65 +</th>
</tr>
</thead>
<tbody>
<tr>
<td>35 to 45</td>
<td>0.69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45 to 55</td>
<td>0.58</td>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>55 to 65</td>
<td>0.03</td>
<td>0.011</td>
<td>0.035</td>
<td></td>
<td></td>
</tr>
<tr>
<td>65 +</td>
<td>0.001</td>
<td>&lt;0.001</td>
<td>0.002</td>
<td>0.122</td>
<td></td>
</tr>
</tbody>
</table>

There was a significant increase in the average drive time when the harvester operated on slopes in excess of 55% (p-values <0.05, Table 14). However, when the harvester was operating on slopes in excess of 55% there was no significant difference in the average drive time (p-values >0.05, Table 14).

The harvester is just one piece of the harvest system puzzle and although it is valuable to understand the reasons behind the changes in productivity observed for the harvester, it is not the sole factor when trying to determine overall economic feasibility of a harvesting system. For the determination of the economic feasibility of the harvesting system, the analysis must be more general and observe the entire harvesting system at the macro-scale.

2.4.2 Harvest System

The results for the comparison of the different harvesting systems in the treatment units can be divided into three separate categories. First are the results from the shift level assessment, detailing the differences in productivity and operability. The second category is the machine rate method results found for each piece of equipment that was utilized in the
study. The third category is the harvest system cost and economic comparison results found between the treatment types.

2.4.2.1 Shift Level Assessment

The results from the shift level assessment between harvesting systems focuses around the results for the forwarder and yarder, since the productivity of the yarding mechanism influenced the economics of the system as a whole. The productivity of the forwarder was influenced by the total number of bunks that were forwarded and the number of bunks that were forwarded in an hour. The productivity values for the three forwarder treatments are in Table 15.

**Table 15.** The shift level productivity values for the forwarder treatment units.

<table>
<thead>
<tr>
<th>Treatment Unit</th>
<th>Total bunks</th>
<th>Bunks/hr</th>
<th>Pieces/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 (control, Flat)</td>
<td>17.5</td>
<td>1.66</td>
<td>238.19</td>
</tr>
<tr>
<td>4 (Adv. Haul)</td>
<td>7</td>
<td>0.70</td>
<td>100.47</td>
</tr>
<tr>
<td>5 (Fav. Haul)</td>
<td>17.5</td>
<td>1.57</td>
<td>192.74</td>
</tr>
</tbody>
</table>

The results of the shift level assessment of the forwarder show that when the forwarder was operating on steep terrain (>35%) and was traveling loaded in an adverse direction to the landing (treatment unit 4) there was a 58% decrease in productivity compared to the flat terrain control unit (treatment unit 6) with pieces per hour values of 100.47 and 238.19, respectively (Table 15). Conversely, when the forwarder was operating on steep terrain
(>35%) and was traveling loaded in a favorable direction to the landing (treatment unit 5) there was only a 19% decrease in overall productivity compared to the flat terrain control unit (treatment unit 6) with pieces per hour values of 192.74 and 238.19, respectively (Table 15). The most productive forwarder harvesting system was the flat terrain harvesting system found within the control (treatment unit 6).

Although the productivity of the forwarder was driven by the number of bunks yarded, the productivity of the yader was driven by the number of pieces yarded and the number of turns per hour. As mentioned in the methodology, the number of pieces was adjusted for the tree-length and whole-tree harvesting systems (treatment unit 1 and treatment unit 2, respectively) to provide a compatible basis of comparison between the three cable yarding treatment units. The results of the shift level productivity assessment of the yader are summarized in Table 16.

**Table 16.** The shift level productivity values for the Koller yader treatment.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>turns/hr.</th>
<th>Pieces/turn</th>
<th>Pieces/turn (adjusted)</th>
<th>Pieces/hr. (adjusted)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (control) *MF - TL</td>
<td>11</td>
<td>3.65</td>
<td>4.8</td>
<td>51.35</td>
</tr>
<tr>
<td>2 *HRV - WT</td>
<td>9</td>
<td>3.92</td>
<td>5.88</td>
<td>50.15</td>
</tr>
<tr>
<td>3 *HRV - CTL</td>
<td>13</td>
<td>7.14</td>
<td>7.14</td>
<td>92.04</td>
</tr>
</tbody>
</table>

*CTL - Cut-to-length, HRV - Harvester Felling, MF - Manual Felling, TL - Tree-length, WT - Whole Tree

The value of pieces per hour is the critical factor for the productivity of the yader. The results showed that there was a 79% increase in productivity for the yader when the yader was operating on skyline roads where the harvester was cutting and decking cut-to-length
stems (treatment unit 3) when compared to the control of manual felling with tree-length processing (treatment unit 1) with pieces per hour values of 92.04 and 51.35, respectively (Table 16). Conversely, there was little difference (2.4% decrease) when the yarder was yarding whole trees that were cut and decked by the harvester (treatment unit 2) when compared to the control (treatment unit 1) with pieces per hour values of 50.15 and 51.35, respectively (Table 16). The increase in productivity within treatment unit 3 results from the number of turns per hour and the number of pieces per hour that were also the highest amongst the three cable yarding treatment units with values of 13 and 7.14, respectively. Although the comparison of productivity is an integral part of determining the economic feasibility of a harvesting system, the most important aspect when determining economic feasibility is the overall per unit cost of a given harvesting system.
2.4.2.2 Equipment Cost

The base values used for the cost analysis were the hourly equipment costs ($/SMH) that were determined through the machine rate method and are listed in Table 17.

Table 17. The calculated values for the hourly equipment costs for the equipment utilized within this study.

<table>
<thead>
<tr>
<th>Piece of Equipment</th>
<th>Harvester</th>
<th>Forwarder</th>
<th>Loader</th>
<th>Yarder (5 loggers)</th>
<th>Manual Felling (1 cutter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed Cost ($/SMH)</td>
<td>$45.31</td>
<td>$30.21</td>
<td>$29.37</td>
<td>$13.26</td>
<td>$0.34</td>
</tr>
<tr>
<td>Variable Cost ($/PMH)</td>
<td>$65.96</td>
<td>$67.89</td>
<td>$49.70</td>
<td>$19.12</td>
<td>$3.98</td>
</tr>
<tr>
<td>Labor Cost ($/SMH)</td>
<td>$31.19</td>
<td>$26.73</td>
<td>$25.65</td>
<td>$108.00</td>
<td>$40.50</td>
</tr>
<tr>
<td>Pick Up Truck ($/SMH)</td>
<td>$14.00</td>
<td>$14.00</td>
<td>*</td>
<td>$14.00</td>
<td>$14.00</td>
</tr>
<tr>
<td>Total ($/SMH)</td>
<td>$138.49</td>
<td>$112.64</td>
<td>$86.26</td>
<td>$147.28</td>
<td>$58.74</td>
</tr>
</tbody>
</table>

*The loader operator utilized the same pick-up as the yarder crew

By using the total hourly costs ($/SMH) from Table 17 multiplied by the number of hours spent within each treatment unit, a total cost for each unit was established. The total cost was split between the total cost for felling operations and the total cost for yarding operations for each treatment unit. Using the total cost values developed for felling and yarding operations within each treatment unit, a cost per unit was developed to provide a basis for comparison between the different treatment units (Table 18).
Table 18. The total cost, total production and per unit cost for felling operations in each treatment unit; where MF = manual felling and Harv. = harvester felling, including the % change with respect to the control treatment unit.

<table>
<thead>
<tr>
<th>Treatment Unit (Felling Equipment)*</th>
<th>1 (MF)</th>
<th>2 (Harv.)</th>
<th>3 (Harv.)</th>
<th>4 (Harv.)</th>
<th>5 (Harv.)</th>
<th>6 (Harv.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Cost ($                     )</td>
<td>675.51</td>
<td>1,869.62</td>
<td>3,012.16</td>
<td>1,523.39</td>
<td>3,046.78</td>
<td>2,769.80</td>
</tr>
<tr>
<td>Total Production (stems)</td>
<td>315</td>
<td>326</td>
<td>897</td>
<td>437</td>
<td>865</td>
<td>1,030</td>
</tr>
<tr>
<td>Cost Per Stem ($)</td>
<td>2.14</td>
<td>5.74</td>
<td>3.36</td>
<td>3.49</td>
<td>3.52</td>
<td>2.69</td>
</tr>
<tr>
<td>% Change (cost/stem) to Control</td>
<td>Control</td>
<td>167%</td>
<td>57%</td>
<td>30%</td>
<td>31%</td>
<td>Control</td>
</tr>
</tbody>
</table>

*Unit 1: Manual Felling – tree-length stems for yarder, Unit 2: harvester felling and decking whole trees for yarder, Unit 3: harvester cut-to-length and decking for yarder, Unit 4: harvester cut-to-length for forwarder steep and adverse haul, Unit 5: harvester cut-to-length for forwarder steep and favorable haul, Unit 6: harvester cut-to-length for forwarder flat.

From Table 18 it can be seen that the highest per unit cost for felling operations was in treatment unit 2 with a cost per stem of $5.74 and an increase in cost over the control (treatment unit 1) of 167%. Both of the control treatment units 1 and 6 had the lowest per unit felling costs for their respective groups with costs per stem of $2.14 and $2.69, respectively (Table 18). Besides the extreme cost differential in treatment unit 2, the per unit cost for felling in treatment units 3, 4 and 5 were similar with per stem cost values of $3.36, $3.49 and $3.52, respectively (Table 18).

The cost of felling operations was not the sole basis for comparison between the treatment units. A cost comparison between the different treatment units was also conducted with respect to yarding operations (Table 19).
Table 19. The total cost, total production and per unit cost for yarding operations in each treatment unit; where K301 = the combined yarder and loader and For. = forwarder, including the % change with respect to the control treatment unit.

<table>
<thead>
<tr>
<th>Treatment Unit (Yarding Equipment)</th>
<th>1 (K301)</th>
<th>2 (K301)</th>
<th>3 (K301)</th>
<th>4 (For.)</th>
<th>5 (For.)</th>
<th>6 (For.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Cost ($)</td>
<td>3,327.80</td>
<td>4,845.75</td>
<td>6,713.99</td>
<td>2,478.08</td>
<td>2,252.80</td>
<td>1,914.88</td>
</tr>
<tr>
<td>Total Production (Adjusted Pieces)</td>
<td>398</td>
<td>606</td>
<td>1,922</td>
<td>1,008</td>
<td>2,149</td>
<td>2,509</td>
</tr>
<tr>
<td>Cost Per Adj. Piece ($)</td>
<td>8.36</td>
<td>8.00</td>
<td>3.49</td>
<td>2.46</td>
<td>1.05</td>
<td>0.76</td>
</tr>
<tr>
<td>% Change (cost/Adj. piece) to Control</td>
<td>Control</td>
<td>-4%</td>
<td>-58%</td>
<td>222%</td>
<td>37%</td>
<td>Control</td>
</tr>
</tbody>
</table>

Table 19 shows that the per unit yarding costs for the Koller yarder treatment units (1, 2 and 3) were higher than all of the forwarder treatment units (4, 5 and 6). Within the yarder treatment units, the lowest per unit cost was achieved in treatment unit 3 with a cost per piece of $3.49 and a reduction in cost with respect to control (treatment unit 1) of 58% (Table 19). Although treatment unit 3 had a large drop in cost relative to control, treatment unit 2 had only a modest reduction in cost of 4% over the control (treatment unit 1, Table 19). Within the forwarder treatment units, the largest increase in cost was seen in treatment unit 4 with a 222% increase in cost over the control (treatment unit 6, Table 19).

