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A Case Study Approach for Assessing Operational and Silvicultural Performance of Whole-Tree Biomass Harvesting in Maine

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A CASE STUDY APPROACH FOR ASSESSING OPERATIONAL AND SILVICULTURAL PERFORMANCE OF WHOLE-TREE BIOMASS HARVESTING IN MAINE

By

Charles E. Coup

B.S. The Pennsylvania State University, 2006

A THESIS

Submitted in Partial Fulfillment of the

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(in Forest Resources)

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The University of Maine

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A CASE STUDY APPROACH FOR ASSESSING OPERATIONAL AND SILVICULTURAL PERFORMANCE OF WHOLE-TREE BIOMASS HARVESTING IN MAINE

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Thesis Advisor: Dr. Jeffrey G. Benjamin

An Abstract of the Thesis Submitted
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In the Northeastern United States, re-emerging markets for renewable energy are driving interest in increasing the harvest of underutilized biomass material from Maine's forest. These markets may offer opportunities for forest managers to implement silvicultural treatments that have previously been foregone due to their high cost. However, many operational challenges arise in using current harvesting systems to harvest biomass material profitably while simultaneously achieving silvicultrual objectives. This research uses a case study approach to analyzing some of the possibilities and obstacles in implementing biomass harvesting in Maine.

The first three studies investigate a factorial silvicultural and operational case study involving whole-tree biomass harvesting in conjunction with herbicide injection. The first study investigated the use of combined biomass harvesting and herbicide treatment as a means of rehabilitating northern hardwood stands dominated by dense

understory thickets of small diameter American beech (*Fagus grandifolia* Ehrh.) and striped maple (*Acer pensylvanicum* L.). Prior to being harvested, a portion of beech and striped maple trees were treated using glyphosate stem injection as a means of controlling post harvest regeneration. Efficacy of the herbicide treatment was evaluated the first growing season after harvesting. During the harvest operation, a second study evaluated the productivity and impact of the feller-buncher using two trail spacings to determine if operational efficiency could be increased. A third study was carried out after the harvest to quantify and evaluate the damage inflicted by the operation at each trail spacing.

A related case study was then conducted that attempted to develop an organized methodology for analyzing and improving the long-term efficiency of whole-tree harvest operations using statistical process control (SPC) in order to better evaluate the long-term impacts of modifying harvesting systems. The methodology was developed using actual operation data collected on several whole-tree system machines used throughout Maine.

Results from the combined herbicide injection and biomass harvest case study indicated that whole-tree harvesting could utilize most of the beech and striped maple component of the stand while also effectively controlling the density of post-harvest beech regeneration. The harvest study found that feller-buncher productivity was not significantly different when operating at either of the two trail spacings; however, a tradeoff was found between efficient bunching and bunching frequency, with the narrower trail spacing using less time per bunch but requiring more bunches to be produced. Trail occupancy levels resulting from use of the narrower trail spacing were considerable, which could pose potential difficulties in future management. However, the frequency and patter of damage to the residual trees caused by the harvest operation was not significantly different between the two trail spacings.

The second case study demonstrated that Statistical Process Control could offer a unique perspective on evaluating operational variability and showed great potential as a tool for improving forest harvesting processes. The study revealed several challenges in applying this approach to whole-tree harvesting operations. These challenges are primarily related to how operational data is collected and organized, and how the underlying causes of variation are interpreted.

ACKNOWLEDGEMENTS

Numerous individuals and organizations have contributed to the success of this research. I would first like to thank the Committee, Dr. Jeremy Wilson, Dr. Robert Wagner, Dr. Robert Rice, and Thesis Advisor Dr. Jeffrey Benjamin, for their advice and guidance throughout the thesis preparation process.

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S.D.G.

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PREFACE

Maine's use of woody forest biomass for producing renewable energy has increased dramatically in recent years, but harvesting biomass from the State's forests for the purpose of producing energy is not a new endeavor. Changes in harvesting systems and forest management practices in the decades leading up to the 1970s laid the groundwork for expanded biomass utilization. During this time the logging industry experienced a period of vast technological innovation in timber harvesting equipment both within the industry and by equipment manufacturers in North America and Europe, especially Scandinavia (Silversides 1988, Erickson 1988, Brown 1996, MacDonald and Clow 1999). Rubber-tired articulated skidders and forwarders designed specifically for forest operations were becoming widely available on the commercial market and replacing crawler tractors and horses in the forest (Erickson 1988, Monte 2005). Soon to follow was the emergence of high-speed, tracked, feller-bunchers utilizing off-road technology developed for military applications, and industrial road-side whole-tree chippers (Butts and Preston 1979, Erickson 1988). Many industrial logging companies in Maine adopted fully mechanical harvesting systems, making utilization of low-value material more economical (Fowler 1974).

Mechanization likely aided in the expanded use of even-aged management practices and the maximum utilization concept where stands were whole-tree clearcut, with the entire aboveground portion of all trees on site including trunk, branches, and leaves brought to the road-side (Fowler 1971, Hornick 1974). Residual materials unsuitable for higher value products were comminuted for fiber or fuel as a means of increasing the utilization of woody material from a site. During this time Young (1964) introduced the “complete-tree concept” in which he suggested that even the stump and roots of trees should be utilized in clearcutting operations. This level of exploitation was never widely implemented in the United States; however, the practice has become more common in Nordic countries in recent years (Laitila *et al*. 2008). Mechanized whole-tree clearcutting practices were commonly implemented in Maine during the 1970s – 1980s to salvage stands dominated by balsam fir (*Abies balsamea* (L.) Mill) that were dying as a result of the spruce budworm (*Choristoneura fumiferana* (Clemens)) outbreak (Seymour 1992). Whole-tree clearcutting offered operational incentives of increased yield per acre and low cost per unit volume of chips. Pulp mills during this era were also more willing to blend whole-tree chips with clean mill chips (Erickson 1988).

The 1973 and 1979 oil crises resulted in an explosion of interest in using wood for energy. Legislation passed during the late 1970s encouraged the development and construction of new renewable energy facilities as generation sources of electricity for regional grids. In 1979, Maine enacted the Small Power Production Facilities Act (SPPFA, MRSA 33 §3302) which endorsed an overall policy based upon diversifying energy producing systems and sources while also reducing the State’s dependence on fossil fuels. Maine’s utilities were required to enter into long-term contracts for electricity from small, independent, renewable energy facilities. This legislation was in response to identical legislation passed at the national level in 1978 as part of the National Energy Policy Act, namely the Public Utilities Regulatory Policies Act (PURPA), which required public utilities to buy electricity from qualifying non-utility power production facilities (known as qualifying facilities QFs, or non-utility generators NUGs) that produced energy using renewable resource inputs (Hirsh 1999, Lamoureax 2002). Under PURPA, utilities were required to pay QFs or NUGs the avoided cost that the utility would have had to incur if the power from the QF or NUG was not available (Danielsen *et al*. 1999). In Maine, the Public Utilities Commission (PUC) decided that avoided cost would be calculated based on the projected cost of the Seabrook nuclear power plant in Seabrook, New Hampshire, resulting in rates that were substantially higher than if avoided costs were based on much lower fuel price forecasts (Cyr 1986, Laitner *et al*. 1994).

The demand for whole-tree chips for the production of electricity increased dramatically in the late 1970s and early 1980s. Pulp and paper industries which were already about 38 percent energy self-sufficient were beginning to co-generate more of their energy with wood fuel, with some relying completely on wood energy (Zerbe 1988). The first large energy-specific demand for wood chips in the Northeast developed in the late 1970s at the S.D. Warren plant in Westbrook Maine (Formerly Scott Paper Co. and now Sappi Fine Paper North America) and the Burlington Electric Department (BED) in Vermont (Donovan and Huyler 1986). At that time S.D. Warren was contracting with approximately 14 logging companies each delivering approximately 18,150 tonnes of chips per year.

From 1982 to 1992, the proportion of Central Maine Power Company's total electricity sales derived from power purchased from QFs and NUGs grew from 5% to 38%, 70% of which was provided by wood based biomass facilities (Laitner *et al*. 1994). In 1986, there were around 15 electricity generating installations in Maine using wood fuel with seven more planned for construction (Cyr 1986). By 1992, 9 co-generators (i.e., facilities that adapted their industrial processes to produce electricity as a by-product of normal manufacturing activities) and 7 independent power producers (i.e., stand-alone facilities designed only to generate electricity for sale) were under contract to supply electricity to Maine's three largest utilities (Central Maine Power, Bangor Hydro-Electric Company, and Maine Public Service Company) with several more producing electricity for in-house use only (Laitner *et al*. 1994).

From 1980 to 1987 the number of whole-tree chipping firms in Maine jumped from 5 to 51, 40% of which were fully mechanized (Morse 1987). An early report by the Maine Forest Service on whole-tree operations in the state indicated that a considerable percentage (41%) of the whole-tree chip supply was derived from clear-cuts (Morse 1987). However, according to a survey conducted by Huyler (1989), whole-tree chipping operations in northern New England predominantly implemented single entry, integrated, partial harvests where higher value products were sorted at the landing. The survey found that some clearcutting was taking place but only on a small proportion of the harvests.

Biomass harvesting in Maine increased from 0.81 million green tonnes in 1985 to a peak of more than 1.87 million green tonnes in 1992, comprising almost 13% of the total annual wood production in the State (Morse 1987, Maine Forest Service 1990 - 2008). This boom in renewable energy, however, was followed by a downturn in Maine's economy and a surplus of electricity supply created by accelerated efforts to conserve energy (Laitner *et al*. 1994). Furthermore, rates for renewable energy based on avoided cost as required by the Federal Energy Regulatory Commission (FERC) under PURPA proved to be substantially higher than market prices for electricity (Johnson 1994, Innovative Natural Resources 2005). As a result, long-term contracts were bought out or re-negotiated and a number of biomass power plants closed (Johnson 1994, Danielsen *et al*. 1999). In 1992, five power purchase contracts in Maine, totaling almost 6.5 percent of the total contracted utility capacity, were terminated with more soon to follow (Laitner *et al*. 1994).

Current interest in increased utilization of forest biomass for energy again is in direct response to volatile global petroleum markets and concerns over dependence on foreign supplies as national energy needs continue to grow (Kingsley 2007). There has also been a resurgence of national support for expanding the production of renewable energy as concerns over the impact of greenhouse gas emissions from burning fossil fuel intensifies (Cloughesy 2006). In 2007, the country's renewable energy share was approximately 7% of the total consumption, of which biomass supplied 53% (Energy Information Administration 2009).

In Maine, the PUC adopted rules in 1999 for the State's Renewable Portfolio Standard (RPS) as a result of the State's 1997 electric-utility restructuring law. The rules require each competitive electricity provider operating in Maine to purchase and supply at least 30% of their total retail electric sales from renewable sources. In 2006, Maine enacted legislation (L.D. 2041) creating a renewable portfolio goal to increase new renewable-energy capacity 10% by 2017. The goal was later transformed to a mandatory standard in 2007.

In recent years, many of the biomass facilities constructed and commissioned in Maine in the 1980s have returned to service, resulting in a dramatic increase in woody biomass utilization. Currently there are approximately 11 independent commercial biomass facilities where electricity is the primary or sole product, and a large number of forest product manufacturing facilities also burn wood to cogenerate steam, heat, and electricity for internal use or sale to the grid (Innovative Natural Resources 2005, North

East State Foresters Association 2007). Although still in development, technologies for converting wood to biofuels such as cellulosic ethanol and a number of other bioproducts may create additional markets for biomass in the future (Benjamin *et al*. 2009).

The amount of biomass currently being consumed by bioenergy facilities throughout Maine is at the highest recorded level since the State began keeping records in 1985 (Figure P.1). In 2007, energy facilities throughout Maine used over 3.4 million green tonnes of biomass including 686,310 green tonnes imported from out of state[1] (Maine Forest Service 2008). Consequently, the annual harvest of biomass in Maine for commercial scale energy production is also at the highest historical level (Figure P.2). The most recent data from 2007 indicate that 3,195,698 green tonnes of biomass were harvested directly from Maine's forest, comprising 21% of the total annual harvest (Maine Forest Service 2008).

The feedstock material specifications for most industrial biomass facilities are generally broad because combustion is currently the predominant technology used to convert biomass into different forms of useful energy (i.e., hot air, hot water, steam and electricity) for commercial or industrial uses (Bain *et al*. 1998, North East State Foresters Association 2007). Additionally pre-conversion processing usually entails comminuting biomass material to a specified fuel size range. The benefit of these processes is that the biomass feedstock used for energy production can essentially be derived from any portion of any type of tree, regardless of size, quality, or species. However, because larger trees of higher quality have a greater financial value when utilized at their "highest and best use" as other forest products, the material typically relegated for biomass consists of

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[1] Forest energy wood imported from Connecticut, Massachusetts, New Hampshire, New York, Pennsylvania, Rhode Island, Vermont, and Eastern Canada.

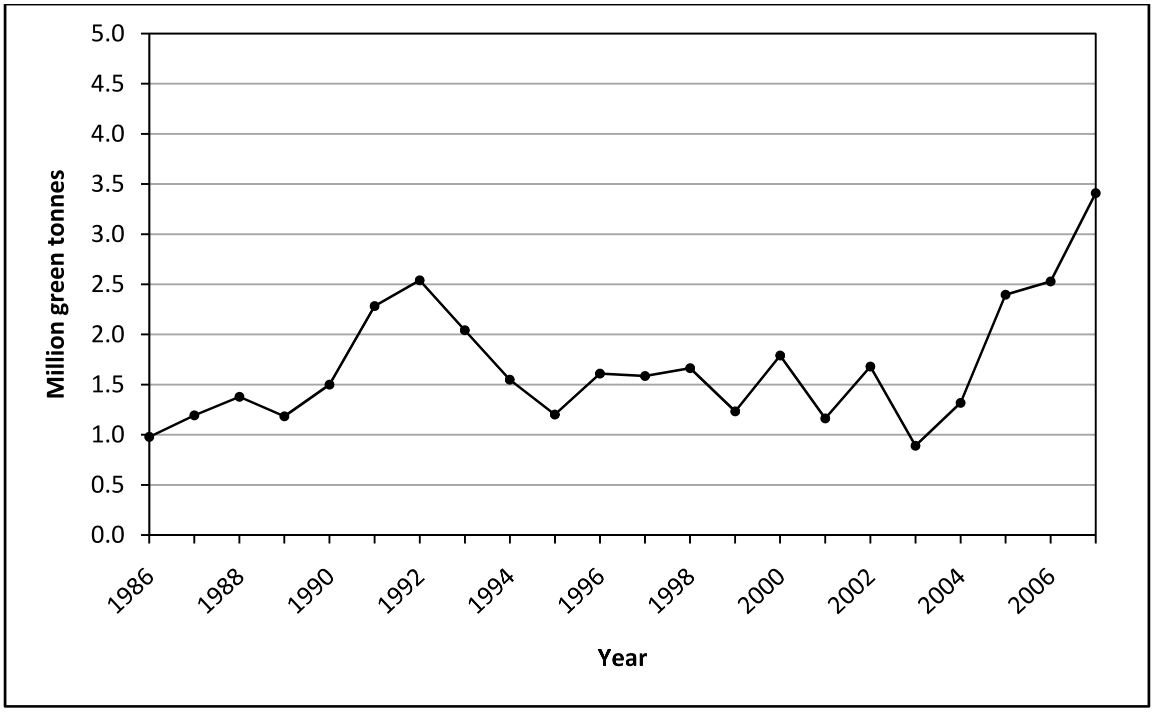

Figure P.1.Total annual mass (million green tonnes) of biomass chips processed by facilities in Maine from 1986 to 2007. Biomass chips are produced in the woods by chipping the entire tree, including branches and tops, and typically used as energy fuel (Maine Forest Service 1990 - 2008, including unpublished data).

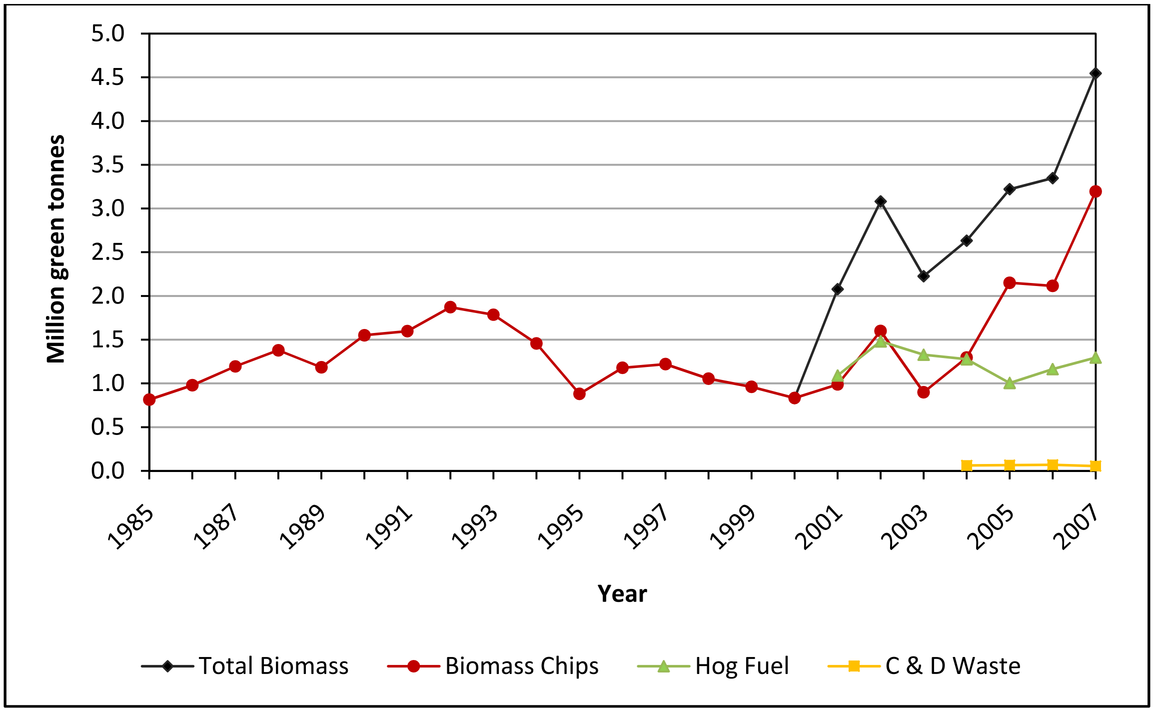

Figure P.2. Breakdown of the annual mass (million green tonnes) of woody biomass harvested and procured in Maine by source from 1985 to 2007. Biomass chips are produced in the woods by chipping the entire tree, including branches and tops, and typically used as energy fuel. Hog fuel is any woody residue produced from mills, such as sawdust, bark or shavings, and used as energy fuel. Construction and demolition waste (C & D Waste) is ground up wooden debris left over from construction and demolition that is burned by wood to energy (Maine Forest Service 1990 - 2008, including unpublished data).

unusable portions of trees, or poor quality, small size trees as well as undesirable species (Damery *et al*. 2009, Benjamin *et al*. in review). Because the term biomass can refer to the total mass of roots, stems, branches, bark and leaves of all tree and shrub species in the forest as well as the wood product harvested specifically for the purposes of producing energy (Helms 1998), the term *energy wood* will be used when referring to the product, and biomass will be used for referring to the broader forest resource (Benjamin *et al*. in review).