The individual felling and yarding costs were not the only comparisons that were made between treatment units, but rather they provide greater detail into the changes in productivity and cost between the different harvesting systems in the treatment units. The overall harvest system cost in each treatment unit served as the final decision of economic feasibility between the various treatment units.
2.4.2.3 Harvest System Cost

The total harvest system cost for each treatment unit is a function of the yarding costs, felling costs and the value of overhead, profit and risk (OPR). The total cost of harvesting and the break down between the felling cost, yarding cost, and OPR were graphed in Figure 12.

\[ \text{Total Cost} = \text{Yarding Cost} + \text{Felling Cost} + \text{OPR} \]

**Figure 12.** The total cost for each harvesting system (treatment unit) differentiated by felling cost, yarding cost and the cost of overhead, profit and risk; the harvest areas and total volumes extracted differed between treatment units (C = control, MF = Manual felling, HRV = harvester, YRD = Koller yarder, FOR = forwarder, TL = tree-length, WT = whole-tree, CTL = cut-to-length, Adv = Adverse haul, FAV = favorable haul, FLAT = flat terrain).

From Figure 12 it can be seen that the highest total cost was achieved in treatment unit 3, with the largest proportion of the total cost being the cost of yarding. The lowest total cost was achieved in treatment unit 4 (Figure 12). The total cost is a component of the per unit ($/load) cost of a harvesting system. The per unit ($/load) cost, as previously discussed, is a better indicator of the economic feasibility of the harvesting system. The per unit cost for
the entire harvesting system is a product of the total cost and the total productivity for a
given treatment unit. Per unit costs ($/load) for the six different harvest systems are
displayed in Figure 13.

![Cost per Load Chart](image)

**Figure 13.** The cost per load for each of the six different harvesting systems (treatment units; 
C = control, MF = Manual felling, HRV = harvester, YRD = Koller yarder, FOR = forwarder, TL = 
tree-length, WT = whole-tree, CTL = cut-to-length, ADV = Adverse haul, FAV = favorable haul, 
FLAT = flat terrain).

The most profound result that can be seen from Figure 13 is that all of the forwarder 
treatment units have lower costs per load than the yarder treatment units. Within the 
forwarder treatment units, the highest per load cost was seen in treatment unit 4 and the 
lowest per load cost was seen in the control (treatment unit 6, Figure 13). The lowest cost 
per load within the yarder treatment units was in treatment unit 3 and the highest cost per 
load was found in treatment unit 2 (Figure 13). The values of total cost and cost per load
that were used in Figure 13 and figure 14, including the percent change in cost against control are summarized in Table 20.

Table 20. The total and per unit ($/adjusted piece and $/load) for the six different full treatments, including the % change with respect to the harvest system control.

<table>
<thead>
<tr>
<th>Treatment Unit (Harvesting System)*</th>
<th>1 (M-Y-TL)</th>
<th>2 (H-Y-WT)</th>
<th>3 (H-Y-CTL)</th>
<th>4 (H-F-ADV)</th>
<th>5 (H-F-FAV)</th>
<th>6 (H-F-FLAT)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Felling Cost ($)</strong></td>
<td>675.51</td>
<td>1,869.62</td>
<td>3,012.16</td>
<td>1,523.39</td>
<td>3,046.78</td>
<td>2,769.80</td>
</tr>
<tr>
<td><strong>Yarding Cost ($)</strong></td>
<td>3,327.80</td>
<td>4,845.75</td>
<td>6,713.99</td>
<td>2,478.08</td>
<td>2,252.80</td>
<td>1,914.88</td>
</tr>
<tr>
<td><strong>Total Cost + Overhead ($)</strong></td>
<td>4723.91</td>
<td>7,924.13</td>
<td>11,476.85</td>
<td>4,721.73</td>
<td>6,253.50</td>
<td>5,527.92</td>
</tr>
<tr>
<td><strong>Cost per Adj. Piece ($)</strong></td>
<td>11.87</td>
<td>13.08</td>
<td>5.97</td>
<td>4.68</td>
<td>2.91</td>
<td>2.20</td>
</tr>
<tr>
<td><strong>Cost per Load ($) (274 pieces/load)</strong></td>
<td>2353.14</td>
<td>3,582.86</td>
<td>1,636.14</td>
<td>1,283.49</td>
<td>797.33</td>
<td>603.69</td>
</tr>
<tr>
<td><strong>% Change (cost/load) Against Control</strong></td>
<td>Control</td>
<td>10%</td>
<td>-50%</td>
<td>113%</td>
<td>32%</td>
<td>Control</td>
</tr>
</tbody>
</table>

*M = Manual Felling, H = Harvester, Y = Koller Yarder, F = Forwarder, WT = Whole Tree, TL = Tree Length, CTL = Cut-to-length, ADV = Adverse Haul, FAV = Favorable Haul, FLAT = Flat Terrain (<35%)

The primary result derived from Table 20 is that the forwarder treatment units had lower per load costs than the yarder treatment units. Even though treatment unit 4 had an increase in cost of 113% over the control (treatment unit 6) the cost per load of $1,283.49 was lower than that of treatment unit 3 which had the lowest cost per load of the yarder treatment units with a cost per load of $1,636.14 (Table 20). Although the results are important, it should not be overlooked that treatment unit 3 had a reduction in cost of 50% with respect to the control (treatment unit 1, Table 20). Thus, the standard operating procedure in treatment unit 1 (control) was not the most cost effective manner in which to
utilize the yarder. With that said, it is also not cost effective to utilize the yarder at all when first entry commercial thinning is being conducted in harvest units with suitable characteristics for steep slope forwarder applications.

2.5 Discussion

2.5.1 Detailed Assessment of the Harvester

The Ponsee Ergo harvester is capable of achieving economically feasible production on steep slopes. However, the level of productivity in the operation of the harvester on steep terrain is a question that was answered within the results of this study. The shift level results for the harvester showed that the most productive method of utilizing the harvester was flat (<35%) terrain control unit (treatment unit 6) with a productivity rate of 62 stems cut and processed per hour (Table 3). All other treatment units were conducted on steep terrain (>35%) and had reductions in productivity against the control (treatment unit 6) of 10-45% (Table 3). The reductions in productivity can, in part, be attributed to the loss of one productive hour per day from when the harvester traveled on return trails outside of the unit. However, this time impact does not explain all of the lost productivity when the harvester operated on steeper terrain (>35%). Thus, the detailed time study data was used to identify the time measures, such as average cycle time and average within unit drive time, which contributed to the reduction in harvester productivity.

Average Cycle Time

The average cycle time is a direct link to the productivity of the harvester when in a productive state (i.e. when felling and processing a stem). As such, reductions in the average
cycle time represent an increase in the productivity of the harvester and increases in the average cycle time represent decreases in harvester productivity. The average cycle time was analyzed in two ways; the first analysis compared the overall average cycle time of each harvester treatment unit with that of the other harvester treatment units. The second analysis was to compare the average cycle times for each slope class within each of the three unique harvester treatment units (based on harvesting techniques).

When the comparisons were made between the harvester treatment units, two results were found. The first was that treatment unit 2, which saw the harvester felling and decking whole trees on steep (>35%) slopes, had the lowest average cycle time. The reason that treatment unit 2 had the lowest average cycle time is that treatment unit 2 was the only harvester treatment unit that did not have a processing component within the cutting cycle. Since there was no processing component, which is the longest component in the harvesters’ cutting cycle, it inevitably had the lowest average cycle time. Treatment units 3 through 6 all had the harvester utilizing cut-to-length felling and processing, which provides a basis for comparison.

The second result was that treatment units 3, 4 and 5 had significantly higher average cycle times than that of the control unit (treatment unit 6). The higher average cycle times seen in treatment units 3, 4 and 5 indicates that within those three steep terrain, full cut-to-length units, the harvester’s cutting ability was reduced when compared with the gentle (<35%) terrain treatment unit 6. Thus, the productivity within those units was reduced, at least to some degree, by the change in the average cycle time. However, it could not be determined from this data analysis whether it was the harvesting technique (cutting for the yarder, ghost
trail cutting or movement pattern through the unit (structured or wandering) or the slope of the harvesting unit which caused the increase in the average cycle time.

In order to determine if the changes in cycle time could be attributed to changes in the slope of the harvest unit, an analysis was conducted within the three unique harvest treatment units. The three unique harvest treatment units were treatment units 2, 3 and 4, which were selected, based on the overall characteristics of the felling techniques being utilized. In treatment unit 2 the harvester cut and decked whole trees for the Koller yarder with a single ghost road in between yarding corridors on steep (>35%) terrain. In treatment unit 3 the harvester completed full cut-to-length felling and processing for the Koller yarder with two ghost roads between each yarding corridor on steep terrain. In treatment unit 4 the harvester completed cut-to-length felling and processing, with no ghost roads for the forwarder on steep terrain. Thus, there was a substantial difference between these units in terms of the felling and processing techniques. The results from the comparisons made of the average cycle times against the five slope classes showed that in all three unique treatment units, there was no significant difference in the average cycle time when compared as a function of slope class (one-way ANOVA F-test p-values >0.05). This result shows that slope had no impact on the differences that were seen in the average cycle time. Thus, when coupled with the results from the comparison of the average cycle time between treatment units, the differences seen are related to changes in the felling techniques as detailed in Table 2 or in the observed difference in harvester movement through the unit as detailed in Figure 7 and Figure 8. But, the average cycle time only describes the productivity of the harvester when in the process of cutting stems. Thus, the average cycle time is only
part of the harvesters’ overall productivity. The other part of the harvesters’ productivity is the amount of time spent driving between individual stems or between groups of stems which is the average drive time.

*Average Drive Time*

The average drive time has a direct influence on the productivity of the harvester. A decrease in the average drive time provides for increased production because more time was spent felling and processing stems, whereas an increase in average drive time provides for decreased production because more time was spent driving rather than felling and processing stems. Similar to the average cycle time analysis, the analysis of the average drive time was done in two ways. First the average drive time was compared across the harvester treatment units. The results showed that the average drive time for the gentle terrain control unit (treatment unit 6) was significantly lower than all other harvester treatment units. Also, there was no significant difference between all other harvester treatment units. Thus, the steep (>35%) terrain harvester treatment units not only had higher average drive times but those increases were the same across all of the treatment units. The one thing that the steep terrain harvester treatment units had in common was that they were on steep terrain (>35%). It would be simple to conclude that the increase in slope was the direct reason that there was a proportional increase in the average drive time across the harvester treatment units. However, further analysis showed that this was not entirely the case.

The second way of comparing the average drive time was to compare the average drive time for each of the five slope classes within each of the three unique harvester treatment units.
The results of this analysis showed that there were increases in the average drive time with increases in slope. However, this was limited to slopes greater than 65%+ across all steep terrain treatment units with varying influence of lower slope classes on the increase in average drive time. These results present a rather interesting conundrum, in that, there were increases occurring in the average drive time as slope increased but the increases were consistent across all of the steep terrain harvester treatment units. What this showed was that the increase in average drive time seen between the steep terrain units and the flat terrain unit cannot be completely attributed to increases in slope. Another source of increased average drive times on steep terrain is the way in which the harvester would move through the unit on steep terrain versus flat terrain (Figure 7 and Figure 8). The structured pattern (Figure 8) itself created a situation where the harvester was forced to cut all of the trees that it could reach before moving again, the wandering pattern (Figure 7) created a situation where the harvester would make short movements to access trees as efficiently as possible. Thus, the shorter and more frequent drive times of the wandering pattern (Figure 7) aided in providing the gentle terrain control unit (treatment unit 6) with a lower average drive time and consequently higher productivity. However, the increased slope in the steep terrain harvester treatment units had the most impact on the increase in average drive time despite the inconsistency of the increases across the different slope classes and the differences in harvester movement through the unit.

**Detailed Time Study Synthesis**

When the results from both the macro-level study and micro-level are analyzed, the reason that changes occurred in the operational nature of the harvester operating on steep terrain
can be seen. Although the macro-level data showed that there were differences in the average cycle time between the flat terrain and steep terrain units, the differences were not found to be related to slope. Thus, the harvester was able to cut just as productively on steep terrain as it could on flat terrain. However, the difference in average cycle time was either due to the felling techniques (Table 2) or factors that were not considered within the scope of this study. Which factors actually caused the differences cannot be discerned with the data from this study. With respect to the average drive time, most of the differences can be attributed to increases in the slope of the harvesting unit, especially at extreme 65%+ slopes. But, the increases seen due to increasing slope are too varied to provide a fully inclusive answer. Thus, there is the potential for the harvester movement through the unit (structured or wandering) to affect the average drive time as well as the average cycle time, but this cannot solely be concluded by the data within this study.