The growing energy wood markets in Maine may offer many opportunities and challenges. From a forest management perspective, the availability of these low-value energy wood markets can have a substantial impact on the intensity of silvicultural treatments such as rehabilitation, which typically yields high volumes of material that would otherwise have no commercial value (Andersson *et al*. 2002, Manley and Richardson 1995). Markets for this material may provide an opportunity to contribute to wood demands of the bioenergy market and to help defer the costs of forest rehabilitation efforts aimed at improving the composition, growth, and value of future stands. From an operations perspective, energy wood harvesting poses several challenges. Harvesting and delivering low-value energy wood is a relatively expensive process. Maintaining operational productivity is a challenge because of the low value and volume per piece, and because harvesting systems are primarily designed for handling large-diameter trees.

Overview of Chapters and Principal Findings

This research applies a case study approach to assessing silvicultural and operational aspects of whole-tree biomass harvesting in Maine. Chapters 1 through 3 examine three different facets of a biomass harvest conducted in a northern hardwood stand in central Maine. All three studies were overlaid on the same study block replicates. Chapter 4 uses a case study approach to examine variation in harvesting operations using theories of statistical process control (SPC).

Chapter 1, “Effectiveness of Pre-harvest Glyphosate Injection Treatment on Controlling Root and Stump Sprouting of American beech Following Energy Wood Harvesting,” evaluates the silvicultural potential of using energy wood harvesting in conjunction with vegetation management to rehabilitate unproductive northern hardwood stands overtaken by dense thickets of American beech (*Fagus grandifolia* Ehrh.) and other undesirable species. Research has shown that harvesting alone will only exacerbate this problem (Jones and Raynal 1986, Jones and Raynal 1988, Nyland *et al*. 2006b) and that successful rehabilitation strategies require some sort of understory control using herbicides (Kelty and Nyland 1981, Ostrofsky and McCormack 1986). Although this research was not appraised from a financial standpoint, energy wood markets may render an opportunity to help afford these rehabilitation treatments by providing a market for the low-value harvested material. This study evaluated the efficacy of pre-harvest glyphosate injection of beech and striped maple trees using hypo-hatchets in controlling stump sprouting and root suckering following intensive energy wood harvesting. The purpose of the study was to report the impact of the energy wood harvest and early injection treatment results from the first growing season following treatment. Eventually an additional post-harvest foliar application aimed at controlling undesirable regeneration will be incorporated as part of this research as well.

The results of the study indicated that harvesting removed most of the understory beech and striped maple trees from the stands. Pre-harvest vegetation management using the glyphosate treatment successfully controlled post-harvest beech reproduction as the density of stems on plots treated with the herbicide injection was lower than controls one year after harvest. The herbicide treatment generally proved ineffective at controlling striped maple one year after harvest.

Chapter 2, “Productivity and Site Impacts of a Tracked Feller-Buncher in an Integrated Energy Wood Harvest at Two Trail Spacings,” focused on the challenge of maintaining operational productivity while harvesting energy wood. Specifically, the study evaluated the effects of modified trail spacing on the productivity of a typical feller-buncher while harvesting small diameter stands. In order to remain productive when harvesting energy wood, larger volumes of material must be handled to compensate for the small piece size. The study proposed using narrower trail spacings as a means of reducing travel and bunching time for the feller-buncher. Time and motion studies were conducted on a single machine with the same operator while harvesting using one of two trail spacings. Because reducing trail spacing results in higher levels of trail occupancy on a site, trail density was also evaluated. The operation was considered to be an integrated energy wood harvest as some pulp material was sorted at the landing.

The results did not indicate any substantial increases in productivity between the two trail spacings. This result was due to a tradeoff between efficient bunching and the number of bunches produced. In other words, extra time saved on bunching was offset by having to make more bunches, and vice versa. Results of the trail area study confirmed that narrower trail spacing resulted in trail occupancy levels that could negatively influence long term forest management.

Chapter 3, “An Assessment of Residual Stand Damage Following Whole-Tree Biomass Harvesting at Two Trail Spacings in Central Maine,” evaluated the damage to residual trees resulting from the energy wood harvest described in Chapter 2. Because energy wood harvesting typically is integrated with intermediate silvicultural treatments where a portion of the stand remains after harvesting (Manley and Richardson 1995), it is important to evaluate the residual impacts of the harvest, particularly when using modified methods. A complete inventory and evaluation of residual trees was conducted shortly after harvesting and skidding operations were completed. Assessment of damage was conducted using a methodology adapted from Ostrofsky *et al*. (1986) that considered wound size, location, and severity.

Results did not indicate a significant difference in the amount or pattern of residual damage caused by the harvest operation at either trail spacing. Patterns of residual damage were expected to be similar since the same mechanical system and operators were used at both spacings; however, the frequency of damage was expected to be greater at the narrower trail spacing because of the increased trail density. The lack of a significant difference between the harvest treatments was not easily explained by the variables measured and was further limited by the small sample size. Damage levels were disconcertingly high at both trail spacings; however, they were comparable to results from other published studies of mechanized whole-tree harvest operations in hardwood stands.

Chapter 4, “An Approach for the Application of Statistical Process Control Techniques for Process Improvement of Forest Operations,” presents an approach to understanding the inherent variability of forest operations. While attempting to evaluate the productivity of the harvest in Chapter 2 it became apparent that traditional case study approaches to forest operations research inadequately identify how modified harvesting practices affect an operation’s productivity over the myriad of conditions encountered over time. Questions were raised about how the size of the material being harvested influenced the machine’s productivity, and what the feller-buncher’s usual productivity was. Answering these questions required an approach to studying the harvesting system that went beyond the limits of the in-field case study approach.

A methodology was developed to understand the variation of harvesting systems as a means to improve productivity over time by applying the principles of SPC. A search of the forest operations literature in the United Stated and Canada did not produce any studies that had developed a definitive approach to applying SPC in this manner. As a result, the statistical theory in this chapter is described in some detail. A methodology was developed for applying SPC to harvest operations using actual harvesting data collected on whole-tree system machines operated in Maine. Overall, the approach to understanding harvesting operations using SPC showed great potential if key challenges can be addressed.

Chapter 1:

EFFECTIVNESS OF PRE-HARVEST GLYPHOSATE INJECTION TREATMENT ON CONTROLLING ROOT AND STUMP SPROUTING OF AMERICAN BEECH FOLLOWING ENERGY WOOD HARVESTING

1.1 ABSTRACT

A combined study of vegetation management with energy wood harvesting was conducted as a potential treatment solution for rehabilitating northern hardwood stands plagued by dense advance reproduction of American beech and other unwanted tree species. Regeneration of beech and striped maple treated with pre-harvest herbicide injection were compared to untreated controls following energy wood harvesting at two trail spacings using a complete factorial study design. Harvesting treatments were comprised of a conventional mechanized whole-tree system using trail spacings of either 36.6 m or 12.2 m. Pre-harvest injection treatment consisted of injecting all beech and striped maples trees > 7.6 cm DBH with full-strength glyphosate (Accord Concentrate ®) using TSI hypo-hatchets at approximately one hack per 2.5 cm of DBH.

Harvesting did not result in significant differences ($\alpha = 0.05$) in residual stand structure between the two trail spacing, but did reduce beech and striped maple basal area from 83 to 97%. Pre-harvest vegetation management using the glyphosate hypo-hatchet treatment successfully controlled post-harvest beech reproduction as the density of stems on plots treated with the herbicide injection was 70 to 80% lower than controls one year after the harvest ($F = 16.92$, $p = 0.0012$). Herbicide treatment proved ineffective at controlling striped maple one year after harvest.

1.2 INTRODUCTION

From a forest management perspective, the availability of low-value energy wood markets can have a substantial impact on the intensity of silvicultural treatments. For example, rehabilitation treatments which yield high volumes of material that typically have no commercial value may be implemented (Andersson *et al*. 2002, Manley and Richardson 1995). Markets for this material may provide an opportunity to both contribute to the wood demands for the bioenergy market and help to defer the costs of forest rehabilitation efforts aimed at improving the composition, growth, and value of future stands.

In particular, energy wood markets in this regard may offer a considerable opportunity to help rehabilitate the extensive and problematic condition in northern hardwood stands across Maine where understory composition is dominated by dense thickets of American beech (*Fagus grandifolia* Ehrh.), and other shade tolerant competitors such as striped maple (*Acer pensylvanicum* L.) (Nyland *et al*. 2006a). In many cases, this condition arose as a result of previous high-grade harvesting practices that preferentially selected the more valuable and higher-quality maple and birch trees while leaving less valuable beech (Houston 1975, Seymour 1995). Harvest disturbances that damaged the superficial root system of residual beech trees triggered prolific root suckering, allowing the species to regenerate, along with stump sprouts and seedlings, at great densities (Jones and Raynal 1986, Jones and Raynal 1988, Jones *et al*. 1989, Houston 2001). Spread of the beech bark disease complex, now prevalent throughout the aftermath forests of Maine, also may have contributed to the proliferation of beech by killing mature overstory trees and prompting salvage harvesting operations (Shigo 1972, Houston 1975, Mielke *et al*. 1986, Ostrofsky and McCormack 1986); however, evidence supporting this hypothesis is lacking (Nyland *et al*. 2006b). Today, these unproductive stands, characterized by highly defective beech thickets of mostly vegetative origin, grow slowly and competitively exclude regeneration of more desirable hardwood species (Houston 2001, Farrar and Ostrofsky 2006, Nyland *et al*. 2006a).

Harvesting alone, at any intensity in stands with high densities of understory beech, generally promotes further beech development; exacerbating the problem and often leading to regeneration failures (Kelty and Nyland 1981, Houston 2001, Nyland *et al*. 2006a, Nyland *et al*. 2006b). Successful rehabilitation strategies require integrated understory vegetative control using herbicides (Kelty and Nyland 1981, Ostrofsky and McCormack 1986). A number of studies have found that ground-applied herbicide treatment prior to, or in combination with, harvesting helps to reduce beech sprouting and encourages the growth of other more desirable hardwood species (Kelty and Nyland 1981, Ostrofsky and McCormack 1986, Kochenderfer *et al*. 2004, Kochenderfer *et al*. 2006). The current markets for energy wood may provide a feasible means for landowners to rehabilitate unproductive beech dominated stands using an integrated system of energy wood harvesting and vegetation management.

The objectives of this study were to 1) evaluate the efficacy of pre-harvest glyphosate injection in controlling post-harvest suckering and sprouting of American beech stems, and 2) identify the effect of energy wood harvesting on the undesirable beech and striped maple component of a degenerated northern-hardwood stand including all stems ≥ 2.54 cm DBH for energy wood using a conventional mechanized whole-tree harvest.

1.3 METHODS

1.3.1 Study Area

The study area consisted of a mid-site northern hardwood stand located near Springy Brook Mountain in Township 32, Hancock County Maine on lands managed by Huber Resources Corporation. The site was comprised of a sugar maple (*Acer saccharum* Marsh.), American beech, and yellow birch (*Betula alleghaniensis* Britt.) overstory, but had regenerated primarily to a beech dominated mid-story and understory with a high component of striped maple. The beech component of the stand included some larger and older residual trees left during previous harvesting but primarily consisted of a dense sapling and pole component that occupied much of the area. Other species occurring in varying amounts throughout the study area included white ash (*Fraxinus americana* L.), red spruce (*Picea rubens* Sarg.), eastern white pine (*Pinus strobus* L.), hophornbeam (*Ostrya virginiana* (Mill.) K. Koch), eastern hemlock (*Tsuga canadensis* (L.) Carr.), and northern red oak (*Quercus rubra* L.). Beech trees in all size classes were largely infected with beech bark disease, greatly reducing their economic value. While the complete land use history is not accurately known, it is likely that the area was last harvested ca. 1940 – 1950s when it was selectively high-graded for high-quality hardwood logs (Shina 2008, personal comm.).

Three replicate study blocks, each 1.2 ha (73.2 m x 165.0 m) in size, were established within the study area (Figure 1.1). Stand characteristics for each block are summarized in Table 1.1. Block 3 had a higher initial density of trees ≥ 2.5 cm DBH than blocks 1, and 2. Average basal area was similar among all three blocks. Mean DBH was 8.5 cm for block 1, 12.0 cm for block 2, and 7.9 cm for block 3. Trees less than 10 cm

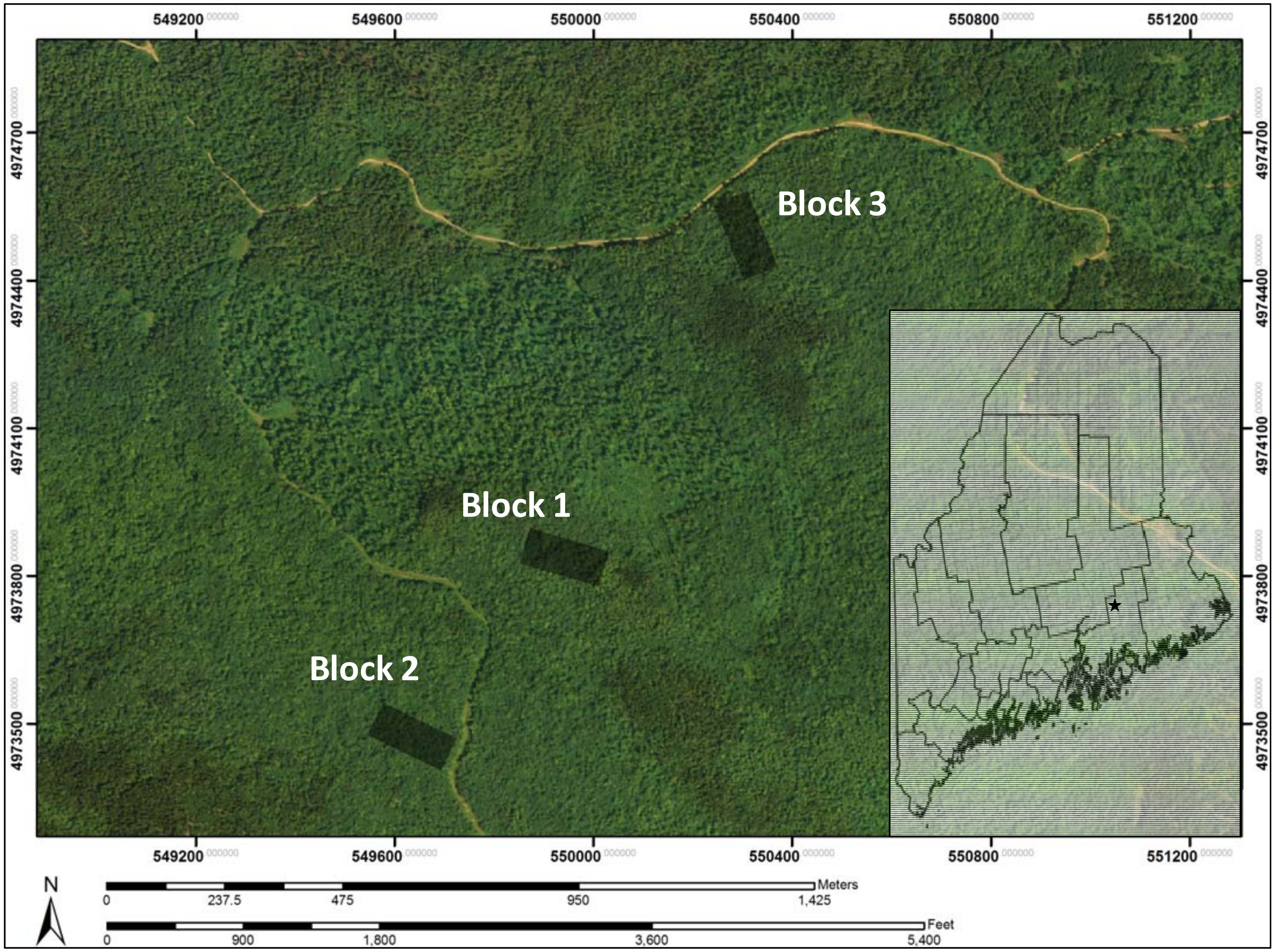

Figure 1.1. Location of the three study block replicates within the study area, T32, Hancock County, Maine. Imagery captured during the 2006 growing season, prior to harvesting.

Table 1.1. Average number of stems and basal area by size class and species for each study block prior to treatment.

	Block 1		Block 2		Block 3	
DBH size class (cm)	Number of stems (no./ha)	Basal area (m^2/ha)	Number of stems (no./ha)	Basal area (m^2/ha)	Number of stems (no./ha)	Basal area (m^2/ha)
< 2.5*						
Beech	7,551		5,111		9,116	
Striped maple	3,775		8,195		3,821	
Sugar maple	7,275		15,792		92	
Yellow birch	3,177		1,243		230	
Other**	553		1,658		1,704	
2.5 – 9.9						
Beech	958	2.5	677	1.6	1,698	3.0
Striped maple	406	0.6	42	0.0	479	1.2
Sugar maple	52	0.1	188	0.4	0	0.0
Yellow birch	146	0.2	21	0.0	21	0.0
Other	42	0.1	10	0.0	94	0.2
10.0 – 19.9						
Beech	250	4.4	302	5.6	198	2.4
Striped maple	10	0.1	0	0.0	73	0.9
Sugar maple	0	0.0	52	0.9	10	0.1
Yellow birch	0	0.0	0	0.0	31	0.4
Other	10	0.3	0	0.0	0	0.0
20.0 – 29.9						
Beech	73	3.3	156	7.6	146	7.5
Striped maple	0	0.0	0	0.0	0	0.0
Sugar maple	10	0.4	21	0.8	31	1.5
Yellow birch	0	0.0	0	0.0	42	1.6
Other	10	0.4	0	0.0	0	0.0
≥ 30.0						
Beech	52	4.7	73	9.8	63	5.2
Striped maple	0	0.0	0	0.0	0	0.0
Sugar maple	21	2.2	42	5.9	0	0.0
Yellow birch	0	0.0	0	0.0	31	3.2
Other	21	3.0	0	0.0	0	0.0
Total beech	8,884	14.9	6,319	24.6	11,221	18.1
Total striped maple	4,191	0.7	8,237	0.0	4,373	2.1
Total sugar maple	7,358	2.7	16,095	8.0	133	1.6
Total Yellow birch	3,323	0.2	1,264	0.0	355	5.2
Total others	636	3.8	1,668	0.0	1,798	0.2
All species	24,391	22.3	33,583	32.6	17,881	27.2

* Includes all stems ≥ 15.24 cm tall.

** Other species includes white ash (*Fraxinus americana* L.), red spruce (*Picea rubens* Sarg.), eastern white pine (*Pinus strobus* L.), hophornbeam (*Ostrya virginiana* (Mill.) K. Koch), eastern hemlock (*Tsuga canadensis* (L.) Carr.), and northern red oak (*Quercus rubra* L.).

DBH accounted for 98 percent of the total stems in blocks 1 and 2, and 97 percent in block 3. Beech comprised 65 – 76% of stems ≥ 2.5 cm and 67% or more of the total basal area on each of the three blocks. More than 90% of beech stems occurring in all three blocks were less than 10 cm DBH. Total beech basal area in trees 2.5 cm and larger for blocks 1, 2, and 3 averaged 14.9 $m^2 \cdot ha^{-1}$, 24.6 $m^2 \cdot ha^{-1}$, and 18.1 $m^2 \cdot ha^{-1}$, respectively. Beech comprised the highest proportion of stems > 2.5 cm DBH except on block 2 where beech densities were substantially lower and sugar maple predominated.

1.3.2 Design and Treatments

A factorial study design was employed, which combined energy wood harvesting with pre-harvest herbicide treatment. Each of the three study blocks were divided in half to give a total of six harvest treatment blocks (0.6 ha, 36.6 m x 164.0 m). Harvest treatments included mechanized whole-tree harvesting using a trail spacing of either 36.6 m or 12.2 m. The harvest prescription was the same for both spacings and consisted of an improvement cut aimed at removing the existing beech-striped maple understory, utilizing all stems ≥ 2.5 cm DBH, while leaving sugar maple and yellow birch. Harvest treatments were randomly assigned to each block pair so productivity and residual stem damage could be compared with trail spacing (see Coup 2009, Ch. 2 page 37, and Ch. 3 page 62).

Each harvest treatment block was divided into thirds (0.2 ha, 36.6 m x 55.0 m) to form a total of 18 equally sized vegetation management treatment plots (Figure 1.2). One of the three vegetation treatment plots in each harvest block was randomly assigned a pre-harvest herbicide injection treatment. The remaining two plots were assigned as

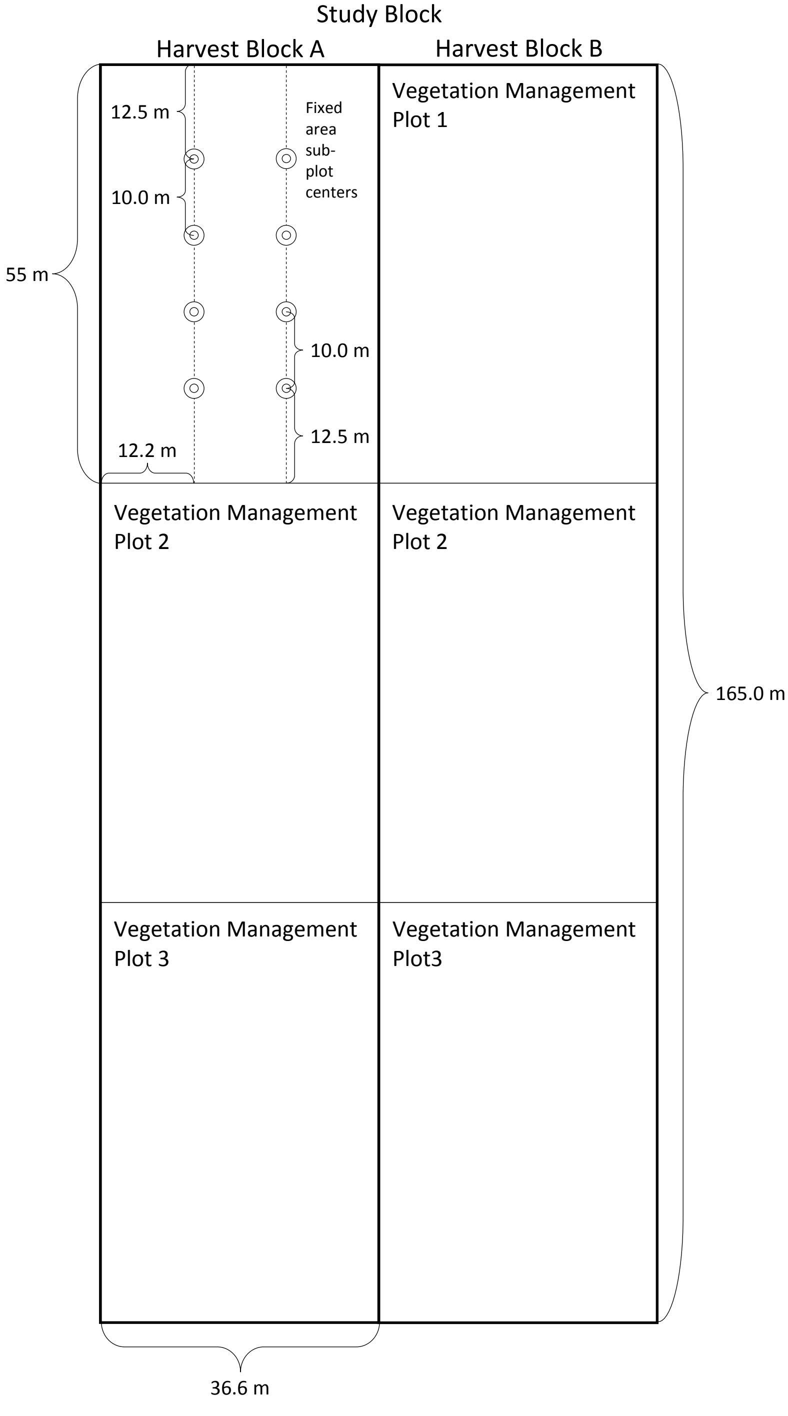

Figure 1.2. Layout and dimensions of study blocks, harvest treatment blocks, vegetation management treatment plots, and permanent fixed area sub-plot centers.

controls and did not receive herbicide treatment[2]. This resulted in a 2 x 2 factorial design with four plot-level treatments. The four combined harvesting and vegetation management treatments included: 1) Mechanized whole-tree harvest using an 36.6 m trail spacing, and pre-harvest herbicide injection, 3) Mechanized whole-tree harvest using an 36.6 m trail spacing, and no herbicide treatment, 2) Mechanized whole-tree harvest using a 12.2 m trail spacing, and pre-harvest herbicide injection, and 4) Mechanized whole-tree harvest using a 12.2 m trail spacing, and no herbicide treatment.

The pre-harvest injection treatment consisted of injecting all beech and striped maple trees > 7.6 cm DBH with full-strength glyphosate (N-(phosphonomethyl) glycine, Accord Concentrate ®) using TSI hypo-hatchets at approximately one hack per 2.5 cm of DBH, administered at waist height around the circumference of the tree. The actual volume of herbicide used was not measured. Stems below 7.6 cm DBH were difficult to inject due to their limberness; however, some were successfully treated by injecting at the base of the tree. The injection treatment was carried out in mid July 2007, 23 – 38 days prior to harvesting. Herbicide treatment efficacy was evaluated by comparing post-harvest stem counts and percentage of ground coverage by species in treated plots versus control plots in each harvest treatment one year after harvesting.

Initial inventories were carried out on each 0.2 ha vegetation management treatment plot to provide biomass estimates for the harvesting study and to monitor treatment effects on subsequent regeneration. Sampling of standing trees ≥ 2.54 cm DBH

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[2] Ultimately an additional post-harvest vegetation management treatment will be randomly assigned to one of the two control blocks in each harvest block, providing a complete randomized 2x3 factorial study design with six treatments and three replications. The post-harvest treatment will involve an understory foliar application of glyphosate (Accord concentrate) and EnTree 5735 tallow amine surfactant with a post-treatment evaluation conducted the following year.

was conducted on nine permanent, fixed area circular sub-plots, each 0.002 ha in size (8% sampling intensity). Sub-plot centers were systematically located within each vegetation treatment plot (Figure 1.2). Species and DBH were recorded for each tree included in the sample. Residual standing biomass ≥ 2.54 cm DBH was re-evaluated directly following harvesting in summer of 2007 using a complete inventory of all standing trees (see Coup 2009, Ch. 3 page 62). Regeneration, including all stems ≥ 2.54 cm tall and < 2.54 cm DBH, was monitored on 0.00045 ha fixed area circular plots nested within each overstory plot (1.8% sampling intensity). A count of the number of stems and an ocular estimate of ground cover percentage were recorded by species for each plot. Stump sprouts were recorded as individual stems; however, the vegetative origin of regeneration (i.e., stump sprout, root sucker, or seedling) was not identified for any species. Initial regeneration measurements only included stems ≥ 15.24 cm tall and < 2.54 cm DBH, and did not include percent cover estimates. Post-harvest evaluation of regeneration plots was conducted in early July 2008, approximately 11 months after harvesting.

Differences in the residual composition between the two harvest treatments among the three study blocks were evaluated using one-way analysis of variance (ANOVA) in R 2.5.1 (R Core Development Team 2007). Dependent variables included mean DBH, residual basal area, and residual stem density. Levene’s test was used to assess group constant variance. The Shapiro-Wilk’s W-statistic was used to test the null hypothesis that variables came from normally distributed populations. These hypotheses were not rejected for the above mentioned dependent variables, and transformations were not employed.

Treatment effects among the four vegetation management and harvest treatment combinations were evaluated using two-way ANOVA. Akaike's information criterion (AIC) was used to find the model that best fit each dependent variable. Four competing models were considered and included a log transformation of the response variable with blocking included as a random effect, an untransformed response variable with blocking included as a random effect, an untransformed response variable with blocking included as a fixed effect, and an untransformed response variable with the blocking effect not included. The model that returned the lowest AIC value was used. Regeneration densities for each species were analyzed using the log transformed model with blocking included as a random effect variable. Percent cover estimates were analyzed using the untransformed model that did not include the block effect. Dependent variables of the two-way ANOVA included regeneration stem counts and percent cover for beech and striped maple regeneration. The extent of sugar maple and yellow birch regenerating one year after treatment was not sufficient to permit statistical inferences on treatment effects. All statistical analyses were performed using a significance level of $\alpha = 0.05$.

1.4 RESULTS

1.4.1 Residual Stand Characteristics

Residual basal area and stem density between the two harvest treatments was similar; however, mean DBH was not (Figure 1.3 and Figure 1.4). The aggregate of harvest blocks treated using the 36.6 m trail spacing (blocks 1a, 2a, and 3b) had no difference in pre-harvest and post-harvest mean DBH. However, harvesting on blocks treated with the narrow trail spacing of 12.2 m (blocks 1b, 2b, and 3a) removed a greater

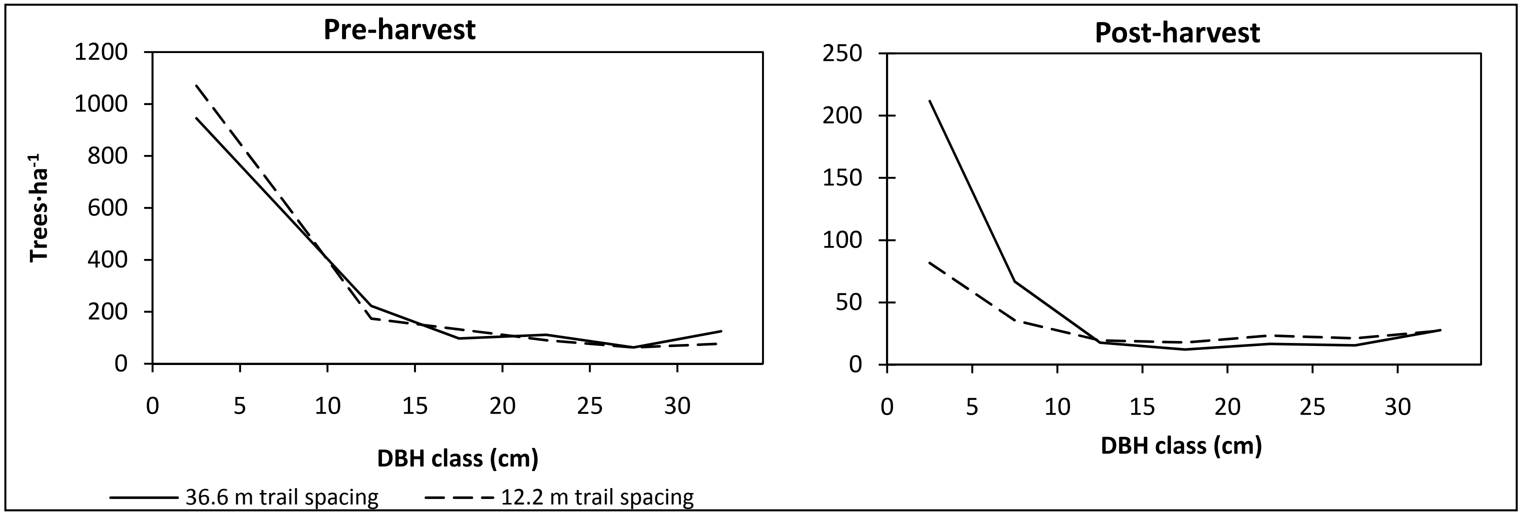

Figure 1.3. Comparison of pre-harvest and post-harvest stem diameter distributions by treatment.

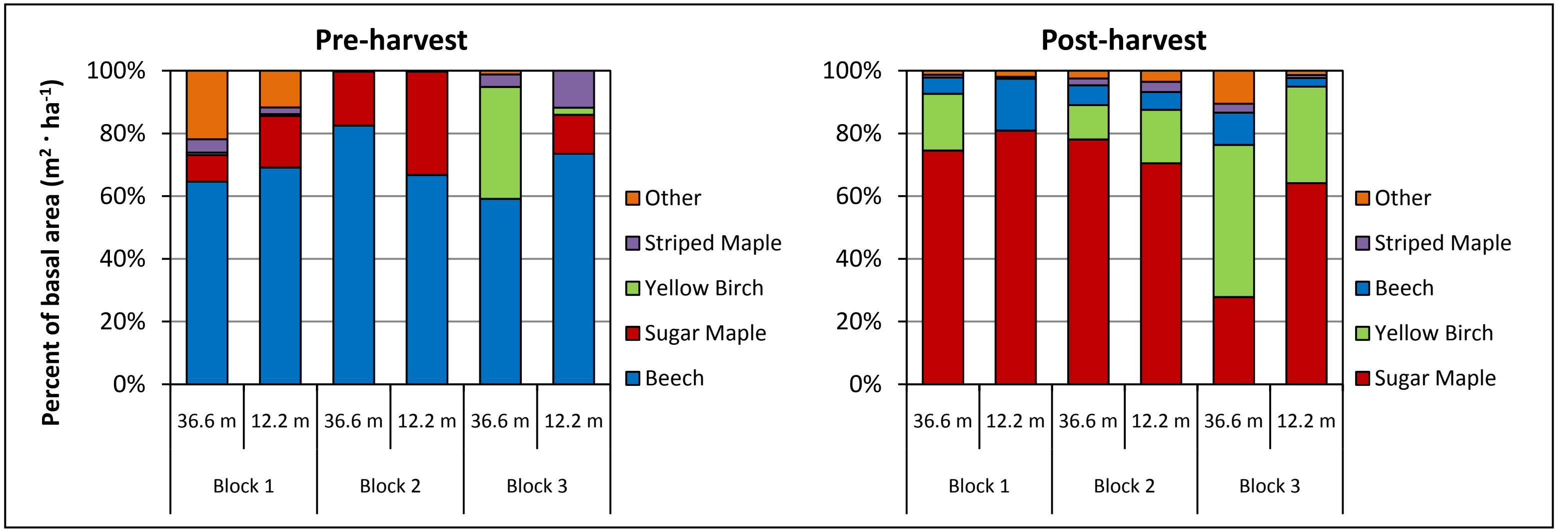

Figure 1.4. Comparison of pre-harvest and post-harvest species composition by study block and treatment.

number of trees from the smaller diameter classes, which resulted in a significantly (F = 16.19, p = 0.0158) higher average DBH across the three replicates compared to the mean residual DBH at the wider trail spacing. Residual basal area did not differ significantly between harvest treatments (F = 0.17, p = 0.7020), but ranged from 2.9 $m^2 \cdot ha^{-1}$ on block 1 using the 36.6 m trail spacing to 7.6 $m^2 \cdot ha^{-1}$ on block 2 using the 12.2 m trail spacing, representing 74 to 87% decreases from pre-harvest basal area estimates. Decreases in overall stem density ($trees \cdot ha^{-1}$) were variable across the six blocks, ranging from 78 – 92% on blocks treated with the wider trail spacing and 83 – 95% on blocks treated with the narrower trail spacing; however, differences in residual stem density by treatment were not significant (F = 1.31, p = 0.3160).

On average, harvesting resulted in a residual beech basal area of only 0.4 $m^2 \cdot ha^{-1}$ at the 36.6 m spacing and 0.6 $m^2 \cdot ha^{-1}$ at the 12.2 m spacing, representing 98 and 97% reductions from pre-harvest levels (Table 1.2). Harvesting also resulted in an average reduction of 83 and 91% in striped maple basal area for the 36.6 and 12.2 m trail spacings, respectively. Average DBH of residual trees was 4.9 cm for beech and 4.2 cm for striped maple at the 36.6 m spacing and 6.0 cm for beech and 5.9 cm for striped maple at the 12.2 m spacing. Harvesting at both trail spacings resulted in approximately 90% of the residual basal area being comprised of sugar maple and yellow birch (Figure 1.5). Mean DBH of residual sugar maple and yellow birch trees was 23.4 cm and 18.3 cm at the 36.6 m spacing and 23.5 cm and 19.7 cm at the 12.2 m spacing.

Table 1.2. Post-treatment stem density (no./ha) and basal area (BA, $m^2 \cdot ha^{-1}$) by size class, species, and harvest treatment for each study block.