Overall, considering the reduction in productivity shown in the shift-level data across all of the steep terrain units, there are four conclusions that can be made. First, the average cycle time was a part of the overall reduction in productivity but not as a function of slope. Second, the average drive time was a part of the overall reduction in productivity and could only be attributed across all units on slopes greater than 65%. Third, the average outside of the unit drive time of approximately 1 hour per day had an impact on overall productivity on steep terrain units. Lastly, there were external factors impacting the overall productivity of the harvester, which could potentially be the felling techniques utilized by the harvester (Table 2), the harvester movement pattern through the harvest unit (Figure 6 and Figure 7) or other factors that were outside of the scope of this study.
2.5.2 Economic Feasibility of the Harvesting Systems

**Forwarder Productivity**

The results of the shift level assessment of the Ponsee Buffalo King Forwarder showed that the productivity of the forwarder decreased in treatment units 4 and 5 where the forwarder was operating on steep terrain with production losses of 58% and 19%, respectively (Table 15). However, the magnitude of the loss in productivity was different between the two steep terrain forwarder treatment units. When the forwarder was traveling loaded with an adverse haul to the landing (Figure 4), as seen in treatment unit 4, the loss in productivity was 58% when compared to the gentle (<35%) terrain control unit (treatment unit 6, Table 15). Treatment unit 5 had the forwarder traveling downhill loaded with a favorable haul to the landing (Figure 5). The productivity loss in treatment unit 5 when compared against the gentle (<35%) terrain control (treatment unit 6) was only 19%.

When comparing treatment unit 4 and treatment unit 5, there was a difference of 39% in productivity between the two steep terrain treatment units; meaning, that traveling loaded in an adverse direction to the landings resulted in a 39% reduction in productivity. There are two reasons behind the reduction in productivity from the adverse haul to the landing. First, when the forwarder was traveling loaded in an adverse direction the total numbers of pieces per bunk were halved in order to make it up the return trail to the landing. Secondly, when the forwarder traveled loaded in an adverse direction it took twice as long to drive to the landing because of reduced travel speeds.
The shift level data also showed that the forwarder lost approximately an hour a day of productivity to return trail travel when operating on steep terrain. This means that the time the forwarder took to drive from the landing to the next steep slope corridor amounted to an hour of productivity loss per day. This coupled with the fact that the forwarder was observed to travel at lower speeds on steeper pitches within the corridors may have contributed in the 19% base reduction in productivity that was seen in treatment unit 5. Treatment unit 4 had the base reduction in productivity of 19% from simply operating on steep terrain (reduction seen within treatment unit 5) with the added 39% decrease in productivity due to the adverse haul to the landing to make the overall reduction in productivity for the treatment unit 58%, with respect to the control (treatment unit 6).

The “take home message” from this study is that when a forwarder operates on steep terrain, land managers should look for every opportunity to avoid adverse skidding and adverse hauls to the landing. However, there will always be situations where the need for adverse skidding and adverse hauling may arise. Thus, the focus should then be placed on the economic comparison between adverse forwarding (adverse skidding and/or adverse hauling) versus cable yarding, which is discussed in the next section.

**Yarder Productivity**

The productivity of the yarder was dependent on many factors. However, the primary variable used for comparison within this study was the adjusted pieces per hour. The results showed that there was a 2.4% reduction in productivity (adjusted pieces per hour) in treatment unit 2 when compared to the control (treatment unit 1). Although the
productivity was lower for treatment unit 2, the value of adjusted pieces per turn was actually higher than that of the control (treatment unit 1), with values of 5.88 and 4.8, respectively (Table 16). Despite the increase in the number of pieces per turn, the loss of productivity came from the reduction in the number of turns per hour, where treatment unit 2 had 9 turns per hour and the control (treatment unit 1) had 11 turns per hour (Table 16). The drop in the number of turns per hour was the result of two difficulties arising from yarding whole trees in a young stand thinning, with a relatively small Koller (K301) yarder. The first observed difficulty was an increase in the number and severity of hang-ups and resets. The increased number and severity of hang ups and resets was observed because of the added length of the bottom log of the stem when trying to navigate through a relatively tight spacing of the residual stand of timber. Having that extra butt log on the stem caused the most problems when lateral yarding distances were increased to retrieve stems from the ghost roads. This problem could be eliminated by not using ghost roads and having a cable yarding corridor every 50 feet; however, in doing so, there would be an added loss of productivity from doubling the number of road changes required. The second observed difficulty which caused a loss in productivity was the inability of the yarder to yard an entire bunched-pile of whole-trees. Since the yarder is a relatively small yarder with low horsepower and low payload capabilities, the presence of bunched whole trees proved troublesome. In order to get the whole trees yarded out of the bunched-piles, each tree had to the choked and moved individually. The most common practice was to hook one tree and have it yarded just off the deck, then set the next tree until all three chokers were set for yarding to the landing. This coupled with the added number of hang-ups and resets caused a
situation where the number of turns per hour was diminished in treatment unit 2. Overall, when comparing treatment unit 2 to the control (treatment unit 1) solely on the basis of productivity, the conclusion would be that the harvesting techniques utilized in the control (treatment unit 1) would be the better option. This is because the things that could be changed to attempt to fix one aspect of productivity would cause another aspect of productivity to be reduced, such as having a cable road every 50 feet to increase the number of turns per hour but increasing the number of required road changes. Thus, the better option would be to simply use the standard operating procedure that was utilized in the control (treatment unit 1) or perhaps use the approach studied in treatment unit 3.

The harvesting techniques utilized in treatment unit 3 had the least number of similarities to the harvesting techniques utilized in the control (treatment unit 1). Thus, treatment unit 3 had the greatest potential for major changes in productivity. The result of the comparison between treatment unit 3 and the control (treatment unit 1) showed that there was an increase in productivity (adjusted pieces per hour) of 79% in treatment unit 3 over the control. The increase in productivity was the result of an increase in both the number of pieces per turn and the number of turns per hour when compared to the control (treatment unit 1) with 7.14 and 4.8 adjusted pieces per hour and 13 and 11 turns per hour, respectively (Table 16). The increase in the number of pieces per turn was the result of the yarder crew being able to bonus up on each choker; whereby, there could be upwards of 3 to 4 pieces wrapped in a single choker. The setting of bonuses on each choker allowed the crew to pull almost an entire bunched pile of logs at a single time. The reason this was possible in treatment unit 3 and not in treatment unit was that all of the pieces were cut-to-length logs
in treatment unit 3, which weighed less than the whole-tree stems that were present in treatment unit 2. The increase in the number of turns per hour in treatment unit 3 was accomplished due to two factors. First, there was a greater volume of wood to be yarded from each cable setting. The increase in wood volume was due to the added 50 feet between cable settings that was achieved by adding an additional ghost road in treatment unit 3. The extra 50 feet eliminated every third skyline road change with respect to the control (treatment unit 1) and increased the amount of time spent productively yarding. The second factor was that log length pieces provided consistent yarding throughout treatment unit 3, where the frequency and duration of hang-ups and resets was reduced when compared to the control (treatment unit 1).

Overall, treatment unit 3 was the highest performing harvesting system when considering the changes in productivity against that of the control (treatment unit 1). The "take home message" is that based solely on the productivity data, when cable yarding on slope conditions similar to those seen in this study, the best option is to use the harvester for full cut-to-length felling, processing and bunching with the largest possible spacing between cable settings. This conclusion only holds for the Koller K301 yarder. If a larger yarder was used, the results of this study may have been different; possibly in favor of the whole-tree pre-bunching that was seen in treatment unit 2. Although there were some considerable changes in productivity related to the yarder that were seen in this study, a decision on the economic feasibility of each harvesting system cannot be made without taking into consideration the cost of each harvesting system.
Cost Analysis

Treatment unit 1 served as the control for the cable yarding treatment units because it represented the standard operating procedure for the contractor utilized within this study. As the control, treatment unit 1 was found to have a cost per load of $3,252.14 (Table 20), a cost per piece of $11.87 (Table 20) and a total cost of $4,723.91 (Table 20). Thus, any change in the cost per load for treatment units 2 or 3 from the cost values associated with the control (treatment unit 1) would represent a change in economic feasibility. The results of the cost analysis for treatment unit 2 showed that the cost per load increased to $3,582.86; which is a 10% increase when compared to the costs associated with the control (treatment unit 1, Table 20). The increase in cost seen in treatment unit 2 over that of the control (treatment unit 1) was not caused by an increase in the cost of yarding but rather by an increase in the felling costs for the harvester. When considering the individual harvesting cost components (i.e. felling and yarding) the yarding costs in treatment unit 2 were 4% lower than the yarding costs associated with the control (treatment unit 1, Table 19). Despite the decrease in yarding costs in treatment unit 2, the felling costs increased enough to cause the entire harvesting system to be more expensive than the control (treatment unit 1). With respect to felling cost, utilizing the harvester for felling and pre-bunching whole trees caused an increase of 167% in the per stem felling cost in treatment unit 2 when compared to the per stem felling costs of the control (treatment unit 1). By looking at the individual harvesting components, it has become apparent that the driving factor for the 10% increase in the per load cost of treatment unit 2 can be attributed to the increases in the cost of operating the harvester. Treatment unit 2 was unique, in that, it was the only unit
where the harvester was felling and pre-bunching whole-trees. Given the increase in cost associated with the harvester in treatment unit 2, the conclusion can be made that having the harvester operate in this fashion would not be economically feasible within the confines of this study.

With a cost per load of $1636.14, treatment unit 3 had a 50% decrease in cost when compared to the control (treatment unit 1, Table 20). The 50% reduction in the per load cost for treatment unit 3 was caused by a 58% decrease in the yarding cost when compared to the control (treatment unit 1, Table 18, Table 20). Despite the reduction in yarding cost, the felling cost in treatment unit 3 actually had an increase of 57% when compared to the control (treatment unit 1). The increase in felling costs caused the total harvesting systems cost to increase for treatment unit 3; however, the increase was offset by the decrease that was realized in the yarding cost. Treatment unit 3 is the most economically feasible harvesting system when considering cable yarding only.

When considering the costs of the forwarder treatment units, the control was set as treatment unit 6. The baseline costs associated with treatment unit 6 were found to be: a cost per load of $603.69, a cost per piece of $2.20 and a total cost of $5,527.92 (Table 20). The results showed that there was a 32% increase in the cost per load for treatment unit 5 when compared to the control (treatment unit 6). The increase in the cost per load in treatment unit 5 can be attributed to both the yarding and felling costs. There was a 31% increase in felling costs in treatment unit 5 when compared to the control (treatment unit 6) and there was a 37% increase in yarding costs of treatment unit 5 over those of the control (treatment unit 6, Table 18, Table 19).
When comparing the per load cost of treatment unit 4 to the control (treatment unit 6) there was an increase of 113% (Table 20). The 113% increase in the cost per load of the harvesting system can be directly attributed to the increase in cost related to the yarding component of the harvesting system. The per piece cost of yarding in treatment unit 4 was 222% higher than that of the control, (treatment unit 6, Table 19). Most of the 222% increase in the yarding cost for treatment unit 4 can be explained by the reduction in productivity due to the adverse haul to the landing. The "take home message" from solely the cost analysis of the forwarder treatment units is that the most cost effective way to utilize the harvester/forwarder is to have them operate on gentle (<35%) terrain and that utilizing an adverse haul to the landing will increase cost. However, when comparing the operating costs of the forwarder treatment units to those of the Koller yarder treatment units the "take home message" changes.

The “take home message” that can be made from the results of the cost analysis is that under all circumstances considered within this study, the harvester/forwarder combination was the most economically feasible solution for steep terrain operations. The most expensive harvester/forwarder treatment unit (treatment unit 4) had a lower cost per load than the least expensive yarder treatment unit (treatment unit 3, Table 20). Thus, when land managers are trying to consider their options for first entry commercial thinning on steep terrain, they should consider the operational and economic feasibility of utilizing the harvester/forwarder as compared to cable yarding operations. Within that same consideration, land managers should look for ways to minimize or eliminate adverse skidding or adverse hauling to the landing, because the most economically feasible steep
terrain operation was treatment unit 5, where there was no adverse skidding and there was a favorable haul to the landing. However, land managers must also consider: the availability of the specialized steep terrain equipment, the safety of crew members and machine operators as outlined in the forest activities administrative rules from Division 7 of the Oregon OSHA administrative rules (OROSHA, 2010) and the potential for detrimental soil impacts from operating ground based machinery on steep terrain.

If a forwarder is not available or there is no physically feasible way to operate the forwarder in a given harvest unit, the best option would then be to consider if the harvester could operate safely within the unit. If the harvester can be safely operate within the unit then the most economically feasible solution would be to have the harvester conduct full cut-to-length felling, processing and pre-bunching with at least two ghost roads between each yarding corridor and swing the pre-bunched logs to the landing with a low cost yarder.

2.5.3 Safety and Soils

Although this study focused on the economics (productivity and cost) of steep terrain first-entry commercial thinning, it must be noted that there are two main considerations outside of the economics that could impact the adaptation or continuation of steep terrain ground based harvesting operations. This first consideration concerns the safety of steep terrain operations. The Oregon Occupational Safety and Health Administration (OSHA) regulate the safety of forest operations through the administrative rules outlined in Division 7 - Forest Activities Administrative Rules. Within subdivision J of the Division 7 rules, there are specific guidelines which restrict the operation of ground based machinery on steep terrain
For the ground based equipment utilized within this study (purpose-built steep terrain double-bogie harvester and forwarder), subdivision J limits the operability to slopes less than 50% (OROSHA, 2010). However, subdivision J also allows for the slope limit of 50% to be exceeded "for limited application or in identified small areas provided the operator and the competent person plan how to safely operate on the steep slopes considering the: a) experience of the operator, b) limitations of the machine and the soil conditions, c) direction of travel (traveling straight up and down the slope), d) requirements for turning the machine or vehicle on the slope, e) weather, f) load sizes g) any other adverse conditions (OROSHA, 2010)." Given the administrative rules that are in place, the safe operation of ground based equipment, with regards to the methods utilized in this study, require that the contractor and operator are well versed in the requirements of the Oregon OSHA administrative rules and in the safe operation of their equipment. For this study specifically, the operations forester and the operators themselves from Miller Timber Inc. would walk the treatment units prior to the commencement of operations and assess the areas in excess of 50% in order to ensure that both the operation would be conducted in a safe manner and that all of the OR-OSHA administrative rules are followed. In summary, when ground based operations are pushed onto slopes that exceed the limits listed in Subdivision J of the Division 7 Administrative Rules (OROSHA, 2010), great care must be taken to ensure the safe operation of the equipment and to ensure that the administrative rules are followed.

Site impacts, although not as important as safety, must be considered along with the economics of steep terrain ground based operations. The primary impact that can occur to a
harvest unit from steep terrain ground based operations is soil disturbance both in the form of compaction and in the form of erosion/sedimentation. Concurrently with this study, another study was conducted on the soil disturbances generated by the operation of ground based equipment on steep terrain. The study was conducted by Zamora, R., Adams, P. and Sessions, J. and is currently a manuscript in review for the Western Journal of Applied Forestry.

2.6 Conclusions

The conclusions of this study can be grouped into two categories, those that related to the detailed analysis of the harvester and those that relate to the economic analysis of the harvesting systems. With respect to the detailed analysis conducted on the harvester, there were four primary conclusions that were made regarding the changes in operability of the harvester when it was operating on steep (>35%) terrain. First, the average cycle time of the harvester was not affected by changes in the slope of the harvest unit, or that as slope increased there was no significant difference in the average cycle time of the harvester. The second conclusion was that when the slope of the harvest unit increased above 65% the average drive time increased. The third conclusion was that there were external factors not considered within this study that had an impact on the productivity of the harvester. The final conclusion from the detailed analysis of the harvester was that by operating on steep (>35%) slopes, the harvester lost an average of an hour of productive time per day.

Although the results of the detailed analysis of the harvester are important and relevant, they cannot answer the fundamental questions posed within this study. In order to answer
the questions, the economic analysis of the different harvesting systems within the different treatment units was examined. The "big ticket" conclusions from the economic analysis was that under all scenarios considered within this study, the harvester/forwarder combination was the cheapest, most cost effective option for conducting first entry commercial thinning on steep terrain. There were two other conclusions that could be made from the economic analysis. First, when operating the forwarder on steep terrain, adverse hauls to the landing will cause drastic reductions in productivity and increases in cost. Second, when utilizing the harvester to process and pre-bunch stems for the Koller yarder, productivity increased and cost decreased.

2.7 Areas for Further Research

Since this study was exploratory in nature, there were many avenues that were found for areas needing further research. The first avenue for further research and study would be to look at the impact of the loss in productivity due to the forwarder having to load log trucks. If land managers were able to secure self loading log trucks for use in forwarder harvest units, there may be a potential to have significant cost savings due to increased productivity of the forwarder (Table 15). The second avenue would be to take a more detailed look into the K301 yarder to see if there are ways to minimize road change times in order to boost productivity (Table 16) and to see if there could be more than 2 ghost roads between cable yarding corridors. The third would be to compare the economic feasibility of the harvester/forwarder combination on steep terrain to a larger yarder operating in a similar fashion to what was studied here (i.e. Koller K501 yarder). The fourth is that there needs to be an even more detailed analysis of the harvester to determine how the external factors,
such as felling pattern or harvester movement, impact the productivity of the harvester. This study made strides toward answering why the changes in harvester productivity were occurring but the data was not able to provide a definitive answer; thus, this should be a focus of future study. Also, a detailed analysis should be conducted on all of the pieces of the harvesting system puzzle that was studied here to provide answers as to why changes in productivity were occurring throughout all of the differing treatment units.

Lastly, further research is needed for two key areas outside of the economics and operations areas of steep terrain ground based harvesting. The first is safety; more research needs to be conducted to determine the specific factors and/or site conditions that can influence the safety of steep terrain ground based harvesting. By determining the factors and/or site conditions more specifically, the practice of steep slope ground based harvesting could be applied on a broader scale than what is currently allowed within the Oregon OSHA forest activities administrative rules (OROSHA, 2010). Concurrently with safety, further research is needed into the site impacts that can arise through the practice of steep terrain ground based harvesting. The site impacts could range from soil compaction to residual stand damage, but without further study, the true site impacts of steep terrain ground based harvesting may not be realized.
2.8 Literature Cited


Chapter 3

Biomass Assessment by Ownership Group, Slope and Elevation for Timberlands in Western Oregon

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October 24, 2013
3.1 Abstract

There have been many biomass assessments that have taken place in recent years due to the growing concerns regarding global climate change. Despite the widespread nature of biomass assessments, little has been done to compare the biomass availability between sites with unique characteristics such as ownership group, elevation and slope. By looking at unique characteristics a better understanding can be developed regarding the impact of biomass availability on forest operations. This study works to fill this gap in the contemporary literature by conducting a biomass assessment based on the ownership group (forest service, other federal, state & local and private), the elevation characteristics and the slope characteristics of timberlands in western Oregon. This assessment focused on comparing the biomass per acre (bone dry tons, BDTons) within a given unique feature to identify the trends or relationships that exist. With respect to ownership group, this study found that forest service lands had significantly more biomass per acre (BDTons) than all other ownership types and private lands had significantly less biomass per acre (BDTons) than all other ownership types. Other federal and state & local timberlands had no significant difference with respect to biomass per acre (BDTons). In order to make true comparisons within the elevation and slope categories, the impact of ownership group on these variables had to be accounted for to remove any possible bias. Thus, the categories of elevation and slope were looked at within each ownership group (forest service, other public and private) to provide a comparison with minimal bias. The study found that the amount of biomass per acre was not significantly different with changes in slope or elevation. The implications of these results on biomass harvesting operations was considered and discussed herein.
3.1.1 Acknowledgements

I would like to acknowledge the efforts and support of multiple individuals in the preparation and execution of this study. Dr. Temesgen Hailemariam was instrumental in the development of this study from the planning stages through to the determination of the results. Dr. Loren Kellogg provided great insight into the direction of the study and into the operational conditions that should be considered within the study. Karen Waddell from the U.S. Forest Service FIA team provided essential technical aide in the acquisition of the data used for this study. Lastly, I would like to acknowledge the insights of Bianca Eskelson, in her critical review of the study, which proved to strengthen the results and findings.
3.2 Introduction

Biomass in its general form is a term that describes the biotic matter present on the landscape. More recently, the term has been applied to describe the presence of woody material in a forested setting. The advent of the current usage of the term "biomass" can be attributed to the growing concerns regarding global climate change. There are two reasons for the link between biomass and global climate change. The first reason is that biomass represents the accumulation of carbon from the atmosphere. Thus, having adequate knowledge about the amount of biomass present on the landscape would allow researchers to study the movement and sequestration of carbon within a forest. The second reason is that biomass can be utilized as a source of energy itself. Thus, having an adequate assessment of the amount of biomass present on the landscape would allow for better planning and development of renewable energy facilities. Although biomass as a term can be rather ambiguous, the current definition provides the context for the assessment of the forested landscape in a new way.

Although there have been many biomass assessments that have occurred in recent years (i.e. "the billion ton report" (Biomass, 2005), Schroader et. al (1997), etc.) these assessments have only provided a gross understanding of the net amount of biomass that is present on a given landscape. The biomass assessments that have been conducted previously are lacking in their detail regarding the relationship between different forest conditions and how those relationships impact the availability of biomass. This study fills part of this information gap by conducting a biomass assessment to identify the differences that exist between differing forest conditions. The specific forest conditions that serve as the basis for comparison are
ownership group, elevation and slope. These forest conditions were selected because of their potential impact on the availability of biomass for the development of the bio-energy sector. With considerable differences in regulations and forest practices across ownerships (federal, state, private), it is only logical to assume that the ownership group would influence the potential biomass availability of a given forested landscape. Similarly, given the nature of contemporary forest roads, elevation has a major impact on the availability of biomass for the bio-energy sector. Generally, as elevation increases, the slope of forest roads increases and accessibility of harvesting sites decreases. Thus, in order for chippers, grinders and chip vans to access these areas, significant changes must be made to the road network to accommodate their travel (Sessions et al. (2010)). Lastly, current biomass harvesting technology is limited to flatter terrain (<35% slopes). One of the primary reasons for this is that the harvesting systems required to harvest biomass on steeper terrain (i.e. cable systems or helicopters) are highly expensive and given the low-value nature of biomass, would not be applicable for use.

Western Oregon, as indicated in Figure 14, is a region that provides high variability with respect to ownership, elevation and slope. Thus, it was selected as the base area for this biomass assessment. Given the large land area involved, it was not feasible to conduct independent sampling of the differing forest conditions. Thus, this assessment utilized the plot and area information developed by the U.S. Forest Service's Forest Inventory and Analysis (FIA) program. The FIA program is a congressionally mandated forest inventory that occurs on a recurring basis to provide an assessment of the forested resources within the
United States. Given the large scale nature of the FIA program, the plot information and subsequent area calculations were well suited for the objectives of this study.

Figure 14. A map of the study area (western Oregon), all counties west of the black dividing line and outlined in red were included in this study.
3.3 Study Objectives

The objectives of this study were as follows:

- Make Comparisons of the total biomass/ac (BDTons) as a function of ownership group, elevation and slope to determine:
  - If there are biomass differences between each category.
  - If differences occur, quantify the magnitude of difference and their significance.

The study objectives are meant to be both broad and specific, in that, they are broad enough to provide an element of exploration for the topic but are specific enough as to prevent data-snooping or resulting bias.