	Block 1				Block 2				Block 3			
	36.6 m trail spacing		12.2 m trail spacing		36.6 m trail spacing		12.2 m trail spacing		36.6 m trail Spacing		12.2 m trail spacing	
DBH size class (cm)	(no./ha)	BA	(no./ha)	BA	(no./ha)	BA	(no./ha)	BA	(no./ha)	BA	(no./ha)	BA
< 2.5*												
Beech	32,782		28,362		16,299		12,708		41,530		15,102	
Striped maple	3,868		9,300		14,733		7,459		12,800		5,893	
Sugar maple	3,131		6,630		16,207		11,879		92		0	
Yellow birch	5,801		3,407		1,750		1,934		737		2,578	
Other**	921		13,076		12,615		2,763		553		1,197	
2.5 – 9.9												
Beech	68	0.1	65	0.1	105	0.2	85	0.1	80	0.1	305	0.4
Striped maple	27	0.0	37	0.0	60	0.1	15	0.0	15	0.0	83	0.1
Sugar maple	3	0.0	12	0.0	42	0.1	30	0.1	0	0.0	2	0.0
Yellow birch	13	0.0	3	0.0	17	0.0	2	0.0	0	0.0	0	0.0
Other	8	0.0	8	0.0	7	0.0	0	0.0	0	0.0	95	0.2
10.0 – 19.9												
Beech	2	0.0	18	0.3	12	0.2	3	0.0	0	0.0	10	0.2
Striped maple	0	0.0	0	0.0	7	0.1	0	0.0	2	0.0	7	0.1
Sugar maple	8	0.1	28	0.5	17	0.4	32	0.6	8	0.2	8	0.2
Yellow birch	5	0.1	0	0.0	7	0.1	3	0.1	5	0.1	0	0.0
Other	0	0.0	8	0.1	2	0.0	2	0.0	2	0.0	7	0.1

Table 1.2. (Continued)

	Block 1				Block 2				Block 3			
	36.6 m trail spacing		12.2 m trail spacing		36.6 m trail spacing		12.2 m trail spacing		36.6 m trail spacing		12.2 m trail spacing	
DBH size class (cm)	(no./ha)	BA	(no./ha)	BA	(no./ha)	BA	(no./ha)	BA	(no./ha)	BA	(no./ha)	BA
20.0 – 29.9												
Beech	0	0.0	5	0.2	2	0.1	5	0.2	0	0.0	2	0.1
Striped maple	0	0.0	0	0.0	0	0.0	2	0.1	0	0.0	0	0.0
Sugar maple	17	0.7	37	1.9	40	2.1	45	2.3	27	1.4	12	0.6
Yellow birch	2	0.1	0	0.0	2	0.1	3	0.1	10	0.5	18	0.9
Other	0	0.0	0	0.0	3	0.2	0	0.0	0	0.0	0	0.0
≥ 30.0												
Beech	0	0.0	2	0.6	0	0.0	0	0.0	0	0.0	0	0.0
Striped maple	0	0.0	0	0.0	0	0.0	2	0.1	0	0.0	0	0.0
Sugar maple	13	1.3	33	3.6	25	2.9	18	2.2	12	1.2	10	1.2
Yellow birch	2	0.4	0	0.0	5	0.6	5	1.0	7	0.7	25	2.5
Other	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	2	0.3
Total beech	32,852	0.2	28,452	1.2	16,417	0.4	12,801	0.4	41,610	0.1	15,418	0.7
Total striped maple	3,894	0.0	9,337	0.0	14,800	0.2	7,477	0.2	12,816	0.0	5,983	0.2
Total sugar maple	3,173	2.2	6,740	6.0	16,330	5.5	12,004	5.1	139	2.8	32	1.9
Total Yellow birch	5,823	0.5	3,410	0.0	1,780	0.8	1,947	1.2	758	1.3	2,622	3.4
Total others	929	0.0	13,093	0.2	12,627	0.2	2,764	0.0	554	0.0	1,300	0.5
All species	46,670	2.9	61,032	7.5	61,954	7.0	36,993	7.0	55,877	4.2	25,355	6.7

* Regeneration data taken 1 year after herbicide treatment and harvesting. Includes all stems ≥ 2.54 cm tall.

** Other species includes white ash (*Fraxinus americana* L.), red spruce (*Picea rubens* Sarg.), eastern white pine (*Pinus strobus* L.), hophornbeam (*Ostrya virginiana* (Mill.) K. Koch), eastern hemlock (*Tsuga canadensis* (L.) Carr.), and northern red oak (*Quercus rubra* L.).

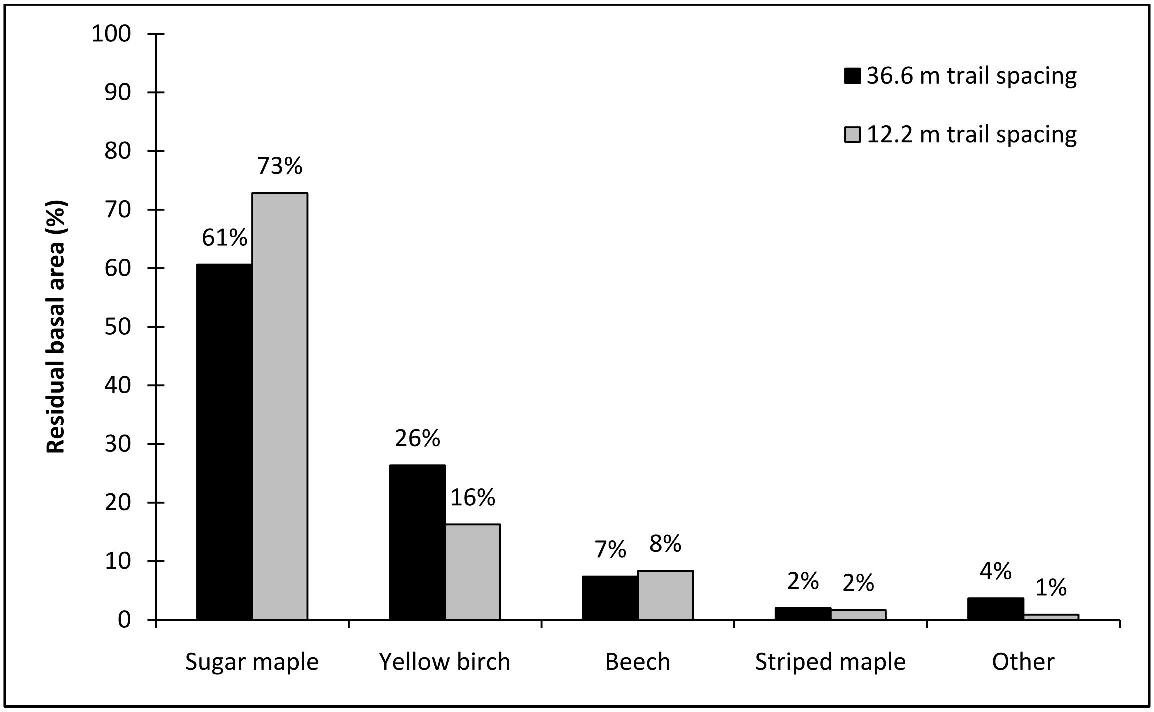

Figure 1.5. Mean percent of residual basal area for trees ≥ 2.54 cm DBH by species and harvest treatment.

1.4.2 Herbicide Efficacy

Regeneration abundance from the first growing season following harvesting is summarized by species and treatment in Table 1.3. Results of the ANOVA indicated that mean density (stems·ha^{-1}) of beech on plots treated with the pre-harvest glyphosate injection were different than control plots ($F = 16.92$, $p = 0.0012$; Figure 1.6). Density differences between harvesting treatments were not significant ($F = 0.07$, $p = 0.7966$). Interaction between harvest treatments and vegetation treatments was not significant for beech or any of the other response variables ($p \geq 0.05$); therefore, only the results of the main effects are reported. Average density of beech regeneration on control plots at the 36.6 m trail spacing was found to be nearly three times the density (27,947 stems·ha^{-1}) of plots treated with the pre-harvest herbicide injection treatment (10,682 stems·ha^{-1}). At the 12.2 m spacing, average beech densities on control plots were over five times greater (37,616 stems·ha^{-1}) than treated plots (7,367 stems·ha^{-1}). Average density of striped maple on treated plots was not different ($F = 0.14$, $p = 0.7138$) than control plots. Density differences between harvesting treatments were also not significant for striped maple ($F = 0.67$, $p = 0.4297$).

Estimates of percent ground cover on treated plots were not different from controls for beech or striped maple ($F = 0.66$, $p = 0.4307$ and $F = 0.01$, $p = 0.9264$, respectively; Figure 1.7). The percentage of beech ground cover on blocks harvested using the 36.6 m trail spacing ranged from 5 to 12% on plots receiving the herbicide treatment and from 5 to 17% on control plots. At the 12.2 m trail spacing, percent cover for beech ranged from 6 to 13% on treated plots and from 4 to 29% on controls. Striped maple percent ground cover ranged from 1 to 8% on both treated and control plots at the

Table 1.3. Average stem count and percent cover for regeneration ≥ 2.54 cm tall and < 2.54 cm DBH one year after treatment by species and treatment.

	36.6 m trail spacing				12.2 m trail spacing			
	Pre-harvest Injection		Control		Pre-harvest injection		Control	
	Number of stems (no./ha)	Percent Cover (%)	Number of stems (no./ha)	Percent Cover (%)	Number of stems (no./ha)	Percent Cover (%)	Number of stems (no./ha)	Percent Cover (%)
Beech	8,288	8.5	27,947	8.6	7,367	8.9	37,616	14.0
Striped Maple	10,682	5.0	6,906	3.4	6,630	3.3	11,464	5.7
Sugar Maple	8,748	6.1	5,295	3.7	6,998	2.9	5,801	4.6
Yellow Birch	1,565	0.7	4,282	1.6	2,578	0.9	1,750	4.8
Other*	13,813	5.2	460	1.0	12,155	1.0	2,118	1.8
Total	43,095	25.5	44,891	18.3	35,728	17.0	58,749	30.8

* Other species includes white ash (*Fraxinus americana* L.), red spruce (*Picea rubens* Sarg.), eastern white pine (*Pinus strobus* L.), hophornbeam (*Ostrya virginiana* (Mill.) K. Koch), eastern hemlock (*Tsuga canadensis* (L.) Carr.), and northern red oak (*Quercus rubra* L.).

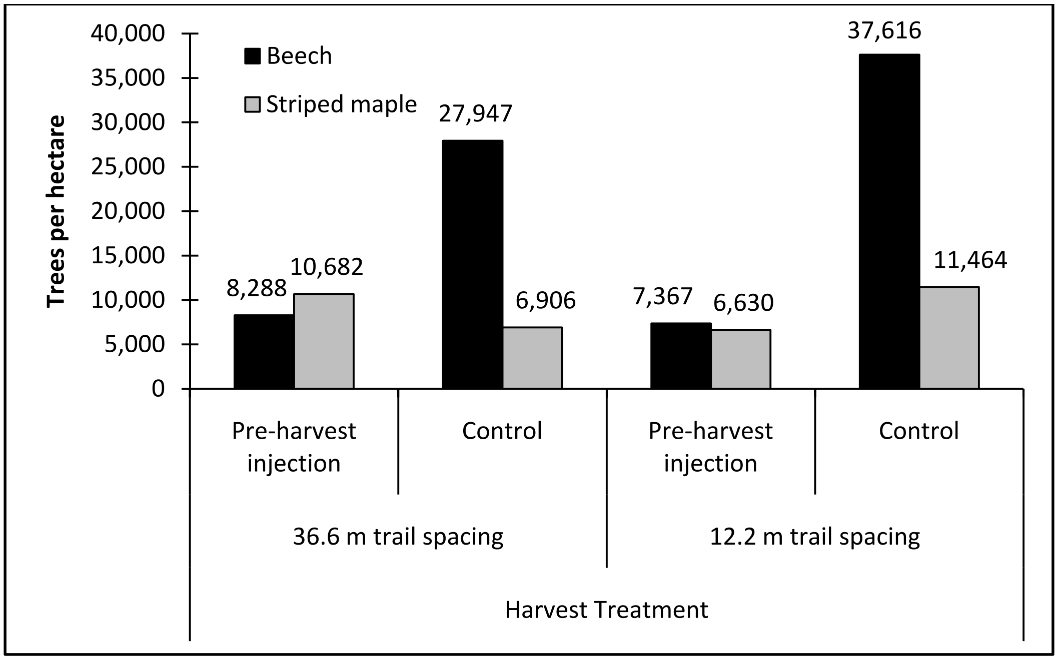

Figure 1.6. Stem count for American beech and striped maple regeneration (≥ 2.54 cm tall and < 2.54 cm DBH) one year after harvesting by harvest treatment and vegetation management treatment.

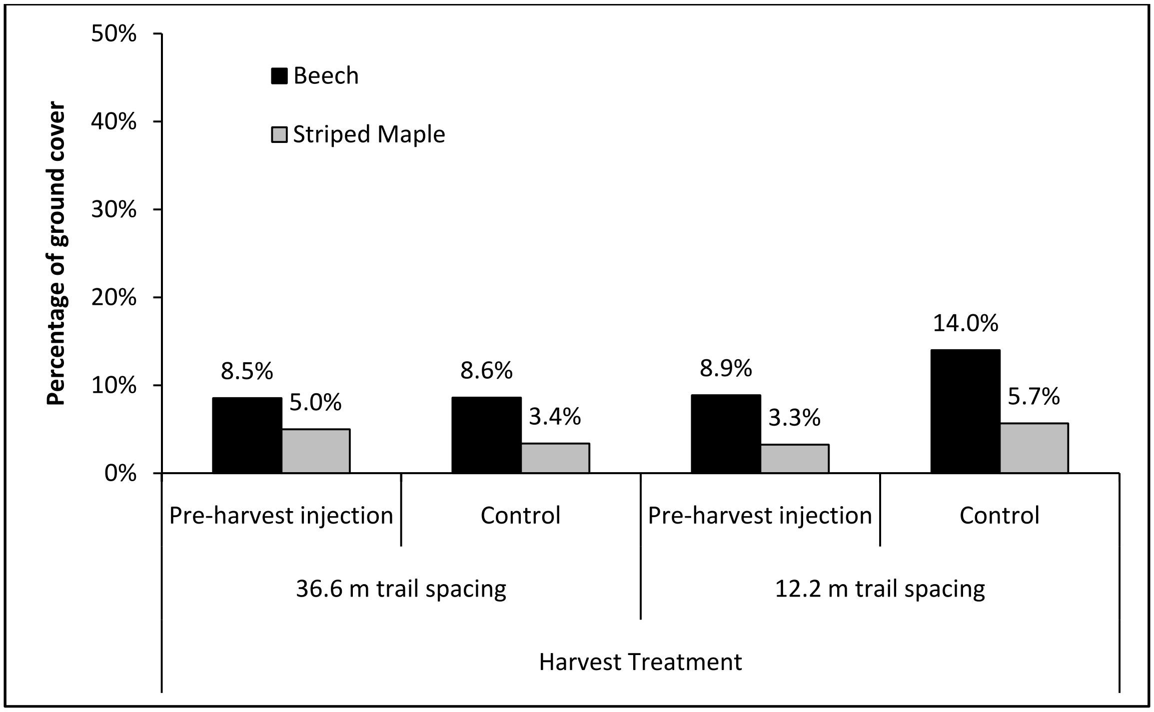

Figure 1.7. Percent of ground cover for American beech and striped maple regeneration (≥ 2.54 cm tall and < 2.54 cm DBH) one year after harvesting by harvest treatment and vegetation management treatment.

36.6 m trail spacing, and from 2 to 5% on treated plots and 1 to 13% on control plots at the 12.2 m trail spacing.

1.5 DISCUSSION AND CONCLUSIONS

Whole-tree energy wood harvesting was successful at removing most of the understory beech and striped maple stems from the stands. Substantial reductions in these species resulted in the post-harvest composition at both trail spacings being dominated by larger diameter sugar maple and yellow birch. Spacing of trails did not produce different residual stand structures. Pre-harvest glyphosate injection using hypo-hatchets was effective at reducing the number of post-harvest American beech stems (≥ 15.24 cm tall and < 2.54 cm DBH) within one year after harvesting. These results are consistent with those of other studies successfully using glyphosate injection or stump treatments to control beech (Kelty and Nyland 1981, Ostrofsky and McCormack 1986, Kochenderfer *et al*. 2004, Kochenderfer *et al*. 2006).

While striped maple density was lower than controls at the 12.2 m trail spacing, the average density was higher than controls on blocks treated using the 36.6 m trail spacing. These results likely reflect the inability of the injection treatment to control seed origin striped maple. While striped maple is able to reproduce vegetatively through basal sprouting and layering (Hibbs and Fischer 1979, Gabriel and Walters 1990), sexual reproduction is generally the more common strategy (Stalter *et al*. 1997). The herbicide treatment was more efficient at controlling beach because the species primarily reproduces vegetatively (Tubbs and Houston 1990), allowing the herbicide to translocate through the roots of treated stems to attached root systems (Kochenderfer *et al*. 2006).

Although difficult to derive from the data, the injection treatment likely was successful at controlling individual trees, but did little to control seed origin regeneration.

Percent ground cover may have been influenced by a number of unharvested beech and striped maple saplings just below 2.54 cm DBH that were included as part of the regeneration tally. These trees had little effect on density estimates but substantially influenced cover estimates.

Chapter 2:

PRODUCTIVITY AND SITE IMPACT OF A TRACKED FELLER-BUNCHER IN AN INTEGRATED ENERGY WOOD HARVEST AT TWO TRAIL SPACINGS

2.1 ABSTRACT

Feller-buncher productivity was evaluated for an integrated mechanical whole-tree harvest removing pulpwood and energy wood from natural hardwood stands dominated by small diameter, diseased beech (*Fagus grandifolia* Ehrh.) in central Maine. Two trail spacings (36.6 m and 12.2 m) were tested to determine if modified harvesting practices could improve the productivity of a tracked, swing-to-bunch feller-buncher. Time studies were conducted on the feller-buncher to assess the influence of narrower trail spacings on the productivity of the harvest operation. Trail area was also quantified for each of the harvest layouts.

Feller-buncher productivity did not differ ($p = 0.58$) between the two trail spacings. Mean productivity in green tonnes per hour was 74.7 using an 36.6 m spacing and 58.2 using a 12.2 m spacing. Time study elements did not differ between the two trail spacings ($p \geq 0.05$). Primary trails occupied approximately 13% of the harvested area at the 36.6 m spacing and 34% at the 12.2 m spacing. Based on the results of this study there was no advantage to selecting one trail spacing over the other.