3.4 Hypotheses

Ownership

- All federal timberlands have higher biomass per acre (BDTons) than either state & local or private.
- Private timberlands have the lowest biomass per acre (BDTons) than all other ownership groups.
- Forest Service and other federal timberlands have the same amount of biomass per acre (BDTons) with state & local being the median between all federal and private.
Elevation

- Biomass per acre (BDTons) will increase with increasing elevation, with the highest overall biomass per acre being located on the highest elevations.

Slope

- Biomass per acre (BDTons) will increase with increasing slope, with the highest overall biomass per acre (BDTons) being located on the steepest terrain.

3.5 Methodology

The methodology that was used to develop this biomass assessment can be broken into three distinct segments. The first segment involves the acquisition and formatting of the FIA plot data and the area determination for each stratum, the second involves the determination of the biomass/ac and total biomass for each stratum and the third involves the comparison between classes within a given forest attribute.

The acquisition of the FIA plot data and the area (acreage) of a given class was conducted using the procedures and processes outlined in the PNW FIA database handbook (FIA, 2011). The procedures revolved around the construction of data queries from Microsoft Access. Once the raw plot data for western Oregon was acquired, it had to be formatted and compiled to provide a basis from which an assessment could be conducted. The per tree biomass estimates were derived from the regional biomass assessment that provides a single estimate of total standing biomass (lbs.) per live tree. The individual plot data consisted of a list of all the trees (> 1” diameter) located within a given macro-plot (1 acre). Within the
macro-plot is a series of various sub-plots and micro-plots, whose values must be expanded to infer a per acre value. Thus, the total biomass (lbs) for each tree was expanded by the TPA value corresponding to the plot from which the tree was derived. Once all of the individual tree biomass estimates were expanded, the plot total was developed. Once the plot totals (per acre) were developed, the plot information was compiled into a list of plots to provide a data set that could be more readily utilized. The information from each plot that was compiled concurrently onto a single list was: plot ID number, county (of plot origin), total biomass per acre (lbs), ownership group (forest service, other federal, state & local and private), elevation (feet) and slope (%). For all of the attributes that were analyzed within this study, the focus was solely on timberlands, those lands that can be harvested for timber production. Thus, all unique conservation or unproductive lands (i.e. USFS wilderness areas) were not included within the dataset.

The biomass assessment was conducted in two phases, the first allowed for the development of a per acre estimate of standing biomass/ac for each comparison category while the second utilized stratified sampling to develop an estimate of the average biomass/ac and the total biomass for the entirety of western Oregon. Within each group (ownership, elevation, slope) the data list was sorted to form a stratum of data for each comparison category (ownership group, elevation class, slope class). For the ownership group the data was broken into four stratum, 10 - forest service, 20 - other federal, 30 - state & local and 40 - private. For the elevation group, the data was broken into eleven stratum, 0' - 999', 100' - 1999'... 5500'+. For the slope group, the data was broken into ten stratum, 0-9%, 10-19%... >89%. Within each
stratum, simple random sampling techniques were used to develop a sample mean, variance, standard error and a 95% confidence interval.

The comparison of the ownership groups was straightforward, in that, there were no external forces that could influence or bias the result of the comparison. However, since the elevation and slope of a given plot could be influenced by the ownership group, a different approach was used to develop comparison groups for these two categories. With the categories of slope and elevation, the comparison groups were formed within three separate ownership groups. The ownership groups of forest service and private were left the same but the other federal, state and local were combined to form an ownership group called “other public”. Within each of these ownership groups, the data was stratified by elevation and slope, each of which corresponds to a different comparison group. By comparing the changes in biomass with respect to slope and elevation within a given ownership group, some of the bias related to the differences between ownership groups is removed and thus provides a more precise and accurate result.

The comparison of the different strata within a given comparison group was conducted to determine the significance of the trends seen in the side-by-side plotting of the stratum means and their confidence intervals. Once any trends had been noted, a one-way ANOVA F-test () was used to determine if there were any significant differences between the comparison categories. Prior to completing the one-way ANOVA F-test, the data was checked for normality, normality was found for all scenarios presented within this study. If the F-test revealed there to be any significant differences then pair-wise t-tests were conducted to determine the significance of any observed trends. In order to ensure that the equal variance
assumption was valid between the strata, side-by-side box-plots were developed, followed by a plot of the residuals. If irregularities were seen in either the box-plots or the residual plots, the variance ratio was used to test if equal variance was a valid assumption. The variance ratio, F - test (Foster and Christian, 2008) must be below 4 in order for the equal variance assumption to be valid. The variance ratio F - test is outlined below in Equation (1).

\[\text{Equation (1)} \quad \text{Variance Ratio} \ F - \text{Test} = \frac{s_{\text{max}}^2}{s_{\text{min}}^2}\]

Where: \(s_{\text{max}}^2\) = The maximum variance observed across all strata, \(s_{\text{min}}^2\) = The minimum variance observed across all strata.

Once equal variance had been determined and if applicable, transformations were made, the pair-wise t-tests (both two-sided and one-sided) were conducted. Since the pair-wise t-test only provides the significance of a difference, pair-wise confidence intervals were also developed whereby the magnitude of the difference was estimated with a subsequent 95% confidence interval of that magnitude estimate. The results of the pair-wise t-test and the pair-wise confidence intervals were used to determine the significance of the trends that were observed.

3.6 Results and Discussion

The results of this assessment are presented based on the individual category for comparison (Ownership, Elevation, and Slope) at the biomass/ac level.
3.6.1 Ownership

The ownership group provides an insight into the differences in standing biomass that can be attributed to differing regulatory environments and management practices. The four ownership groups (strata) that were assessed and compared in this study are as follows: Forest Service (10), other federal (20), State and Local (30) and Private (40). The biomass assessment was conducted on timberlands only, or those lands which are capable both physically and regulatory to facilitate timber production. When simply comparing the relative weight of each ownership group across the landscape, forest service and private were the dominant ownership groups with weights of .33 and .46, respectively. Other federal (BLM, F&W, etc.) and state & local made up the rest of the landscape with weights of .15 and .06, respectively. The results of the biomass assessment by differing ownership group are summarized in Table 21.

Table 21. The sample size, mean biomass per acre (BDTons) and the respective 95% confidence intervals for each ownership group and the stratified combination.

<table>
<thead>
<tr>
<th>Ownership(*)</th>
<th>( n_h )</th>
<th>Area (Thousand Acres)</th>
<th>Variance (BDTons/ac)</th>
<th>Mean(_h) (BDTons)</th>
<th>UCL(_h) (BDTons)</th>
<th>LCL(_h) (BDTons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 (FS)</td>
<td>723</td>
<td>4,540.80</td>
<td>23710219</td>
<td>157.57</td>
<td>166.65</td>
<td>148.49</td>
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<td>20 (OF)</td>
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<td>2,006.41</td>
<td>14578711</td>
<td>121.61</td>
<td>133.01</td>
<td>110.22</td>
</tr>
<tr>
<td>30 (S &amp; L)</td>
<td>138</td>
<td>878.03</td>
<td>10352517</td>
<td>108.83</td>
<td>122.56</td>
<td>95.10</td>
</tr>
<tr>
<td>40 (Private)</td>
<td>974</td>
<td>6,430.30</td>
<td>6199064</td>
<td>64.45</td>
<td>68.45</td>
<td>60.45</td>
</tr>
<tr>
<td>50 (stratified)</td>
<td>EDF = 1645</td>
<td>13855.57</td>
<td>X</td>
<td>106.06</td>
<td>109.53</td>
<td>102.58</td>
</tr>
</tbody>
</table>

*FS: U.S. Forest Service, OF: Other federal (i.e. BLM, BIA), S&L: State and Local, Private: large and small private timberlands, stratified: combination of all groups.

It can be seen from Table 21 that the mean biomass per acre is comparably larger on federal lands than on private land. Also, considering the relative weights of each stratum, there is a
drastic difference in the number of plots found on private land compared to those found on other lands. In order to allow for a better view of possible trends between the differing ownership groups, the means and confidence intervals for each ownership group and the stratified total were plotted in Figure 15.

**Figure 15.** The sample mean with a 95% confidence interval for each ownership group and the stratified total (10 = FS, 20 = OF, 30 = S & L, 40 = Private, ST = stratified).

From Figure 15, there is a general downward trend from federal lands to private lands. In order to provide evidence for this downward trend, a one-way ANOVA F-test was conducted to determine if there was a general significance to the trend. The one way ANOVA F-test provided strong evidence that there are differences in the biomass per acre based on the ownership group (One-way ANOVA p-value = <2.2e-16). Thus, in order to determine which trends were significant a pair-wise t-test was conducted followed by the development of pair-wise confidence intervals. However, prior to conducting the pair-wise t-test, the data was checked to ensure that there were no violations of the assumptions required for t-tests.
After developing side-by-side box-plots for the ownership groups (appendix I) there seemed to be a potential violation of the equal variance assumption. However, after viewing a plot of the residuals (appendix I) and finding a variance ratio of 3.82, it was determined that the data does not violate the equal variance assumption and can be used, in form, within a pair-wise t-test. The pair-wise t-test was conducted both as a two-sided test and a one-sided test and the results can be seen in Tables 22 and 23.

Table 22. The p-values resulting from the two-sided pair-wise t-test conducted between ownership groups (bolded values are non-significant comparisons).

<table>
<thead>
<tr>
<th>Two-sided Pair-wise T-test P-values (Equal)</th>
<th>10</th>
<th>20</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>6.00E-10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>2.30E-10</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>&lt;2E-16</td>
<td>&lt;2E-16</td>
<td>3.70E-09</td>
</tr>
</tbody>
</table>

Table 23. The p-values resulting from the one-sided pair-wise t-test, alternative less, conducted between ownership groups (bolded values are non-significant comparisons).

<table>
<thead>
<tr>
<th>One-sided Pair-wise T-test P-values (Alt. less)</th>
<th>10</th>
<th>20</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>3.00E-10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>1.20E-10</td>
<td>0.068</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>&lt;2E-16</td>
<td>&lt;2E-16</td>
<td>1.80E-09</td>
</tr>
</tbody>
</table>

From Tables 22 and 23 it can be seen that the trend observed from the plot of the stratum means (Figure 15) is significant for all but one comparison. With corresponding two-sided and one-sided p-values of .14 and .068, respectively, there is no significant difference in the amount of biomass per acre (BDTons) on state & local lands and other federal lands (Tables 22 and 23). This relationship is logical, in that, both state & local and other federal tend to
have similar management practices and regulatory environments. What is more profound than the relationship between State & Local and Other Federal is the relationship that both the forest service and private lands have against all other ownership groups. With p-values well below .0001, the forest service by far has the most biomass per acre (BDTons) than any other ownership group (Tables 22 and 23). Similarly, private lands had significantly less biomass per acre (BDTons) than any other ownership group with p-values well below .0001 (Tables 22 and 23). The trends that were found to be significant follow the logical framework that was used to develop the hypotheses regarding the relationship between FS and private lands. When one considers the regulatory environment and the management practices of the various ownership groups, the results of this assessment should not come as a surprise. With very little harvesting activity occurring on forest service lands when compared to both state & local and private lands, it is only logical to surmise that there would be significantly more biomass per acre (BDTons) on forest service land than on other ownership groups.

With the significance of the trends now known, the next step was to quantify the magnitude of the significant differences. In order to quantify the magnitude of the significant differences, pair-wise confidence intervals about the magnitude were developed for all comparisons and can be found in Table 24.
Table 24. The magnitude of difference for the significant (*non-significant) relationships found between the various ownership groups, including a 95% confidence interval of the estimated magnitude.

<table>
<thead>
<tr>
<th>Ownership Group Differences</th>
<th>Magnitude (BD Tons)</th>
<th>LCL (BD Tons)</th>
<th>UCL (BD Tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 to 20</td>
<td>35.955</td>
<td>50.1235</td>
<td>21.7865</td>
</tr>
<tr>
<td>10 to 30</td>
<td>48.74</td>
<td>67.6795</td>
<td>29.801</td>
</tr>
<tr>
<td>10 to 40</td>
<td>93.1165</td>
<td>101.073</td>
<td>85.16</td>
</tr>
<tr>
<td>20 to 30*</td>
<td>12.785</td>
<td>29.371</td>
<td>-3.8005</td>
</tr>
<tr>
<td>20 to 40</td>
<td>57.1615</td>
<td>65.592</td>
<td>48.731</td>
</tr>
<tr>
<td>30 to 40</td>
<td>44.3765</td>
<td>54.715</td>
<td>34.038</td>
</tr>
</tbody>
</table>

From Table 24 it can be seen that the largest magnitude of difference occurs between forest service (10) and private (40) lands with a difference of 93.12 (BDTons/ac). The smallest significant magnitude of difference occurred between the forest service (10) and other federal (20) with 35.96 (BDTons/ac, Table 24). The magnitude of difference between the forest service and private lands is drastically high and is a representation of the difference in management practices and the regulatory environment. There are two specific management practices that can be attributed to this striking difference between the two ownership groups. The first is the rotation length, whereby, the forest service essentially has no "rotation" length; whereas, private has a relatively short rotation length. The forest service practices two main management strategies, uneven-age management and habitat restoration thinning. Uneven-age management is focused around variable retention harvesting; whereby, stands are managed to include a range of: age classes, stem densities and species. Habitat restoration thinning is a management technique to reduce the relative density of stands to speed the transition of the stand into late-successional (late-seral) stand.
characteristics to provide habitat for endangered species. The management on forest service timberlands is in stark contrast to the operations on private timberlands which practice even-aged management. The rotation length on private timberlands generally averages 40-45 years for Douglas-fir. Thus, forest service lands in general, have older and larger stems than does private timberlands. The second differing management practice lies in the intensity of harvesting. The forest service harvests significantly below their growth levels every year whereas private lands strive to achieve a one to one harvest to growth ratio. Thus, the forest service has considerably less harvesting across the landscape when compared to private land. Given the systematic nature of the FIA inventory process, it is far more likely to have a plot located in either a clear-cut or in regeneration on private land than on federal land; which, when combined with the effect of having larger timber will cause a large disparity in the amount of biomass per acre (BDTons). Essentially, the results of this assessment followed closely to the hypotheses developed for this comparison except for the other federal ownership group. The other federal ownership group proved to not be the same as forest service land and subsequently was found to be the same as state and local lands.

One must not conclude quickly that the best potential for biomass harvesting lies within the forest service ownership group due to the significantly higher amount of biomass per acre. When the results are put into a context of management objectives and continuity of supply, the reverse may be occurring. Whereby, the forest service has the least potential for biomass harvesting operations. The bulk of current biomass harvesting revolves around the utilization of residual residues from timber harvesting operations. Thus, the habitat based management strategies (NW Forest Plan, 1994), and relatively low volumes of timber production on forest
service timberlands may provide very few opportunities for biomass harvesting. However, there is still a potential on forest service timberlands to utilize biomass harvesting operations within the confines of the habitat based management strategies for habitat restoration and improvement activities. But the use of biomass operations for habitat restoration and improvement activities may prove to have low consistency and continuity making long term biomass harvesting operations unfeasible. Thus, despite the significantly low amount of biomass per acre on private timberlands, this ownership group may prove to have the greatest potential for a consistent and continual biomass supply.

Although the ownership group has the largest impact on the potential for the development of biomass harvesting operations, the next step would be to consider how current biomass harvesting operations may be expanded to include a larger proportion of the land-base than what is currently available. In order to begin to develop an understanding of how biomass harvesting operations can be expanded to include a greater portion of the landscape, the impact of slope and elevation must be considered. Slope and elevation, more so than almost any other timber stand characteristic, influence the cost of forest operations and thus, will also have an impact on the development of biomass harvesting.

3.6.2 Elevation

Elevation is of concern with regards to biomass for bio-energy because of the road networks that are used to access higher elevation timber tracts (Sessions et al., 2010). The importance lies in the amount of biomass that can be derived from higher elevations, because if there is significantly more biomass on higher elevation stands, then it may be beneficial to re-
engineer road networks to provide access for chip vans and biomass equipment (Sessions et al., 2010). Thus, a biomass assessment that compares the amount of biomass on higher elevation sites to lower elevation sites would provide beneficial information for operations planners. The comparison of elevation was broken into three ownership classes; whereby, within each of the three ownership class, the plot data was stratified by elevation. The three ownership classes were forest service, other public and private.

*Forest Service*

The first step in the comparison of the biomass per acre by elevation class within the forest service ownership group was to develop a side-by-side boxplot (Figure 16).

**Figure 16.** The side-by-side boxplot of the forest service biomass per acre plot data when stratified by elevation class.
From Figure 16, it can be seen that there were no apparent variations in the plot data when compared based on elevation class. However, the boxplots do not provide enough inference to develop an understanding of the differences. Thus, statistical comparisons using the one-way ANOVA F-test were made between the elevation classes to determine if any significant differences exist. The one-way ANOVA F-test showed that there were no significant differences occurring between any of the elevation classes (One-way ANOVA F-test p-value = 0.152). Since the one-way ANOVA f-test showed that no significance differences were occurring within the data, then there was no need to progress to other forms of analysis. Thus, the data showed that there is no significant difference in the amount of biomass per acre (BDTons) between different elevation classes within the forest service ownership group, when the elevation classes were defined in the fashion of this study.

Other Public

The stratification of the other public plot data by elevation class resulted in the formulation of the following side-by-side boxplot (Figure 17).
Figure 17. The side-by-side boxplot of the other public biomass per acre plot data when stratified by elevation class.

From Figure 17 it can be seen that there were some trends that may lead to differences in the amount of biomass per acre occurring within the other public ownership group with changes in elevation. However, any difference portrayed by the side-by-side boxplot must be verified through statistical analysis. The one-way ANOVA F-test showed that there were no significant differences occurring between the elevation classes in the other public ownership group, when the elevation classes were defined in the fashion of this study (One-way ANOVA F-test p-value = .056).

Private

The stratification of the private plot data by elevation class resulted in the formulation of the following side-by-side boxplot (Figure 18).
Figure 18. The side-by-side boxplot of the other public biomass per acre plot data when stratified by elevation class.

From Figure 18 it can be seen that there was not any major differences in the median values between the different elevation classes, but there was an apparent discrepancy in the variance between the different elevation classes. Although the difference in variance seemed high based on the side-by-side boxplot, the variance ratio was found to be 1.28, which is well within the range considered for the assumption of equal variance to be valid. With the equal variance assumption verified, the next step was to determine if significant differences were occurring between the elevation classes. The one-way ANOVA F-test showed that there were no significant differences between the elevation classes (One-way ANOVA F-test p-value =
0.701. Thus, there was no significant difference in the amount of biomass per acre between the different elevation classes, when the elevation classes were defined in the fashion of this study.

The primary result that was found across all ownership groups was that there was no significant difference in the amount of biomass per acre across the various elevation classes. This may make it seem as though there is no conclusion that can be made from the results, but that is far from the case. The fact that there was no statistically significant difference in the amount of biomass per acre provides a strong result from which landowners can make decisions regarding higher elevation biomass harvesting operations. When a landowner must make a decision regarding the applicability of biomass harvesting operations on a given site, they must look at all the factors that will influence the cost and profitability of the operation. First, they would look at the cost of transporting the biomass equipment (grinder, chipper, chip vans, etc.) and the biomass itself to and from a harvest unit. Second they would look at the amount of volume of biomass that could be generated from the harvest unit. Lastly, landowners would have to consider the costs of site preparation or other management activities that might be offset through the use of biomass harvesting. Elevation plays a major role in the first and second consideration but may not have an impact on the third consideration. Higher elevation harvest sites are generally located in areas that are further from product market locations and they generally have road systems that are more complex with respect to the alignment and grade. To further compound the issue, the existing high elevation road networks were designed for stinger steered log trucks and not for chip vans, which have a larger curve footprint through increased off-tracking (Sessions et al. (2010)).
Provided the difficulties in transportation mentioned previously, it can be said that transporting biomass from higher elevation sites would incur higher transportation costs and would make biomass harvesting operations less feasible. Thus, it could be argued that it would require a greater volume of biomass on a higher elevation harvest units in order to offset the increased cost of transportation. From the results of this study it can be said that there will not, in general, be more biomass on higher elevation sites than what would be found on lower elevation sites. However, that should not discount the finding that there is no statistically significant difference in the amount of biomass across all elevation classes, meaning that a landowner can expect, in general, to have the same biomass volume generated on higher elevation sites that is generated on lower elevation sites. By understanding that there is essentially the same volume of biomass no matter the elevation, landowners will have a more profound ability to make decisions regarding the applicability of biomass harvesting operations in a given harvest unit. Overall, finding no significant difference in the amount of biomass per acre with changes in elevation proved to be a result in and of itself, with the potential to influence the decisions of landowners.

3.6.3 Slope

Slope is a factor that is directly related to the physical and economic feasibility of biomass harvesting operations. Traditionally, biomass operations are limited to flatter (<35%) terrain. This limitation is derived from the physical feasibility of ground based equipment, which typically only operates on terrain that is less than 35% in slope. When harvesting on sites above 35% slope, either cable systems or helicopter operations are currently proven to be effective. Cable systems and helicopters are highly expensive operations that can prove to be
economically infeasible for biomass harvesting. However, newer machine technologies are making it possible to operate ground-based machinery on steeper mid-slope grades (<70%). The confounding issue however, is the high cost of these new technologies. Thus, there is a strong need to develop an understanding of the availability of biomass on steeper slopes, in order to provide a basis for decisions regarding the purchase of these newer technologies.

The best way to assess the potential of western Oregon timberlands based on the category of slope was to stratify the timberlands of western Oregon first by ownership group and then by slope class within each ownership group. The slope classes that were used for this assessment were at a set interval of 10% with slope classes ranging from: 10 = 0-9%, 20 = 10-19%....90 = 80+%.

*Forest Service*

The following side-by-side boxplot represents the distribution of biomass per acre values found from the stratification of the forest service plot data by slope class (Figure 19).
Figure 19. The side-by-side boxplot of the forest service biomass per acre plot data when stratified by slope class.

From the distribution seen in Figure 19 it can be seen that there were some differences occurring in the data. But in order to determine the significance of any differences that may have been present in the distribution, further statistical analysis was required. From the statistical analysis it was found that there were no significant differences occurring between any of the slope classes, with respect to biomass per acre (One-way ANOVA F-test p-value = 0.051). Since the one-way ANOVA F-test showed that no significant differences were occurring between the slope classes, there was no need to progress to more detailed statistical analyses. Although the amount of biomass per acre did not increase with increasing slope as was hypothesized, there is still importance in the result that there was no change in biomass availability with changes in slope.
Other Public

The land bases held in the other public ownership group work to bridge the divide between the relatively large and contiguous forest service land bases and those of the private industry. The other public ownership category had the potential for more profound results through the diffuse nature of the ownership groups land holdings. The following side-by-side boxplot represents the distribution of the biomass per acre plot data with respect to slope class for the other public ownership group (Figure 20).

**Figure 20.** The side-by-side boxplot of the other public biomass per acre plot data when stratified by slope class.
From Figure 20 it can be seen that there was a potential difference in the amount of biomass per acre at the lowest slope class when compared to the rest of the distribution. However, the potential was proven to be inconsequential through the use of further statistical analysis. The one-way ANOVA F-test showed that there was no significant difference between the various slope classes with respect to the amount of biomass per acre (One-way ANOVA F-test p-value = .66). Although it may seem as though finding no statistically significant differences means there were no results, which is far from what occurred. Finding no statistically significant differences is a result on its own, because it has implications for the way landowners may make decisions regarding biomass harvesting.

*Private*

The private ownership group represents interests that have the greatest ability to make significant leaps forward in the development of biomass harvesting. However, that ability it also constrained to biomass harvesting that will either turn a profit or offset costs that would have been occurred had it not been done. Thus, the implications of the results of this study may have the largest impact on the private ownership group. The following side-by-side boxplot represents the distribution of the biomass per acre plot values when stratified by slope class (Figure 21).
Figure 21. The side-by-side boxplot representing the distribution of the biomass per acre plot values for the private ownership group when stratified by slope class.