2.2 INTRODUCTION

Growing interest in renewable energy has given rise to substantial markets utilizing woody forest biomass for large-scale bioenergy production in Maine. Currently a number of bioenergy facilities operate throughout the Northeast to produce energy by burning energy wood. These facilities exist either as independent operations or as cogeneration plants (Benjamin *et al*. 2009). In 2007, Maine facilities processed 5,590,324 green tonnes[3] of energy wood. The total amount of energy wood harvested directly from Maine's forests that year (3,195,698 green tonnes[4]) represented 21% of the total statewide harvest (15,032,357 green tonnes) (Maine Forest Service 2008). Ensuring an adequate supply of energy wood material to the growing Northeast bioenergy markets will require harvesting systems that have the ability to produce, handle, and process biomass material in ways that minimize handling, maintain quality, and minimize cost.

The whole-tree (WT) harvesting method where the entire aboveground portion of the tree including bole, branches, and needles or leaves is extracted to road-side, is currently the most common harvest method used in Maine (Benjamin 2009). While WT harvesting is generally carried out using mechanical systems that can be comprised of a variety of machines, the standard WT system is comprised of swing-to-bunch feller-bunchers with circular saw heads for felling and rubber-tired grapple skidders for primary transportation (Eckardt 2007). Because all material is brought to road-side at once and because both feller-bunchers and grapple skidders can generally handle a range of tree sizes simultaneously, whole-tree harvesting is a relatively easy and cost effective harvest method for energy wood utilization (Stokes *et al*. 1984, Andersson *et al*. 2002). Two approaches are possible in adapting current mechanized WT harvesting systems to energy

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[3] Value includes forest energy wood imported from Connecticut, Massachusetts, New Hampshire, New York, Pennsylvania, Rhode Island, Vermont, and Eastern Canada.

[4] Value includes forest energy wood exported to Connecticut, Illinois, Indiana, Michigan, New Hampshire, New York, Oregon, Pennsylvania, Tennessee, Vermont, Virginia, Washington, Eastern Canada, China, Germany, and Thailand.

wood utilization. The first requires the use of new technology, and the second consists of modifying the working methods of existing systems.

Several different pieces of equipment specifically designed for efficiently harvesting and transporting energy wood are commercially available and include specialized harvesting heads, slash compaction and bundling systems, and mobile chipping machines (Andersson *et al*. 2002, Turner 2005). These technologies require significant capital investment, and often these expenses have to be accrued in addition to conventional equipment mixes because their purpose built designs do not allow for efficient production of higher value products. In some cases, specialized equipment with a low level of integration with current harvesting systems may require using a two-pass system where round wood and energy wood are harvested in separate operations: a method that has not proven to be as cost effective as one-pass systems where round wood and energy wood are harvested simultaneously (Miller *et al*. 1987).

Because of its low value compared to other forest products, energy wood is currently being harvested in conjunction with higher value round wood products using conventional mechanical systems (Evans 2008, Damery *et al*. 2009). While mechanical WT harvesting systems are physically capable of harvesting and recovering woody biomass, they must also be cost effective. This requirement necessitates identifying, at least in the short-term, efficient means of incorporating energy wood utilization into conventional WT harvesting systems.

Harvesting with a standard WT system typically involves the feller-buncher harvesting trails for subsequent skidding in either a herringbone pattern or perpendicular-to-road pattern. Trail spacing typically requires that the feller-buncher track some distance off the primary skidding trail on secondary "ghost trails" to harvest the forested strips (Meek 1999). In conventional round wood harvests, primary felling-skidding trails are commonly spaced from 20 to 30 m apart (Shina 2009 personal comm.). However, as the spacing between trails increases, the feller-buncher is required to take on more of the primary transportation, carrying the wood farther distances from the stump to the bunching site, a task it was not designed to do efficiently (Greene *et al*. 1987, Johnson 2002). Inefficient feller-buncher use becomes even more problematic under an energy wood scenario where larger volumes of material must be handled to compensate for the low volume and value per piece.

Productivity of the feller-buncher is important because it typically sets the pace for the operation. One approach to maintaining feller-buncher productivity while harvesting energy wood may be to reduce trail spacings to a distance that would not require the feller-buncher to leave the trail while harvesting. This would reduce the time spent traveling to and from the bunching site. However, decreasing the distance between trails would result in an increase in the area impacted by harvesting and skidding trails.

The objectives of this study were to 1) compare the productivity of a conventional tracked, swing-to-bunch feller-buncher primarily harvesting energy wood using a trail spacing of either 12.2 m or 36.6 m, and 2) quantify and compare the extent of site impact in the form of trails caused by using these trail spacings.

2.3 METHODS

2.3.1 Study Site

The study area was located in Township 32, in Hancock County, Maine on lands managed by Huber Resources Corporation (Figure 2.1). The site was comprised of a sugar maple (*Acer saccharum* Marsh.) and yellow birch (*Betula alleghaniensis* Britt.) overstory but had regenerated primarily to a beech (*Fagus grandifolia* Ehrh.) dominated mid-story and understory with a high component of striped maple (*Acer pensylvanicum* L.). Other species occurring throughout the study area included white ash (*Fraxinus americana* L.), red spruce (*Picea rubens* Sarg.), hophornbeam (*Ostrya virginiana* (Mill.) K. Koch), and eastern hemlock (*Tsuga canadensis* (L.) Carr.). Beech trees in all size classes were largely infected with beech bark disease, greatly reducing their economic value. Given the high proportion of small-diameter and low quality beech trees, energy wood was expected to be a primary product from the harvest.

Three replicate study blocks, each 1.2 ha (73.2 m x 165.0 m) in size, were established in the study area. Blocks 1 and 2 were relatively flat with slopes ranging from 2 – 6%, while Block 3 had a northern aspect and a moderate slope of 18 – 21%. Practical perpendicular slope limits for most feller-bunchers are between 30 – 50%, with the upper limit including self-leveling machines, although slopes as low as 15% have been shown to affect the productivity of non-leveling machines (Gingras 1988, 1989). Each of the three study blocks were divided into two equally sized harvest blocks (0.6 ha, 36.6 m x 165.0 m) and randomly assigned one of two harvest layout treatments. Planned treatments included mechanized WT harvest using a trail spacing (measured from trail centerlines) of (*i*) 36.6 m, or (*ii*) 12.2 m. Trail spacings were established by using one

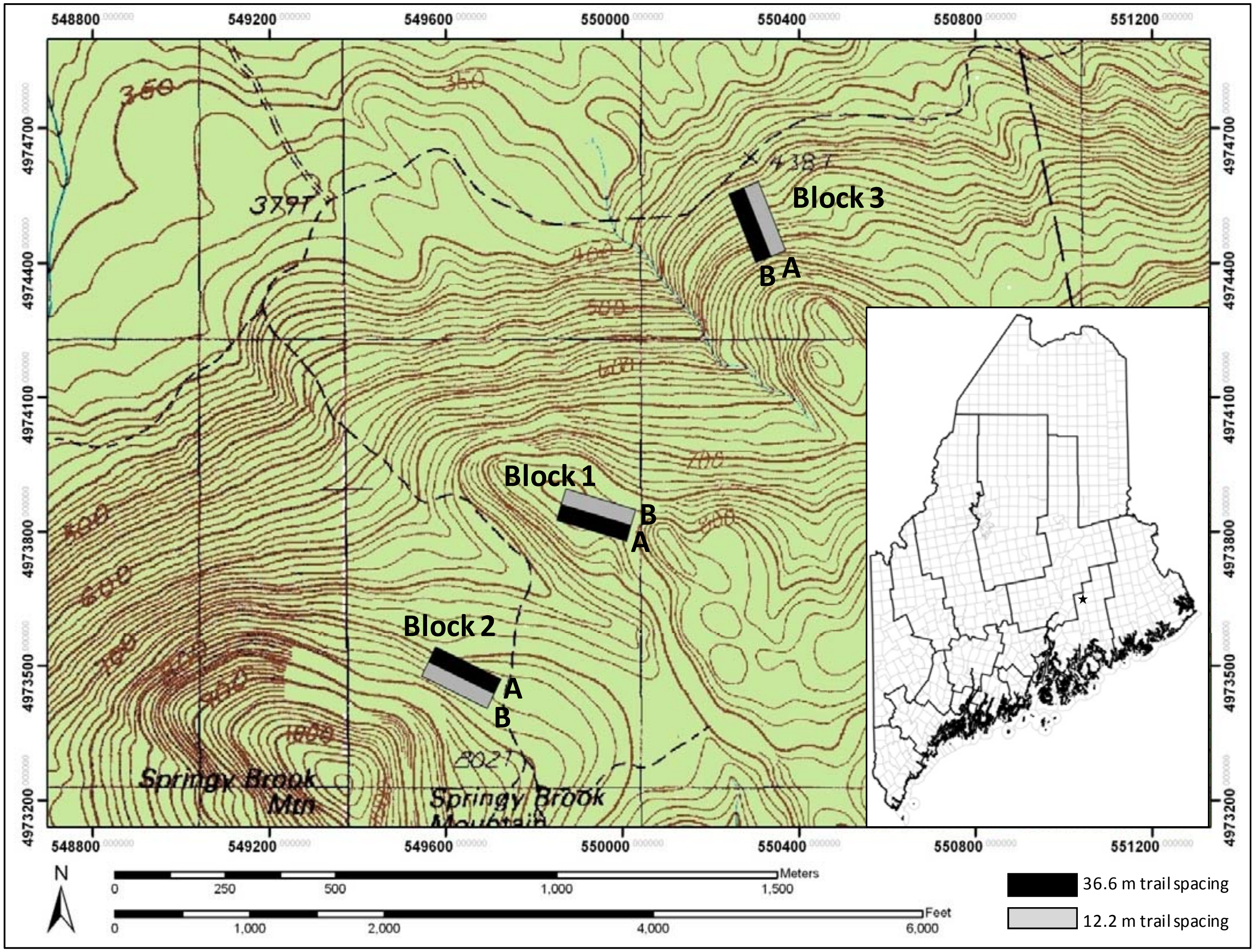


Figure 2.1. Study block locations in T32, Hancock County, Maine. Harvest blocks (A & B) represent one half of each study block. Black harvest blocks were treated with 36.6 m trail spacing and grey harvest blocks were treated with 12.2 m trail spacing.

trail in harvest blocks assigned a spacing of 36.6 m and three trails in harvest blocks assigned a spacing of 12.2 m (Figure 2.2).

Prior to the harvest an 8% cruise using 24 fixed area sample plots was conducted in each harvest block to determine the quantity and composition of standing biomass (Coup 2009, Ch. 1 page 14). All trees, including both live and standing dead ≥2.54 cm at DBH, within the plot were sampled. Species and DBH were recorded for each sampled tree. A complete tally of all standing residual trees was conducted following harvesting and skidding activities (Coup 2009, Ch. 3 page 62). Species and DBH were again recorded for all standing residual trees ≥ 2.54 cm at DBH. Total green tree weight estimates were calculated for both pre and post-harvest cruises using species specific DBH-weight relationship equations developed by Young *et al*. (1980).

Average stand conditions before and after harvesting are shown in Table 2.1 (see also Figure 1.3 and Figure 1.4). Because of the small size of the study blocks, pre-harvest variations in conditions between harvest block pairs were considered to be negligible. Therefore, variations in conditions among the three study block replicates affected each treatment equally, but increased the overall variation in the results.

2.3.2 Harvesting System and Operations

After the block boundaries were established and clearly marked, and stand information was obtained, each block was harvested. Harvest operations were conducted using a contractor hired by Huber Resources Corporation. Operations began in mid-August 2007 and were completed on all blocks before the end of the month. Conditions

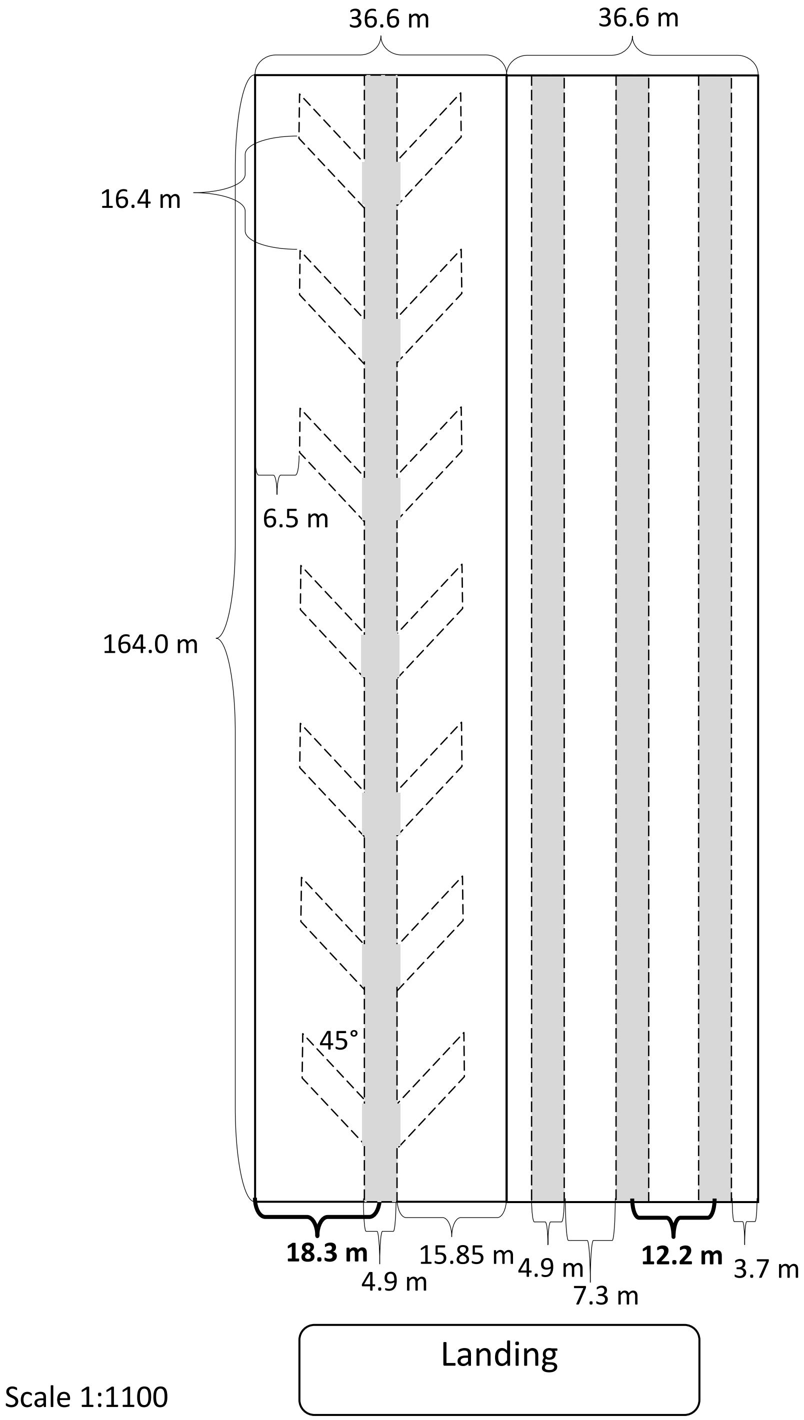


Figure 2.2. Theoretical layout of primary harvest/skid trails for 36.6 m spacing (left, 18.3 m represents one half of the 36.6 m trail spacing) and 12.2 m spacing (right). Theoretical layout of secondary spur trails for the 36.6 m spacing treatment was based on the maximum reach of the feller-buncher (8.2 m). The length of the spur trails was based on the median reach (½·(max - min)) of the feller buncher (6.5 m).

Table 2.1. Mean pre-harvest and residual DBH (cm), density (trees·ha^{-1}), basal area (m^{2}·ha^{-1}), and total green weight of biomass (tonnes·ha^{-1}) by harvest treatment and block (0.6 ha). Number of individuals sampled (*n,N*), and percent difference from pre-harvest conditions are also included.

Harvest treatment	Block	*n*	DBH	Density	BA	Green weight
			(Pre-harvest stand)*			
36.6 m trail spacing						
	1a	100	8.7	2083	23.1	230.7
	2a	81	12.6	1688	35.8	404.1
	3b	128	8.3	2667	28.2	289.6
	Avg.		9.9	2146	29.0	308.1
12.2 m trail spacing						
	1b	98	8.3	2042	21.8	215.6
	2b	71	11.3	1479	29.5	343.0
	3a	152	7.6	3167	26.6	267.5
	Avg.		9.1	2229	26.0	275.4
		N	DBH	Density	BA	Green weight
			(Residual stand)†			
36.6 m trail spacing						
	1a	101	10.2	168	2.9	29.9
	2a	211	11.4	352	7.4	75.3
	3b	351	7.9	586	6.8	68.4
	Avg.		9.8	369	5.7	57.9
	Diff. (%)		-0.5	-82.8	-80.4	-81.2
12.2 m trail spacing						
	1b	154	14.5	257	7.5	71.4
	2b	153	14.6	255	7.6	78.1
	3a	100	13.5	167	4.2	42.7
	Avg.		14.2	226	6.4	64.1
	Diff. (%)		56.7	-89.9	-75.2	-76.7

* Based on an 8% cruise of all trees ≥ 2.54 cm DBH using 24 fixed area sample plots in each harvest block.

† Based on a complete tally of all residual stems ≥ 2.54 cm DBH.

were very favorable for timber harvesting, with dry weather and firm ground occurring throughout the operations.

The harvest prescription for each block was an improvement cut to remove the existing beech and striped maple understory, utilizing all stems ≥2.54 cm DBH, while leaving the sugar maple and yellow birch, unless they were growing in the trail. The feller-buncher operator ultimately selected which trees were felled and collected. Target basal area retention levels for species or area were not specified for any of the blocks. Mechanical WT harvesting was conducted using a John Deere 853G tracked, swing-to-bunch feller-buncher equipped with an FS22 (55.9 cm) continuous-type disk-saw felling head. The machine had a fixed-level cab, a track width of approximately 3.2 m, and a maximum boom reach of approximately 8.2 m. Detailed harvest equipment specifications can be found in Appendix A. The feller-buncher was operated in all blocks by the same operator who had many years of experience with his equipment.

Trails were not marked prior to harvesting; however, the beginning location for the first trail in each harvest block was identified for the operator, and all block boundaries were clearly marked. In each harvest block the feller-buncher first harvested an access trail for itself and the grapple skidders. Trees harvested in the trail were piled alongside the corridor and later added to the main bunches. Upon reaching the end of the block the feller-buncher worked backward along the access corridor, harvesting the areas between access trails. Trees were accumulated and bunched in the main trail with the butts facing the landing. After completing one half of the study block with its assigned trail spacing treatment, the other half of the block was harvested with the other treatment.

Felled trees were taken to the landing using John Deere 648G-III rubber tire grapple skidders after harvesting operations were completed in each block.