From Figure 21 it can be seen that there is only one noticeable difference in the distribution of the slope classes, which occurs at slope class 60. However, the one-way ANOVA F-test showed that there was no significant differences occurring between the various slope classes with respect to the amount of biomass per acre within the private ownership group (one-way ANOVA F-test p-value = 0.51).

Although none of the ownership groups had any statistically significant differences in the amount of biomass per acre when stratified by slope class, there are still some profound results that can be drawn from the findings. Since there was no change in the amount of
biomass per acre with changes in slope class, then it can be said that biomass is distributed equally across the landscape when thinking of the distribution as being by slope. Thus, whether a landowner decides to conduct biomass harvesting operation on flat terrain (0-35%) or steep terrain (65+ %) the amount of biomass that can be acquired will be the same. Understanding that there is a homogenous amount of biomass across slope classes provides landowners with the ability to make decisions regarding the slope levels they can profitably operate within. Although understanding the relationship between the amount of biomass per acre and the slope provides land managers with a basis for making decisions, the impact of this study’s results on the direction of decisions is far from certain. Generally, it could be said that landowners may be more willing to pursue costlier harvesting technologies for steep slope biomass harvesting if they knew there was added volume on steep slopes to offset the increase in cost. Since the results of this study show that there would not be an increase in volume with increasing slope, then the ability of land managers to offset costs through increases in volume would not be possible. Thus, the results of this study may not influence the decision making of landowners with regard to steeper terrain biomass operations but rather those decisions would be based on external factors such as market price for biomass or the offset of site preparation costs.

3.6.4 Stratified Totals

Although this biomass assessment was conducted primarily for the comparison of various categories, there was an opportunity to develop a total biomass assessment for all of western Oregon from three separate stratified sampling procedures. The biomass per acre
(BDTons) and total biomass (BDTons) for western Oregon as determined by the three different stratifications can be seen in Table 25.

**Table 25.** The estimated biomass per acre (BDTons) and total biomass (BDTons) and the subsequent 95% confidence intervals for all of western Oregon.

<table>
<thead>
<tr>
<th>Stratification Type</th>
<th>Est. Bio/ac (BDTons)</th>
<th>UCL (BDTons)</th>
<th>LCL (BDTons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ownership</td>
<td>106.06</td>
<td>109.53</td>
<td>102.58</td>
</tr>
<tr>
<td>Elevation</td>
<td>106.88</td>
<td>110.73</td>
<td>103.02</td>
</tr>
<tr>
<td>Slope</td>
<td>106.76</td>
<td>110.66</td>
<td>102.85</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stratification Type</th>
<th>Est. Tot. Bio. (BDTons)</th>
<th>UCL (BDTons)</th>
<th>LCL (BDTons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ownership</td>
<td>1,469,503,480.17</td>
<td>1,517,653,897.10</td>
<td>1,421,353,063.23</td>
</tr>
<tr>
<td>Elevation</td>
<td>1,480,831,693.34</td>
<td>1,534,258,118.80</td>
<td>1,427,405,267.87</td>
</tr>
<tr>
<td>Slope</td>
<td>1,479,175,145.32</td>
<td>1,533,250,803.56</td>
<td>1,425,099,487.07</td>
</tr>
</tbody>
</table>

From Table 25 it can be seen that there is very little difference in the estimates for biomass per acre (BDTons) and total biomass (BDTons) between the stratification types. The small variations that do occur are the product of stratified sampling itself, whereby the individual stratum means are weighted to provide an overall estimate of the total mean. Also, the confidence intervals are all similar in width with only minor variations (Table 25). In summary, this assessment has shown that there is considerable potential for biomass productivity in western Oregon.

### 3.7 Conclusions

The results of this biomass assessment provided detail into how unique site characteristics can influence the amount of biomass that is present on a site. By understanding how unique characteristics influence the accumulation of biomass, resource managers will have an
increased ability to make management decisions regarding the applicability of biomass harvesting operation in a given harvest unit. With that said, there were some overlying conclusions that are worth noting.

With respect to ownership group, forest service land had significantly more biomass per acre (BDTons) than all other ownership groups. Conversely, private lands had significantly less biomass per acre (BDTons) than all other ownership groups. Despite the hypothesized difference between other federal and state & local ownership groups, it was found that there was no significant difference between the two groups. Since ownership group is directly related to possible development of biomass operations, through differing management practices and regulatory environments, the results of this study could provide a basis for future market allocation determinations. Also, the presence of the dichotomy between profit based and habitat based management can influence the potential of the different ownership groups to develop biomass operations. The private ownership group may steer clear of biomass operations due to low profitability, while the various public ownership groups may pursue the development of biomass operations as a tool for habitat restoration and maintenance.

With respect to elevation and slope, the study found that there was no statistically significant difference between the amount of biomass per acre and either elevation or slope across the landscape. This result may have some influence on the decision making of landowners regarding the applicability of biomass operations on steep slope and higher elevations. But the one overriding theme was that without an increase in biomass per acre with either increasing slope or elevation, there is not an avenue to offset the higher cost of operating on
steeper slopes and higher elevations. Thus, the applicability of these results to an increase in biomass harvesting operations is ambiguous and no link can be found.

The one big ticket conclusion that can be made from this study is that ownership group will have the largest impact on the amount of biomass present on timberlands in western Oregon. Also, further research is needed to identify the impact of other unique characteristics on the amount of biomass per acre across the landscape. If resource managers can have a strong indication of the amount of biomass that is available on a site through the unique characteristics that are present, then they will be better able to make effective decisions regarding future biomass harvesting operations.
3.8 Literature Cited


Chapter 4

Summary of Conclusions

Benjamin R. Flint

October 24, 2013
4.1 Introduction

The conclusions from the studies conducted within this thesis have the potential to influence the decision making of land managers and future researchers. This thesis spanned from small scale to landscape scale on topics related to the operational considerations of steep slope harvesting of small wood. Within this chapter, the conclusions found within this thesis are summarized in the order they were presented within their respective chapters. Following the summary there is a synthesis of the conclusions.

4.2 Conclusions Chapter 1

Although there were not specific “conclusions” that were presented within chapter 1, there are three common themes from the literature that will suffice as conclusions. The first theme from the literature was that there is a need to develop harvesting systems, whether utilizing new technology or utilizing old technology in new ways, in order to begin harvesting biomass on steep (>35%) terrain. Although many traditional harvesting systems could be utilized to harvest biomass on steep (>35%) terrain, the high cost and low productivity would prove to be cost prohibitive. Thus, by developing new technologies (i.e. purpose built steep slope ground based machine) or utilizing existing technologies in new ways (i.e. tethering) steep slope biomass harvesting may become economically feasible.

The second theme from the literature was that productivity can be increased by “hybridizing” harvesting techniques. By combining two or more traditional harvesting techniques into a single harvesting operation can provide increases in productivity and decreases in cost. This was personified in the results of chapter 2 of this thesis, when the combination of a
harvester and a yarder showed an increase in productivity and a decrease in cost over utilizing a yarder alone. This theme is one that would be the easiest to implement, since the techniques and infrastructure are already in place to provide a quick transition for contractors and land managers.

The third and final theme from the literature was that the integration of chippers and grinders with existing harvesting operations could provide a steady source of biomass at a relatively low cost. The integration of chippers and grinders was considered in two forms, first located with a harvesting operation on the landing and located centrally in an area with multiple operations. Under both circumstances, the literature showed that the biomass yield from a given stand could be increased. The integration of chippers and grinders will help with the collection and supply of biomass derived from forest residues but it may not provide a viable option for the generation of solely biomass. Thus, chippers and grinders are best utilized in concert with other harvesting operations.

In summary, the themes derived from the literature provide a valuable baseline from which to begin research into steep slope biomass harvesting operations. Although a single harvesting practice or method has not been outlined in the literature as the one sole way to harvest biomass, there were a lot of avenues from which successful biomass operations may begin to occur.

4.3 Conclusions Chapter 2

The conclusions of this chapter can be grouped into two categories, those that related to the detailed analysis of the harvester and those related to the economic analysis of the
harvesting systems. With respect to the detailed analysis conducted on the harvester, there were four primary conclusions that were made regarding the changes in operability of the harvester when it was operating on steep (>35%) terrain. First, the average cycle time of the harvester was not affected by changes in the slope of the harvest unit, or that as slope increased there was no significant difference in the average cycle time of the harvester. The second conclusion was that when the slope of the harvest unit increased above 65% the average drive time increased. The third conclusion was that there were external factors not considered within this study that had an impact on the productivity of the harvester. The final conclusion from the detailed analysis of the harvester was that by operating on steep (>35%) slopes, the harvester lost an average of an hour of productive time per day.

Although the results of the detailed analysis of the harvester are important and relevant, they cannot answer the fundamental questions posed within this study. In order to answer the questions, the economic analysis of the different harvesting systems within the different treatment units was examined. The "big ticket" conclusions from the economic analysis was that under all scenarios considered within this study, the harvester/forwarder combination was the cheapest, most cost effective option for conducting first entry commercial thinning on steep terrain. There were two other conclusions that could be made from the economic analysis. First, when operating the forwarder on steep terrain, adverse hauls to the landing will cause drastic reductions in productivity and increases in cost. Second, when utilizing the harvester to process and pre-bunch stems for the Koller yarder, productivity increased and cost decreased.
4.4 Conclusions Chapter 3

The conclusions from chapter 3 can be separated into the three comparison topics that were studied. With respect to ownership group, forest service land had significantly more biomass per acre (BDTons) than all other ownership groups. Conversely, private lands had significantly less biomass per acre (BDTons) than all other ownership groups. Since ownership group is directly related to possible development of biomass operations, through differing management practices and regulatory environments, the results of this study could provide a basis for future market allocation determinations. Also, the presence of the dichotomy between profit based and habitat based management can influence the potential of the different ownership groups to develop biomass operations. The private ownership group may steer clear of biomass operations due to low profitability, while the various public ownership groups may pursue the development of biomass operations as a tool for habitat restoration and maintenance.

With respect to elevation and slope, the study found that there was no statistically significant difference between the amount of biomass per acre and either elevation or slope across the landscape. This result may have some influence on the decision making of landowners regarding the applicability of biomass operations on steep slope and at higher elevations. But the one overriding theme was that without an increase in biomass per acre with either increasing slope or increasing elevation, there is not an avenue to offset the higher cost of operating on steeper slopes and at higher elevations. Thus, the applicability of these results to an increase in biomass harvesting operations is ambiguous and no link can be found. The
one big ticket conclusion that can be made from this study is that ownership group will have the largest impact on the amount of biomass present on timberlands in western Oregon.

4.5 Synthesis of the Conclusions

The conclusions from chapters 1 through 3 of this thesis present a strong case for the potential development of small wood and biomass operations in the future. Through the application of the conclusions of the literature review, field study and biomass assessment a land manager will be better prepared to make a decision on the location, type and extent of biomass operations that could occur on the respective land-base. The conclusions of this thesis provide the research community with ample opportunities to expand and explore on the topics and results that were shown. Overall, the conclusions from this thesis may help to accelerate the introduction of new management and harvesting techniques on timberlands in western Oregon.
Bibliography

Bibliography

Bibliography


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   "Operation of Ground Skidding Machines and Vehicles". Or. Admin. R. 437-007-0935


Appendices

Appendix I Shift Level Study Forms

Manual Felling Shift Level Study Form

General Information

Date: _________ Start Time: _________ Stop Time: _________ Number of Cutters: ___.

Production

# Stems Cut: _________.

Delays (> 10 Minutes downtime)

Operational Delays (i.e. Walk in/out of unit and hang-ups, if >10 minutes):

1. Duration (min.): _________ Reason: ________________________________________________.
2. Duration (min.): _________ Reason: ________________________________________________.
3. Duration (min.): _________ Reason: ________________________________________________.

Mechanical Delays (Chain saw repair/maintenance and fuel/lube, if > 10 minutes):

1. Duration (min.): _________ Reason: ________________________________________________.
2. Duration (min.): _________ Reason: ________________________________________________.
3. Duration (min.): _________ Reason: ________________________________________________.