2.3.3 Data Collection and Analysis

A detailed time study was conducted to analyze the productivity of the feller-buncher at the two trail spacings. Felling activities were recorded in the field using two handheld digital video cameras so movements could be analyzed later. One camera was held inside the cab behind the operator to record machine movements associated with the felling head. The second camera was operated outside the machine to record movements associated with the carriage, cab, and boom. Both video cameras were synchronized at the start of each harvest. A post-harvest time study was conducted on each harvest block using the harvest videos and a handheld PDA. Prior to the study a whole-tree harvest configuration was designed using UMTPlus® time and motion study software (Laubrass Inc. 2006) and uploaded to the PDA. The harvesting work cycle consisted of all tasks required to produce one bunch of accumulated whole-trees piled on the ground for subsequent skidding. The work cycle was divided into the four elements shown in Table 2.2.

Time study analysis began when the feller-buncher started cutting within the harvest block and ended when it exited the cutting block. The same researcher conducted the time studies for all the blocks. Two additional work elements were extracted from the time study data and analyzed – *accumulation time*, the time spent accumulating a full load of trees in the head, and *carrying time*, the time to accumulate a full load in the head and place it in the bunch. The count of trees accumulated in the feller-buncher head per

Table 2.2. Definition of work cycle elements used in the feller-buncher time study.

Work Element	Definition
Productive movement	Begins when the feller-buncher starts to move (track movement) and ends when the machine stops moving. This element does not include moving to the bunch drop area.
Selecting tree	Begins when the feller-buncher starts swinging and/or moving the boom towards the tree and ends just before the tree is cut.
Felling	Begins when the head starts cutting through the tree and ends when the stem is lifted from the stump. This is mainly recorded for tree count purposes.
Bunching	Begins after the feller-buncher has cut the last tree and starts moving towards the twitch location and ends when the bunch is dropped from the felling head.

cycle also was collected from the data and analyzed. Because felling time represented such a small segment of the harvest cycle it was combined with selecting tree for the work cycle analysis.

Although energy wood was expected to be the primary product from this harvest, the contractor sorted out pulp-quality logs as well. Road-side products (energy wood or pulp) from each harvest block were piled separately at each landing to allow tracking of production. Weight of pulp logs from each harvest block delivered to local mills was tracked using mill weight tickets for each load. The amount of energy wood produced on each block was estimated by subtracting the pulpwood harvested and the residual standing biomass from the pre-harvest biomass estimates. Using these harvest estimates along with the total harvest time for each block obtained from the time study, productivity in green tonnes per productive machine hour (PMH) was determined.

Because trails were not marked, the actual trail layouts in each harvest block were surveyed following the harvest to determine the extent of site impact from feller-buncher and skidder traffic. The centerline of each trail was dynamically surveyed using a Trimble Geo Explorer XM GPS unit. A width was recorded at 6.1 m intervals from the beginning of each skid trail. The width of primary trails (i.e., trails used by both the feller-buncher and the grapple skidder) was determined by measuring the length perpendicular to the trail from the outer edges of the disturbed soil caused by felling and skidding activities. Secondary spur trails (i.e., trails used only by the feller-buncher) in the harvest blocks treated with the 36.6 m trail spacing were also GPS recorded, but due to their uniformity a standard trail width of 3.0 m was applied. The area of each skid trail was calculated using a GIS. Trail centerline shapes were divided into nodes spaced 6.1 m, corresponding to the locations where widths were recorded in the field. The coordinates for skid trail offsets at each node were calculated using trigonometric functions with the measured trail widths and entered into the GIS as point shapefiles. Polygons were then created using the offset points and area was calculated for each polygon.

One way analysis of variance (ANOVA) was performed using R 2.5.1 (R Core Development Team 2007) to determine whether the harvesting treatments were statistically different. All statistical analyses were performed using a significance level of $\alpha = 0.05$. Dependent variables, including both harvesting productivity variables and residual stand characteristics, were analyzed by harvest treatment. The Shapiro-Wilk's W-statistic was used to test the null hypothesis that samples came from normally distributed populations. Levene's test was used to assess group constant variance. The results of these tests indicated that data transformations were not required ($p \geq 0.05$).

2.4 RESULTS

Average total biomass (energy wood and pulpwood) removed from each harvest block using the wider trail spacing (150.2 green tonnes) did not differ ($F = 0.53$, $p = 0.5051$) from blocks harvested with the narrower spacing (126.8 green tonnes, Table 2.3). Total biomass removed from each block as a proportion of pre-harvest biomass also did not differ between trail spacings ($F = 0.89$, $p = 0.3986$). Feller-buncher productivity is summarized for each harvest block in Table 2.4. The highest productivity (107.6 $\text{tonnes}\cdot\text{PMH}^{-1}$) was achieved on block 2a using the wider trail spacing, and the lowest productivity (36.6 $\text{tonnes}\cdot\text{PMH}^{-1}$) occurred on block 1b using the narrower trail spacing. On average, blocks harvested using the wider trail spacing produced 16.5 more tonnes

Table 2.3. Summary of total biomass (green tonnes) by harvest block and treatment. Pre-harvest biomass estimates are based on cruise data, harvested pulpwood was obtained from mill weight slips, estimates of residual biomass are based on post-harvest inventory data, and harvested energy wood is estimated by subtracting harvested pulpwood and residual biomass from pre-harvest estimates.

Harvest treatment	Block	Pre-harvest biomass	Harvested pulpwood	Harvested energy wood	Total harvested	Residual biomass
				(green tonnes)		
36.6 m trail spacing						
	1a	138.4	16.9	103.6	120.5	17.9
	2a	242.5	35.2	162.1	197.3	45.2
	3b	173.8	31.5	101.2	132.7	41.1
	Avg.	184.9	27.9	122.3	150.5	34.7
	Total	554.7	83.6	366.9	451.5	104.2
12.2 m trail spacing						
	1b	129.4	27.2	59.4	86.5	42.8
	2b	205.8	41.7	117.2	158.9	46.9
	3a	160.5	29.1	105.8	134.9	25.6
	Avg.	165.2	32.7	94.1	127.1	38.4
	Total	495.7	98.0	282.4	381.3	115.3

Table 2.4. Summary of harvest block productivity in green tonnes·PMH^{-1} and trees·PMH^{-1} and the average number of trees in the feller-buncher head per accumulation by harvest treatment and block. Total harvest time (h.hh) is also included.

Harvest treatment	Block	Total harvest time, (h.hh)	Productivity, tonnes·PMH^{-1}	Productivity*, trees·PMH^{-1}	Number of trees per accumulation†
36.6 m trail spacing					
	1a	2.06	58.4	357	5.2
	2a	1.83	107.6	295	4.2
	3b	2.28	58.1	361	5.9
	Avg.	2.06	74.7	338	5.1
12.2 m trail spacing					
	1b	2.37	36.6	384	4.8
	2b	1.88	84.6	333	3.5
	3a	2.52	53.5	370	5.4
	Avg.	2.26	58.2	363	4.6

* Based on a count of the felling time study work elements observed in each block divided by the total harvest time for the block.

†Based on a count of the felling time study work elements observed in each block divided by a count of the bunching work elements in each block.

per PMH than blocks harvested using the narrower trail spacing; however, the difference was not significant ($F = 0.58$, $p = 0.4890$). Productivity in stems·PMH^{-1} varied from 295 – 384 across all six harvest blocks, but also was not significantly different by treatment ($F = 0.88$, $p = 0.4002$).

There were no delays in any of the harvest blocks once the feller-buncher entered the block and began harvesting. Total harvesting times varied from 1.8 hours (block 2a) to 2.5 hours (block 3a), but there were no significant differences in total harvesting time between treatments ($F = 0.74$, $p = 0.4388$). Total harvest times were similar for treatment pairs in the same study block with the widest divergence being only 18 minutes on block 1. Total harvest time differed between treatments by less than three minutes on study block 2.

The variability of the proportion of time allocated to the different work elements tracked in the feller-buncher time study is summarized in Table 2.5. Similar proportions of time were allocated to each of the work elements when averaged across the three blocks in each treatment. On average, approximately three quarters of the total time was spent moving within the stands and selecting/felling trees in each treatment. Bunching time accounted for the remaining proportion of the total harvest time in each treatment. There were no significant differences in total moving times ($F = 0.24$, $p = 0.6489$), selecting/felling times ($F = 0.57$, $p = 0.4924$), or bunching times ($F = 1.03$, $p = 0.3679$), between treatments.

On average the feller-buncher was carrying trees for 43 seconds per bunch at the wider trail spacing and 35 seconds per bunch at the narrower trail spacing. The average time to accumulate a bunch was similar for both treatments: 29 seconds for the wider trail

Table 2.5. Summary of harvest cycle time (in decimal seconds) allocated to move, select/fell, and bunch for John Deere 853G feller-buncher equipped with an FS22 continuous-type disk-saw felling head by harvest treatment and block. Total number of harvest cycles per block is also included.

		Move		Select/Fell		Bunch		
Harvest Treatment	Block	Average time (s.ss)	Proportion of total time (%)	Average time (s.ss)	Proportion of total time (%)	Average time (s.ss)	Proportion of total time (%)	Number of harvest cycles
36.6 m trail spacing								
	1a	7.8	30.7	4.7	45.3	12.6	24.0	142
	2a	9.1	32.7	4.7	38.3	15.0	29.0	128
	3b	8.2	38.5	3.9	38.8	13.3	22.7	140
	Avg.	8.4	33.9	4.5	40.8	13.6	25.2	137
12.2 m trail spacing								
	1b	8.0	35.2	4.3	44.2	9.3	20.6	189
	2b	8.5	35.1	4.2	36.7	10.6	28.2	180
	3a	9.0	30.7	5.0	50.8	9.8	18.5	172
	Avg.	8.5	33.7	4.5	43.9	9.9	22.4	180

spacing and 25 seconds for the narrower trail spacing. Average carrying time and accumulating time per harvest cycle was not significantly different between treatments (*F*-values 2.40 and 0.70; *p* values 0.1964 and 0.4501, respectively). Average bunching time per harvest cycle, however, was significantly different by treatment ($F = 21.42$, $p = 0.0098$), with at the 36.6 m trail spacing requiring an average of 14 seconds per cycle and the 12.3 m trail spacing requiring only 10 seconds per cycle. Blocks treated with the wider trail spacing accumulated on average 4.2 to 5.9 trees per harvest cycle while blocks treated with the narrower trail spacing accumulated 3.5 to 5.4 trees per cycle. The total number of bunches produced on each block (i.e., the number of harvest cycles) were significantly different between the two trail spacings with an average of 43 more being produced at the narrower trail spacing than the wider trail spacing ($F = 44.12$, $p = 0.0027$). The harvest cycle was repeated on average 137 times in each harvest block (267 times per hectare) at the wider spacing and 180 times per harvest block (300 times per hectare) at the narrower trail spacing (Figure 2.3).

Because trails were not laid out prior to the harvest, actual trail layouts as determined by the feller-buncher operator differed from the theoretical layout, particularly because trail mergers occurred within the blocks treated with the narrower trail spacing (Figure 2.4). Primary trails (i.e., trails used by the feller-buncher and grapple skidder) occupied approximately 13% of the harvest blocks treated with the 36.6 m trail spacing and 34% of the harvest blocks treated with the 12.2 m trail spacing. Secondary spur trails (i.e., trails only used by the feller-buncher) occupied an additional 16% of the blocks treated with the wider spacing; however, these single entry trails generally

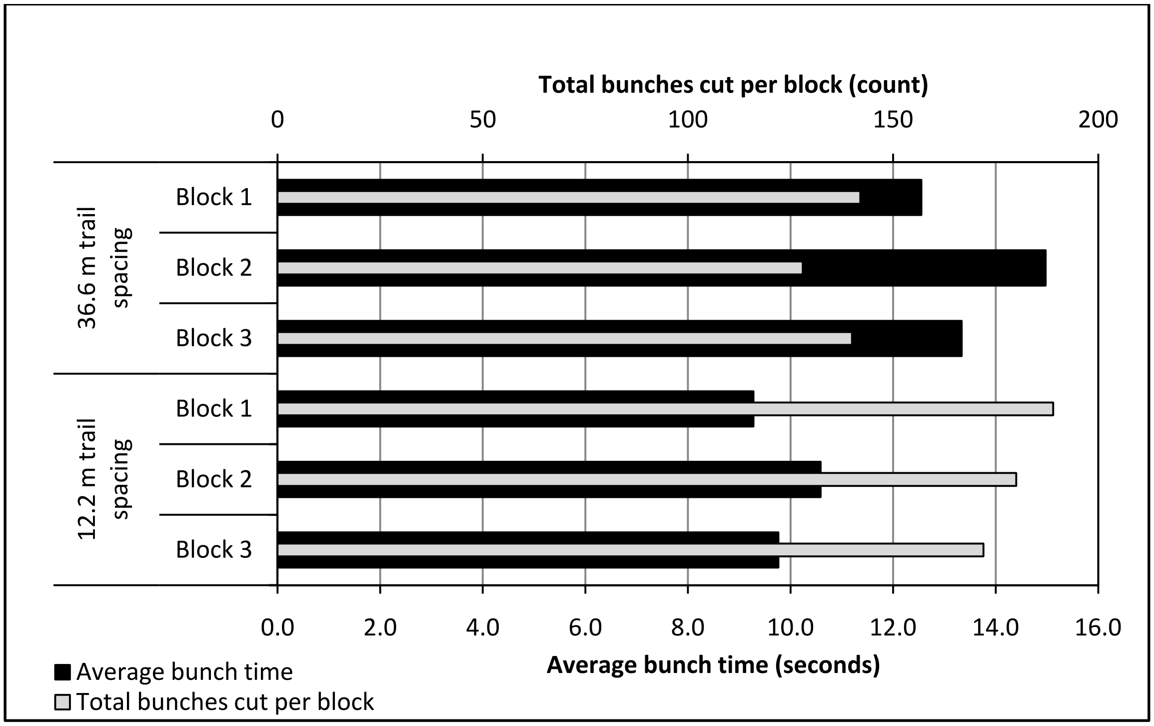
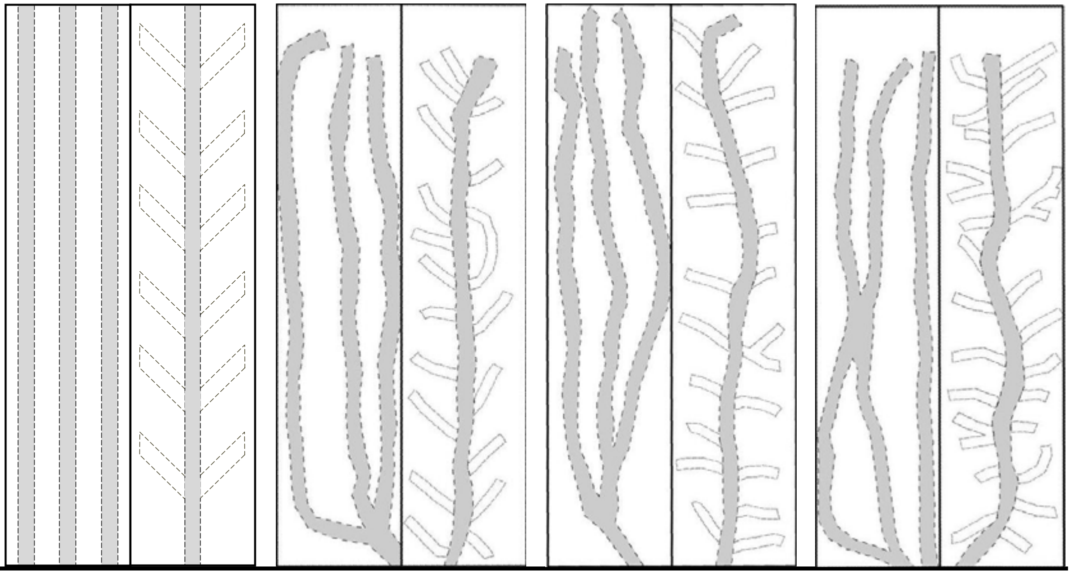


Figure 2.3. Comparison of average bunching time with the total number of bunches produced by harvest block and treatment. Thick black bars represent the average time to carry out the bunching element (s.ss) and are read off of the lower time scale. Narrow grey bars represent the total number of bunches cut in each block and are read off of the upper count scale. Treatment differences were significant for average bunching time (*F* = 21.42, *p* = 0.0098) and total bunches cut per block (*F* = 44.12, *p* = 0.0027).



Harvest Block	Theoretical Design		1B	1A	2B	2A	3A	3B
Primary skid trail area (ha)	0.241*	0.080*	0.212	0.081	0.199	0.080	0.199	0.076
% of block in primary skid trail[†]	40.2	13.3	35.3	13.6	33.2	13.4	33.2	12.7
Secondary spur trail area (ha)		0.079*		0.095[‡]		0.085[‡]		0.104[‡]
% of block in secondary spur trails[†]		13.1		15.8		14.2		17.3
Total primary skid trail length (m)	492.0	164.0	492.7	153.4	494.2	167.1	474.9	160.7
Average primary skid trail width (m)	4.9*	4.9*	4.5	4.7	4.5	4.4	4.0	4.7
Total secondary spur trail length (m)		227.7[§]		324.8		313.1		426.2

*Assumes a standard trail width of 4.9 m

†Based on a 0.6 ha harvest block

‡Assumes a standard trail width of 3.05 m

§Layout based on a maximum feller-buncher reach of 8.2 m from trail centerlines

Figure 2.4. Comparison of theoretical and actual harvest layouts.

represent a very minor disturbance to the residual stand, regeneration, and soil (Meek 1999). Average trail widths were similar between the 36.6 m and 12.2 m trail spacing treatments – 4.6 m and 4.3 m, respectively. The combined trail length in each of the harvest blocks (including secondary spur trails at the 36.6 m spacing) was similar by treatment with the exception of block 3 where steeper topography required the feller-buncher operator to reduce the spacing between secondary spur trails.

2.5 DISCUSSION

This harvesting approach was designed to reduce the effects of bunching distance on feller-buncher productivity when harvesting energy wood. Reducing skid trail spacing to 12.2m for the most part allowed the operator to utilize the reach of the boom to harvest the stand, limiting feller-buncher activity to the trail corridor. The 36.6 m spacing required the feller-buncher to track short distances off the trail to harvest the block. Theoretically, the narrower spacing should have allowed trees to be harvested from the residual strips between trails much faster, but would require more time harvesting corridors. Three times as much time should have been dedicated to harvesting trail corridors at the narrower trail spacing in this study. On the other hand, while the wider trail spacing theoretically should have reduced the amount of time dedicated to harvesting trail corridors, more time should have been required to move from bunching sites on the trail out to the block boundaries and back. Based on the results of this study the trade-offs proved to be relatively equal, resulting in insignificant differences in productivity between the two treatments.

This balance in trade-offs between the two trail spacings cannot be clearly explained by the total proportion of time dedicated to each element of the harvest work cycle as they did not differ significantly between treatments. The expectation was that limiting feller-buncher activity to the harvest trail would result in substantial decreases in the amount of time required to move trees from the stump to the bunch site, thus increasing productivity. Therefore, bunching time was expected to be affected the most using the narrower trail spacing. However, total bunching time at this spacing was only reduced by 4% on average compared to the wider trail spacing.

The insignificant difference between total harvest times can be explained by comparing the average bunching element times with the total number of bunches produced (Figure 2.3). The average bunching time per harvest cycle was significantly shorter at the narrower trail spacing; however, because the narrower spacing required making three times as many trails, the feller-buncher generated significantly more bunches at the narrower trail spacing than the wider trail spacing. The extra time saved on bunching by using the narrower trail spacing was offset by having to make more bunches, with the reverse holding true for the wider spacing, resulting in insignificant differences in total bunching time. It is difficult to determine if the feller-buncher was forced to produce smaller bunches more frequently at the narrower trail spacing based on the data collected from the study. If this were the case, subsequent skidding productivity may have been negatively affected. However, at both trail spacings the feller-buncher operator was observed piling more than one bunch together to produce full twitches for the skidder. Furthermore, there was no difference in the average number of stems accumulated per harvest cycle at the narrower trail spacing compared to the wider spacing.

While trail occupancy at the narrower spacing was similar to densities published in previous studies using similar equipment (Nichols *et al*. 1994), the 12.2 m spacing resulted in a substantial amount of site disturbance compared to the 36.6 m spacing. Trail occupancy represents the areas where 100% of the overstory and regeneration has been removed or destroyed and the soil has been considerably disturbed. While there are currently no laws in Maine regulating trail occupancy on cutovers, narrower trail spacings may make it difficult to comply with the Maine forest practices act (MFPA; 12 MRSA §8867-A to §8888 & MFS Rules Chapter 20) requirement to leave at least 450 stems of acceptable growing stock (which includes American beech) well distributed across the harvest block. Primary trail area estimates in this study may represent a conservative assessment of trail occupancy since trail width can also be measured from damage to damage which can extend out to trees damaged along the trail beyond the disturbed soil.

2.6 CONCLUSIONS

The productivity of a feller-buncher harvesting mostly energy wood was found to be 74.7 tonnes·PMH^{-1} or 338 trees·PMH^{-1} using an 36.6 m trail spacing, and 58.2 tonnes·PMH^{-1} or 363 trees·PMH^{-1} using a trail spacing of 12.2 m. Analysis results suggest that gains in productivity cannot be achieved by reducing trail spacings from a distance of 36.6 m to 12.2 m. The results suggest that while reductions in trail spacing may lead to more efficient bunching for the feller-buncher, the advantage is lost by having to make more bunches. Narrower trail spacings also have the disadvantage of increasing the footprint of the operation. In this study a 6.1 m reduction in trail spacing resulted in a near tripling of primary skid trail occupancy. Increasing the operating area could lead to greater risk of causing damage to the residual stand (Coup 2009, Ch. 3 page 62).

Although no significant differences were found between mean productivity using either trail spacing, average feller-buncher productivity at the wider trail spacing was considerably greater than at the narrower trail spacing. In each of the three study block pairs, the area harvested using the wider trail spacing had productivity levels approximately 10 to 60 percent greater than the block treated with the narrower trail spacing. However, with the combination of considerable site heterogeneity among the three treatment blocks and only three replicates, the power of the experiment to detect trends between the treatments was low.

Chapter 3:

AN ASSESSMENT OF RESIDUAL STAND DAMAGE FOLLOWING WHOLE-TREE ENERGY WOOD HARVESTING AT TWO TRAIL SPACINGS IN CENTRAL MAINE

3.1 ABSTRACT

Residual stand damage was assessed following an integrated energy wood harvest at two trail spacings in mid-site hardwood stands dominated by small-diameter diseased American beech (*Fagus grandifolia* Ehrh.) trees. Three 1.2 ha (73.2 m x 165.0 m) study blocks were established in Hancock County, Maine. Half of each block was treated with an improvement cut using a mechanized whole-tree harvest at a trail spacing of 36.6 m while the other half was treated using a spacing of 12.2 m. Harvesting resulted in an average residual basal area of 5.7 $m^2 \cdot ha^{-1}$ at the wider trail spacing and 6.4 $m^2 \cdot ha^{-1}$ at the narrower trail spacing, representing an 80 and 75% decrease, respectively, from pre-harvest basal area estimates.

Following harvesting and skidding operations, all standing residual trees 2.54 cm or greater at DBH were inspected for damage resulting from the harvest. Overall occurrence of wounds, occurrence of wounds in different size and severity classes, and wound locations were compared. Residual stand damage levels averaged 32% of stems at the 36.6 m trail spacing and 45% at the 12.2 m trail spacing. Wounding patterns in regard to size, severity, and location were similar for both treatments. Overall there were no differences ($\alpha = 0.05$) in the levels of residual stand damage between the two trail spacings ($F = 6.394$, $p = 0.0648$). While it appears that there was no increase in damage

frequency to the residual stand when trail spacing was reduced from 36.6 m to 12.2 m in a mechanized whole-tree energy wood harvest, the overall proportion of trees wounded at both spacings was less than desirable.

3.2 INTRODUCTION

Growing markets for small diameter and low-grade woody biomass for energy (i.e., energy wood) have the potential to improve the economic feasibility of more intensive silvicultural treatments in northern hardwood stands which previously required substantial financial investment. In particular, these energy wood markets may offer managers a commercial means to conduct previously neglected intermediate treatments such as thinning and improvement cuts in immature, overstocked stands (Manley and Richardson 1995). These treatments could maintain a continuous energy wood supply while at the same time promoting the growth of higher value forest products. This possibility is made more practical through advancements in harvesting technology that have allowed mechanical operations to efficiently harvest and handle small-diameter trees. In particular, mechanized whole-tree systems utilizing feller-bunchers and grapple skidders are well suited for efficiently harvesting and collecting a wide range of tree sizes simultaneously (Biltonen *et al*. 1976, Watson *et al*. 1986, Greene *et al*. 1987, Gringas 1988, Hartsough *et al*. 1997).

However, using mechanized systems to conduct thinning or partial harvest treatments in northern hardwoods has the potential to produce negative impacts through excessive damage to the residual stand. Concerns have been raised over operational practices motivated by harvesting energy wood that could potentially conflict with long-term silvicultural objectives (Seymour 1986, Ostrofsky and Dirkman 1991). Harvesting small diameter or low quality trees inevitably raises the harvesting cost per unit volume, which requires larger amounts of material to be handled faster and more cheaply in order to maintain productivity. These operations, which are generally focused on high operational productivity, can pose a substantial risk of damaging the residual stand thereby reducing long-term forest productivity and overall potential value. While harvesting energy wood has the potential to reduce harvesting costs and help achieve desirable stand results (Benjamin *et al*. 2009), damage to residual trees resulting from a mechanized operation can substantially reduce the long-term benefits of silvicultural prescriptions.

Logging injuries that expose the cambium or sapwood of the tree make the wood susceptible to discoloration, disease, and decay (Hornbeck and Leak 1992). Because the emphasis of northern hardwood silviculture is on maximizing value by growing high-quality trees, internal discolorations and decays caused by logging injuries can be serious economic problems (Seymour 1995). Injuries inflicted during logging operations are an important factor to consider in maintaining stand quality, value, and health because it is perhaps the only factor that managers can completely control (Ostrofsky 1988).

Throughout Maine, > 90% of forestlands are currently managed using partial harvesting techniques in which some portion of the stand remains after harvest (Maine Forest Service 1990 - 2008). Energy wood markets could increase the frequency of partial harvesting by offsetting a portion of intermediate silvicultural treatment costs. Whenever a stand is entered for a partial harvest, particularly with fully mechanized systems, there is always some risk that residual trees will sustain injury. A preventative approach to reducing residual stand damage requires careful planning prior to the harvest (Kelley 1983, Ostrofksy *et al*. 1986, Cline *et al*. 1991). Past studies have emphasized the importance of harvest layouts in this regard and greater attention is now given to harvest planning and layout to minimize or eliminate adverse environmental impacts.

The objective of this study was to quantify and evaluate the extent of residual stand damage following integrated energy wood harvesting in northern hardwoods with a mechanized whole-tree harvest system using trail spacings of 36.6 m and 12.2 m. Residual stand damage levels identified in this study were then compared to results from other published studies of mechanized whole-tree harvest operations in hardwood stands.

3.3 METHODS

3.3.1 Data Collection and Analysis

Residual stand damage was assessed immediately following the harvest operation described in Coup (2009, Ch. 2 page 37), where three 1.2 ha (73.2 m x 165.0 m) blocks of northern hardwood stands dominated by an understory of diseased American beech (*Fagus grandifolia* Ehrh.) and striped maple (*Acer pensylvanicum* L.) were whole-tree partially-harvested using a tracked, swing-to-bunch feller-buncher and grapple skidders. Primary skid trails were established at 36.6 m intervals for half of each block (0.6 ha, 36.6 m x 165.0 m; blocks 1a, 2a, and 3b) and 12.2 m intervals for the other half (blocks 1b, 2b, and 3a) to assess the effect of a narrower trail spacing on the productivity of a feller-buncher when harvesting small diameter stems. The harvest prescription called for an improvement cut to remove the existing beech-striped maple component, utilizing all stems ≥ 2.54 cm DBH, while leaving sugar maple (*Acer saccharum* Marsh.) and yellow birch (*Betula alleghaniensis* Britt.) as crop trees.

Residual trees were examined for damage after harvesting and skidding operations were completed. A complete evaluation of all standing residuals 2.54 cm or greater at DBH was conducted within each 1.2 ha harvest block. Assessment of damage was conducted using a methodology adapted from Ostrofsky *et al*. (1986) that considered wound size, location, and severity. Each stem was recorded by species and DBH and classified as “injured” or “uninjured.” The bole of each tree was carefully examined for wounds attributable to harvesting and skidding operations. Each bole wound on an injured residual stem was recorded by wound length (parallel to the stem) and width (perpendicular to the stem) at the maximum extent of the wound, the height from the ground line to the lowest point on the wound, and a severity class (Figure 3.1). Wound severity classes ranged from 1 to 3 and included 1) low, bark contacted but cambium unbroken, 2) medium, bark removed to cambium and wood exposed, 3) high, bark and cambium broken and wood damaged (Figure 3.2). Combinational wounds were assessed by the predominant damage present and were assigned one of the three severity ratings. Multiple wounds were recorded for a single stem if present; however, wounds that were assumed would eventually result in a convergence of damaged area into one larger scar were measured as one continuous wound. The heights of each wound base above the ground line were grouped into 1 m height classes. Root and crown damage observations were noted if visibly present but not quantitatively measured. Stems that were severely bent, pushed over, or uprooted were considered destroyed and were not included in the residual stem count. No attempt was made to differentiate wounds caused by felling and

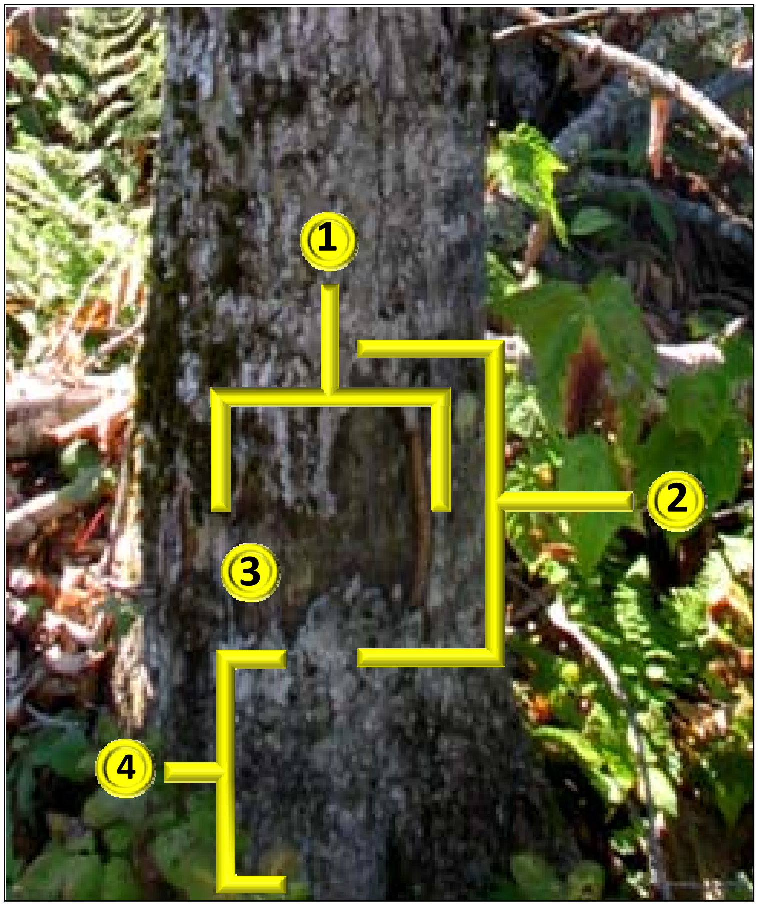


Figure 3.1. Measures recorded for each bole wound, 1) maximum width of wound, 2) maximum length of wound, 3) wound severity class, and 4) distance from the ground line to the lowest point of the wound.

Figure 3.2. Examples of wound severity classes: 1) low, bark contacted and not broken, 2) medium, bark removed to cambium, and 3) high, bark removed and sapwood abraded and broken.

bunching from those caused by skidding. The spatial location of wounded trees in proximity to skidding corridors was also not evaluated.

An area was calculated for each wound using the measured length and width. The area of the wound along with the associated severity class was used to determine an overall damage rating for each bole wound. The damage ratings included minor, moderate, and severe and were derived by giving greater importance to larger and more severe wounds (Table 3.1; Ostrofsky and Dirkman 1991).

One way analysis of variance (ANOVA, R Core Development Team 2007) was used to determine if differences in residual damage at trail spacings of 36.6 m or 12.2 m were significant. All statistical analyses were performed using a significance level of $\alpha = 0.05$. Levene's test was used to assess group constant variance. The Shapiro-Wilk's W-statistic was used to test the null hypothesis that variables came from normally distributed populations. These hypotheses were not rejected for any of the dependent variables, and transformations were not employed. The following dependent variables were analyzed: proportions of trees wounded, mean wound length, average height of wound base above the ground line, mean wound width, average wound area, average proportion of trees receiving two or more wounds, average proportion of wounds in each severity class, the number of injuries on stems < 15cm, the number of injuries on stems > 15 cm, and average proportion of wounds in each damage rating category.

Table 3.1. Process of determining wound damage rating for each bole wound using wound severity class and wound area.

1. Wound severity class

Class No.	
1	Scuff (bark contacted but not broken)
2	Cambial (bark removed to cambium)
3	Wood damage (sapwood abraded and broken)

2. Wound damage class

Wound size	Severity class	Damage class
$< 65\ \mathrm{cm}^2$	1,2	A
> 65 to $< 323\mathrm{cm}^2$	1,2	B
$> 323\ \mathrm{cm}^2$	1,2	C
$< 65\ \mathrm{cm}^2$	3	D
> 65 to $< 323\mathrm{cm}^2$	3	E
$> 323\ \mathrm{cm}^2$	3	F

3. Wound damage rating

None	---
Minor	A,B
Moderate	C,D
Severe	E,F

3.4 RESULTS

3.4.1 General Damage Levels

Summaries of residual damage on all injured trees are shown in Table 3.2 and Table 3.3. Nearly 30% or more of the trees in each block were injured to some degree. Out of a total of 663 residual trees evaluated for damage across the three harvest blocks treated using the 36.6 m trail spacing, 211 (32%) were found to be injured. Mean diameter of the injured trees was 4.1 cm. At this spacing, block 3b had the highest proportion of damaged trees (33%), while block 2a had the lowest (29%). The blocks treated with the narrower trail spacing had an overall proportion of residual trees injured of 45% (185 out of 407); however, the difference between treatments was not significant ($F = 6.394$, $p = 0.0648$). At least half of the residual stems on blocks 2b and 3a were injured. Block 2b had the highest proportion of injured residual stems at the narrower spacing (53%), while block 1b had the lowest (35%). Mean diameter of trees wounded at this spacing was 6.4 cm. At both the wider and narrower trail spacing, the smaller diameter stems, which comprised a major portion of the residuals, received the largest portion of the inflicted wounds (Figure 3.3). There was no difference in the number of injuries on stems < 15 cm DBH ($p = 0.3889$) or > 15cm DBH ($p = 0.0702$) between harvest treatments. Of the injured trees at the wide and narrow spacings, 35 and 31% respectively, had visible root and/or crown damage that ranged from broken branches in larger trees to broken tops in smaller trees and root abrasions in all three severity classes. Bole wounds were not always found on trees with noted crown or root damage.

A small proportion of the stems wounded in both treatments received multiple wounds; however, the average number of injuries found on trees wounded multiple times

Table 3.2. Summary of wound frequency including total residual tree count, percent injury, multiple wound frequency, number of wounds per tree, and the percent of wounds by height class.

Harvest treatment	Block	Total number of residual trees*	Percent of residual trees injured	Percent of wounded trees with multiple wounds	Average number of wounds per wounded tree	Percent of wounds by height class			
						< 1 m	1 – 2 m	2 – 3 m	> 3 m
36.6 m trail spacing									
	1a	101	32.7	14.3	1.1	68.8	28.1	3.1	0.0
	2a	211	29.4	17.9	1.2	71.0	27.5	1.4	0.0
	3b	351	33.0	17.8	1.2	76.4	19.1	3.6	0.9
	Avg.		31.7	16.6	1.2	72.0	24.9	2.7	0.3
12.2 m trail spacing									
	1b	154	35.1	15.2	1.2	82.1	14.3	1.8	1.8
	2b	153	52.9	20.5	1.2	70.3	24.2	1.1	4.4
	3a	100	50.0	43.5	1.6	77.0	20.3	1.4	1.4
	Avg.		46.0	26.4	1.4	76.5	19.6	1.4	2.5

* All standing residuals ≥ 2.54 cm DBH

Table 3.3. Summary of wound characteristics including total wound count, average wound width, length, area, and the proportion of wounds by severity class and damage rating.