Other Delays (> 10 minutes):

1. Duration (min.): _________ Reason: ________________________________________________.
2. Duration (min.): _________ Reason: ________________________________________________.
3. Duration (min.): _________ Reason: ________________________________________________.

Figure 1. The shift-level study form for the manual felling operations within this study.
Harvester Shift Level Study Form

General Information

Date:_________ Start Time:_________ Stop Time:_________ Treatment Type:_________

Production

Report from on-board computer

Fuel Consumption

Fuel Consumption (nearest gallon):_________.

Delays (> 10 Minutes downtime)

Operational Delays (i.e. Wait time or travel between unit/road, if > 10 minutes):

4. Duration (min.): _______ Reason:___________________________.
5. Duration (min.): _______ Reason:___________________________.
6. Duration (min.): _______ Reason:___________________________.

Mechanical Delays (Including Scheduled Daily Maintenance):

4. Duration (min.): _______ Reason:___________________________.
5. Duration (min.): _______ Reason:___________________________.
6. Duration (min.): _______ Reason:___________________________.

Other Delays (> 10 minutes):

4. Duration (min.): _______ Reason:___________________________.
5. Duration (min.): _______ Reason:___________________________.
6. Duration (min.): _______ Reason:___________________________.

Figure 2. The shift-level study form for the Ponsse Ergo Harvester operations within this study.
Forwarder Shift Level Study Form

General Information
Date: _______ Start Time: _______ Stop Time: _______ Treatment (steep (A or N) or flat): ___

Production
# Bunks: ___________ # Truck Loads: _______

Fuel Consumption
Fuel Consumption (nearest gallon): _______

Forwarder Loading Trucks:
7. Duration (min.): _______ 5. Duration (min.): _______
8. Duration (min.): _______ 6. Duration (min.): _______
9. Duration (min.): _______ 7. Duration (min.): _______
10. Duration (min.): _______ 8. Duration (min.): _______

Delays (> 10 Minutes downtime)

Operational Delays (> 10 minutes):
1. Duration (min.): _______ Reason: ___________________________________________________.
2. Duration (min.): _______ Reason: ___________________________________________________.
3. Duration (min.): _______ Reason: ___________________________________________________.

Mechanical Delays (Including Scheduled Daily Maintenance, > 10 minutes):
7. Duration (min.): _______ Reason: ___________________________________________________.
8. Duration (min.): _______ Reason: ___________________________________________________.
9. Duration (min.): _______ Reason: ___________________________________________________.

Other Delays (> 10 minutes):
7. Duration (min.): _______ Reason: ___________________________________________________.
8. Duration (min.): _______ Reason: ___________________________________________________.
9. Duration (min.): _______ Reason: ___________________________________________________.

Figure 3. The shift-level study form for the Ponsse Buffalo King forwarder operations within this study.
Cable Yarding Shift Level Study Form

General Information

Date: ________ Start Time: ________ Stop Time: ____ Number of Crew Members: ____

Treatment Type: ______ Road Number(s): ______.

Production

# Turns: ________ # Pieces: ________ # Loads: ________ Processing Time (min): ______.

Fuel Consumption

Yarder Fuel Consumption (nearest gallon): ________.

Loader and Processor Fuel Consumption (nearest gallon): ________.

Road and/or Landing Change:

1. Duration (min.): ________  4. Duration (min.): ________
2. Duration (min.): ________  5. Duration (min.): ________
3. Duration (min.): ________  6. Duration (min.): ________

Delays (> 10 Minutes downtime)

Operational Delays (i.e. line splice):

11. Duration (min.): ________ Reason: ________________________________.
12. Duration (min.): ________ Reason: ________________________________.
13. Duration (min.): ________ Reason: ________________________________.

Mechanical Delays:

4. Duration (min.): ________ Reason: ________________________________.
5. Duration (min.): ________ Reason: ________________________________.
6. Duration (min.): ________ Reason: ________________________________.

Other Delays (> 10 minutes):

10. Duration (min.): ________ Reason: ________________________________.
11. Duration (min.): ________ Reason: ________________________________.
12. Duration (min.): ________ Reason: ________________________________.

Figure 4. The shift-level study form for the Koller K301 yarding operations within this study.
Appendix II The Machine Rate Method Costing Process

Each piece of equipment on a logging side has its own operating constraints and more importantly its own cost. Thus, in order to accurately detail the cost of the entire harvesting system, accurate costs for each piece within the system must be determined first.

The first step in the development of the individual equipment costs is to find or determine the following values for each piece of equipment: purchase price, salvage value (as a percentage of purchase price), economic life, scheduled machine hours (SMH) per year, interest rate, insurance rate, tax rate, percentage set aside for maintenance and repair (% M&R), the utilization rate of the machine (% UT), the mechanical availability rate (% MA), fuel consumption per hour, wages ($/week, 50 hr work week (40 regular pay, 10 overtime)), fringe benefits and the price of diesel fuel.

The utilization rate, mechanical availability rate, fuel consumption per hour and the scheduled machine hours per year were found through the information provided by the shift-level assessment. More specifically, the utilization rate and the machine availability rate were calculated from the shift level assessment via the following two equations:

\[
\% UT = \frac{PMH}{SMH} \times 100
\]

Where: \%UT = Utilization Rate, PMH = Productive Machine Hours, SMH = Scheduled Machine Hours
Equation (2) \[ \%MA = \frac{SMH - mechanical \ delays}{SMH} \times 100 \]

Where: \( \%MA \) = Mechanical Availability Rate, \( SMH \) = Scheduled Machine Hours

**Fixed Costs**

Fixed costs are considered by many to be simply the cost of ownership of a given piece of equipment. The value of fixed cost is a product of two separate costs, depreciation and IIT (interest, insurance and taxes). Depreciation was calculated in this study using the following equation:

\[ \text{Equation (3)} \quad D \left( \frac{\$}{SMH} \right) = \frac{(P - S)}{N \times (SMH/year)} \]

Where: \( D \) = Depreciation ($/SMH), \( P \) = Purchase Price ($), \( S \) = Salvage Value ($), \( N \) = Economic Life (yrs.)

The value of IIT was found using the average value of yearly investment (AVI) method whereby the AVI is determined first and is then applied to the direct calculation of the value of IIT. The equation used to find the AVI for each piece of equipment is as follows:

\[ \text{Equation (4)} \quad AVI \left( \frac{\$}{year} \right) = \frac{(P-S)\times(N+1)}{(2+N)} + S \]

Where: \( AVI \) = Average Value of Yearly Investment ($/yr), \( P \) = Equipment Purchase Price ($), \( S \) = Salvage Value ($), \( N \) = Economic Life (yrs)
Using the value found for AVI (Equation 4), the value of IIT can then be directly calculated using the following equation:

$$\text{Equation (5) } IIT \left( \frac{\$}{SMH} \right) = \frac{((i+I+T) \cdot AVI)}{(SMH / yr)}$$

Where: IIT = Cost of Interest, Insurance and Taxes ($/SMH), i = Interest Rate (decimal), I = Insurance Rate (decimal), T = Tax Rate (decimal), AVI = Average Value of Yearly Investment ($/yr)

The values determined for the depreciation and IIT are then combined to form the fixed costs of a particular piece of equipment. These values are presented as a cost per scheduled machine hour and will be combined with the values of variable cost, labor cost and the cost of the operator’s pick-up truck to determine the total cost per scheduled machine hour of that individual piece of equipment.

**Variable Cost**

Variable costs are those elements of cost that are only incurred when the machine is in operation. The variable costs as calculated in this study are developed from two separate costs; the cost of maintenance & repair and the cost of Fuel & Lubricants. The cost of maintenance and repair was calculated within this study using the following equation:

$$\text{Equation (6) } M&R \left( \frac{\$}{PMH} \right) = \frac{(%M&R) \cdot D}{%UT}$$

Where: D = Depreciation ($/SMH), %UT = Utilization Rate (%/SMH), %M&R = Maintenance and Repair Rate.
The cost of fuel and lubricants is two-fold, in that, it contains the cost to the operator for the amount of diesel that is consumed and the amount of hydraulic fluid (and/or grease) that is consumed. Although the amount of fuel consumed and the purchase price of diesel at the time of the study is known from the shift-level assessment, the amount of lubricants consumed was not known and was figured into the cost as an industry average of $8.00/PMH, as can be seen in the following equation.

Equation (7)

\[ F&L \left( \frac{$}{PMH} \right) = (Consumption Rate_{\text{Diesel}} \times Price_{\text{Diesel}}) + Cost_{\text{of Lubricants}} \]

Where: Consumption rate = (gallons/PMH), Price = ($/gallon), Cost of Lubricants = Industry Average Values of Lubricant Cost ($/PMH)

The cost of M&R and F&L are combined to develop the total variable cost ($/PMH). Since the value of variable cost is based on productive machine hours instead of scheduled machine hours, a conversion must be made to allow for a final combination for total cost of the machine. The conversion is made by multiplying the per productive machine hour cost by the utilization rate of the machine.

**Labor Cost**

Labor cost is simply the hourly cost of the machines employee(s); which includes the hourly wage and the fringe benefits provided to the employee(s). The labor cost is found in two steps, first by determining the hourly wage equivalent and secondly, using the hourly wage
equivalent, directly calculating the labor cost. The following two equations were used in this study to determine the labor cost for each piece of equipment.

\[
\text{Equation (8)} \quad HWE \left( \frac{\$}{\text{SMH}} \right) = \frac{\text{Gross Weekly Wages}}{\text{Scheduled Hours Per Week}}
\]

\[
\text{Equation (9)} \quad \text{Labor Cost} \left( \frac{\$}{\text{SMH}} \right) = \left( HWE \times (1 + FB\%) \right)
\]

Where: HWE = Hourly Wage Equivalent ($/SMH), FB% = percentage of wage included for fringe benefits (decimal)

**Total cost**

As mentioned previously, the total cost of a given piece of equipment is simply the combination of the three separate cost elements and the cost of the pick-up truck. The following equation summarizes the development of the total cost for each piece of equipment:

\[
\text{Equation (10)} \quad \text{Total Cost} \left( \frac{\$}{\text{SMH}} \right) = FC + (VC \times %UT) + LC + TC
\]

Where: FC = fixed cost ($/SMH), VC = Variable cost ($/PMH), LC = Labor cost ($/SMH), %UT = Utilization rate (decimal), TC = Cost of Operators Pick-up Truck.
Appendix III Machine Rate Method Cost Factors

Table 1. The machine rate method cost components for the five separate machines utilized within this study, with the chainsaw representing the manual felling component.

<table>
<thead>
<tr>
<th>Cost Component</th>
<th>Harvester</th>
<th>Forwarder</th>
<th>Loader</th>
<th>Yarder</th>
<th>Chainsaw (MF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purchase Price ($)</td>
<td>600,000.00</td>
<td>400,000.00</td>
<td>350,000.00</td>
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<td>Salvage Value ($)</td>
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<td>70,000.00</td>
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<td>400.00</td>
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<td>Economic Life (years)</td>
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<td>8.00</td>
<td>8.00</td>
<td>8.00</td>
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<td>SMH/yr</td>
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<td>0.02</td>
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<tr>
<td>% M &amp; R</td>
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<td>1.10</td>
<td>0.90</td>
<td>0.50</td>
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<td>% UT</td>
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<td>0.63</td>
<td>0.63</td>
<td>0.98</td>
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<td>% MA</td>
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<td>900.00</td>
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<td>Fringe Benefits</td>
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<td>0.35</td>
<td>0.35</td>
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<tr>
<td>Diesel Fuel Price ($)</td>
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<td>3.70</td>
<td>3.70</td>
<td>3.70</td>
<td>3.75</td>
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Appendix IV Side-by-Side Box-plots and Residual Plots For Ownership Group

Distribution of Biomass/ac by Ownership group

Residuals vs Fitted

Appendix Figure 5. The side-by-side boxplot and the plot of the residuals for use in the determination of normalcy for the distribution of biomass per acre (lbs) based on ownership group.