Harvest treatment	Block	Total number of bole wounds evaluated	Average wound width (cm)	Average wound length (cm)	Average wound area (cm^2)	Wound severity class			Wound damage rating		
						1	2	3	Minor	Moderate	Severe
36.6 m trail spacing						(% of wounds)			(% of wounds)		
	1a	32	9.5	98.2	1262.6	28.1	21.9	50.0	21.9	34.4	43.8
	2a	69	7.7	61.4	521.7	39.1	39.1	21.7	47.8	33.3	18.8
	3b	110	6.8	58.5	568.8	24.5	28.2	47.3	35.5	29.1	35.5
	Avg.		8.0	72.7	784.4	30.6	29.7	39.7	35.1	32.3	32.7
12.2 m trail spacing											
	1b	56	10.6	105.5	1258.3	41.1	26.8	32.1	23.2	48.2	28.6
	2b	91	11.9	79.5	919.8	29.7	51.6	18.7	44.0	37.4	18.7
	3a	74	9.7	69.0	889.9	39.2	28.4	32.4	35.6	42.5	21.9
	Avg.		10.7	84.6	1022.7	36.6	35.6	27.8	34.3	42.7	23.1

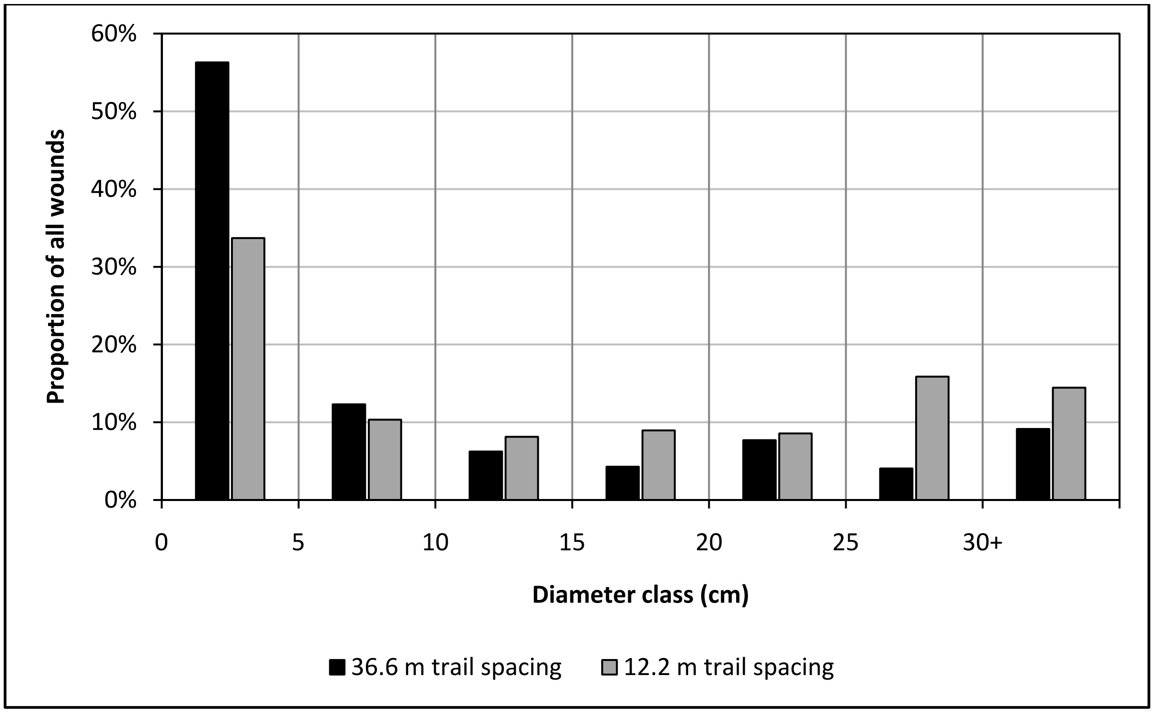


Figure 3.3. Distribution of injuries by diameter class and harvest treatment.

was relatively low. At the wider trail spacing the mean number of wounds per injured tree was 1.2 with over 80% of injured trees receiving only one wound. On blocks treated with the narrower trail spacing, the mean number of wounds per injured tree was 1.3, with approximately 75% of injured trees receiving only one wound. The portion of trees receiving multiple wounds was not different by treatment ($F = 1.25$, $p = 0.3265$). Less than 10% of wounded trees on any of the six harvest blocks received three or more wounds.

3.4.2 Wound Characteristics

Approximately 70% of the wounds received in blocks treated with the wider trail spacing were in severity class 2 (bark broken, wood exposed) and class 3 (bark broken, wood damaged), while 63% of wounds received in blocks treated with the narrower trail spacing were in severity classes 2 and 3 ($F = 1.15$, $p = 0.3436$). There was no difference in average bole wound length ($F = 0.05$, $p = 0.5166$), width ($F = 7.12$, $p = 0.0559$), or area ($F = 0.80$, $p = 0.4226$) between the two spacings. Approximately a third of the wounds for both the 36.6 m (35%) and 12.2 m (34%) trail spacing were classified as "minor" damage. Severe damage ratings comprised 33% and 23% of assessed wounds at the wider and narrower trail spacings, respectively. The proportion of wounds in each severity class and damage category, however, was not different between trail spacings (F-values of 0.01 – 1.40; p-values of 0.66 – 0.93).

The proportion of wounds in each height class was similar for both treatments. Wound bases were within 1 m of the ground on the majority (>70%) of wounds at both spacings. The frequency of wound bases generally decreased with increasing distance from the ground, and only a small portion (<5%) of wound bases were found above 2 m on stems at both the wider and narrower trail spacing. The average height of wound bases above the ground did not differ significantly between treatments ($F = 0.19$, $p = 0.6822$). For both harvest treatments, wounds with their base located below 1 m generally had the greatest average wound area (770 to 1214 cm^2; Figure 3.4). On average, the wound area decreased as the height of the wound base from ground line increased. However, wound area was more variable with height in the blocks treated with the narrow trail spacing as larger wounds were found with their bases located further up the bole on a small number of trees. Over 50% of the wounds with their bases located less than 1 m from the ground in both treatments had a "moderate" to "severe" damage rating (Figure 3.5), and the majority (>50%) of wounds with their base located 1 – 2 m from the ground were rated moderate to severe as well.

3.5 DISCUSSION

3.5.1 General Damage Levels

The proportion of residual stand damage at both spacings was similar to the results reported in other mechanized whole-tree partial harvests in northern hardwood stands; however, it is important to consider the specific conditions of the study (e.g., stand structure and composition, harvest system, prescription, etc.) and the methods used in determining damage results. Biltonen *et al*. (1976) found 20 – 34% of trees were damaged following various thinning treatments using a drive-to-tree feller-buncher and grapple skidder in northern hardwood pole stands in Michigan. Nichols *et al*. (1994) found similar results (20 to 31%, based on residuals >1.5 cm DBH) with a Caterpillar 205

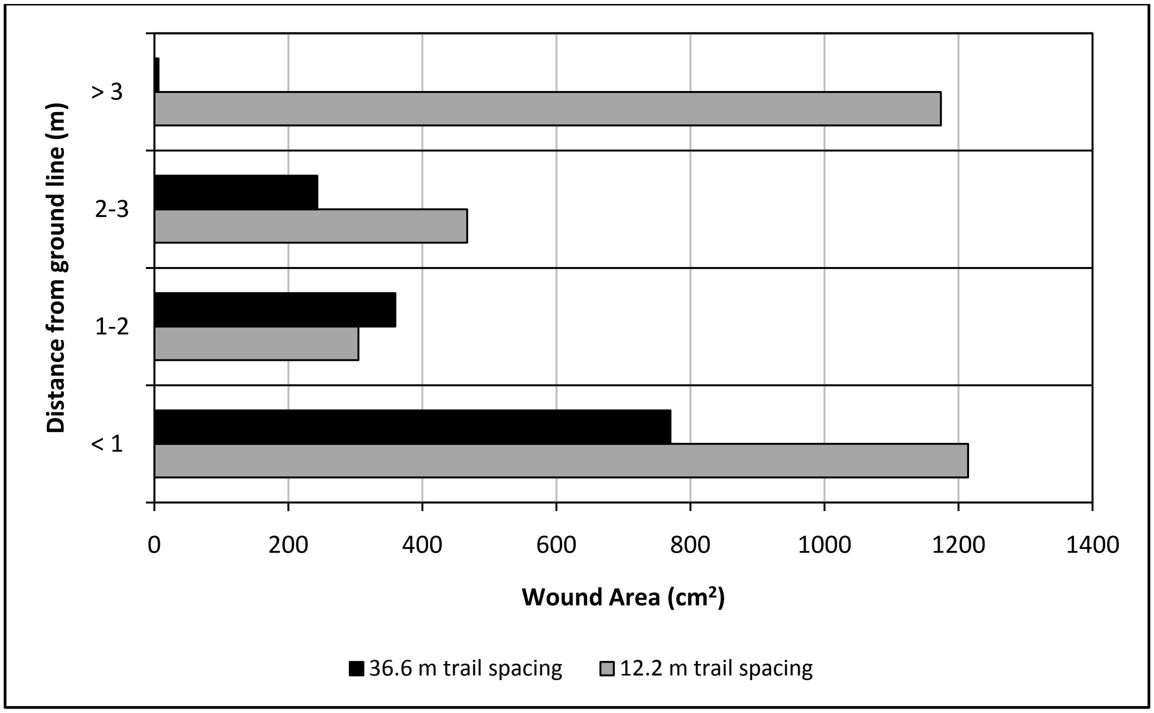


Figure 3.4. Average wound area by height class and harvest treatment.

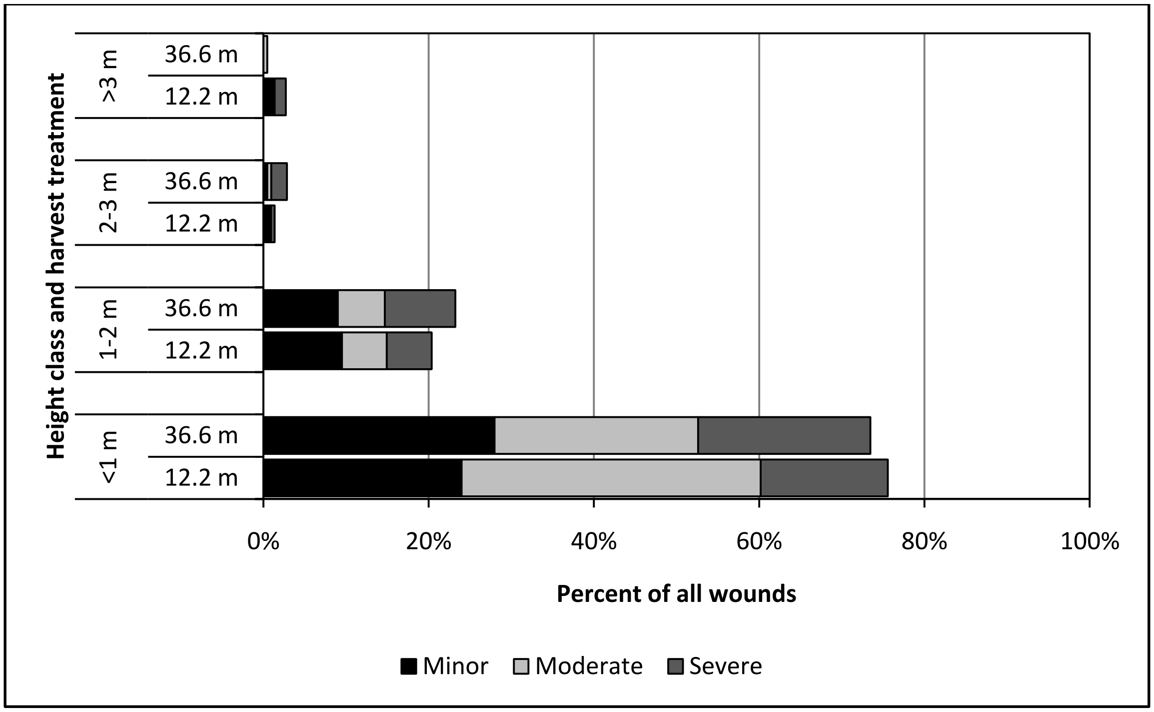


Figure 3.5. Proportion of wounds by height class, harvest treatment, and damage rating.

tracked swing-to-bunch feller-buncher and grapple skidder following partial cutting at two different intensities in a northern hardwood stand in Maine. Using a Drott 40LC feller-buncher and a grapple skidder and employing a strip thinning pattern with selection thinning between strips in a northern hardwood pole stand where trails were spaced at 14.5 m (from trail centerlines), Johnson *et al*. (1980) reported 32% of residual trees sustained damage either by felling or skidding activities.

Residual stand damage was considerable, although not significantly different, at the narrower trail spacing, but similar to results previously published on several drive-to tree feller-buncher operations. Bruhn (1984) indicated an instance in northern hardwoods where 40% of the residual stand (based on residuals >2.5 cm DBH) had received damage in a mechanical thinning study using an Omark Hydro-Ax rubber-tired feller-buncher in conjunction with grapple skidders. Kelley (1983) reported damage results for a mechanical thinning using a Hydro-Ax drive-to-tree feller-buncher and grapple skidder in stands of northern hardwoods mixed with spruce where damage levels reach 41.6% of the residual stand (based on residuals >5.1 cm DBH). The author indicated that damage levels in excess of 40% in thinned areas were considered unacceptable. Ostrofsky *et al*. (1986) examined two mechanically thinned hardwood stands using Morbell and Hydro-Ax drive-to-tree feller-bunchers in Maine and reported average damage levels to residual crop trees of 22, 45, and 53% (based on residuals >1.5 cm DBH). Ostrofsky and Dirkman (1991) noted that these levels of damage were excessively high. In a study of whole-tree harvesting in Vermont, Hannah *et al*. (1981) considered residual damage levels of 21 – 27% excessive.

Although useful for establishing a rough comparison, it should be noted that the damage levels and tolerance limits reported in other studies should be regarded as specific case studies rather than generally expected or accepted results. According to Ostrofsky (1988) generally accepted levels of residual stand damage for feller-buncher operations are between 20 and 40%, although these levels are most likely based on typically encountered damage intensities rather than levels that could be achieved by taking additional precautions (Ostrofksy and Dirkman 1991). For example, Cline *et al*. (1991) reported relatively low damage levels on several stands of mixed-wood (7.8%, n = 11) and hardwoods (13.7%, n = 7) (based on residuals ≥7.6 cm DHB) following whole-tree harvesting using drive-to-tree feller-bunchers (Franklin 105, Bobcat 1213, Hydro Ax 311, and Morbell) and grapple skidders throughout northern New England. They attributed the low damage incidence largely to the amount of pre-harvest planning and the skill and experience of the equipment operators. A more recent study evaluating northern hardwood stands in Michigan for damage after mechanized whole-tree harvesting found in one instance that only 5% of residual trees were damaged following harvesting with a Timbco feller-buncher and grapple skidders (based on residuals ≥ 5.1 cm DBH; Seablom and Reed 2005). The highest level of stand damage reported in the study was 14.4%. These studies both demonstrate that damage incidence levels below 20% can be achieved through well planned layouts and vigilant operators. Ultimately, however, the level of stand damage that is deemed acceptable for any logging operation will largely depend on long-term management objectives and how “damage” is defined.

In addition to the injuries directly inflicted to residual trees as a result of harvesting equipment, Ostrofksy *et al*. (1986) also recognized two additional types of residual stand damage: removing an excessive number of crop trees and the general impact of the harvest on stand vigor through soil compaction, soil disturbance, and increased solar radiation to residual stems. Although not examined in this study, the narrow trail spacings used in the harvest operation may contribute substantially to these often overlooked forms of damage. On average, primary trails occupied approximately 13% of the harvest blocks treated with the 36.6 m trail spacing and 34% of the harvest blocks treated with the 12.2 m trail spacing (see Figure 2.4). These trail occupancy levels generally represent areas where 100% of the overstory and regeneration, regardless of species, were removed or destroyed and the soil had been considerably disturbed.

3.5.2 Wound Characteristics

There was little variability in the type of damage (i.e., wound area, height of wound base, severity, etc.) found between the two treatments. While not differentiated by harvest operation during data collection, crown damage and bole wounds, particularly puncture wounds, occurring higher on the stems would likely have been caused by the feller-buncher, whereas most of the root damage and lower bole abrasions would likely have been inflicted during skidding operations (Bruhn 1986, Nyland 1994). This wounding pattern would hold true for both trail spacings. Indeed most of the damage inflicted in this study at both spacings occurred as large wounds located near the ground, with the majority classified as moderate (abrasions of the bark) to severe (abrasion of the wood) in intensity. These findings are important because scars located closer to the ground are more susceptible to wood-decaying fungi than those higher up the tree (Ohman 1970).

Wounded trees classified as having moderate to severe damage are likely to sustain some value and volume loss (Ostrofsky and Dirkman 1991, Seablom and Reed 2005). However, the amount of decay development will be related to the length of time since injury, the size of the wound, the tree species, the location of the wound, and the tree's vigor (Hesterberg 1957, Shigo 1965, 1966, 1985, Lavallee and Lortie 1968). Generally, the amount of defect associated with stem wounds increases with the surface area of the wound and the time since wounding (Ohman 1970). Hesterberg (1957) found that stem wounds on sugar maple that exposed surface areas of sapwood greater than 1000 cm^2 resulted in decay 50% of the time after 10 years, and 80% of the time after 20 years. Results also demonstrated that wounds on sugar maple less than 10 cm wide were at low risk of decay. Research conducted by Benzie *et al*. (1963), and Ohman (1970) indicated that yellow birch is more susceptible to decay following injury than sugar maple. Lavallee and Lortie (1968) found that stem wounds on yellow birch exposing 600 cm^2 or more of wood usually lead to internal decay. Ohman (1970) found that for both sugar maple and yellow birch, stem wounds decreased lumber and log grades by 10%.

In general, patterns of wounding were expected to be similar among the two trail spacing treatments used in this study because in both instances the same mechanical system operated by the same operators was used. The results of this study support this assumption in that the pattern and character of residual stand damage was not found to be significantly different between the two spacings. However, the frequency of wounding was expected to be different between the two treatments because the narrower trail spacing should have resulted in three times more trail edge exposed to both harvesting and skidding damage (Johnson *et al*.1980, Hannah *et al*. 1981, Kelley 1983, Ostrofsky *et* *al*. 1986, Nichols *et al*. 1994). In particular, skidding damage occurring below 1 meter from the ground was expected to be much higher on the blocks treated at the narrower trail spacing, but the results did not support this hypothesis. The overall residual damage levels on blocks 2 and 3 were 52 and 80% higher, respectively, on the halves treated with the narrower trail spacing than those treated with the wider spacing. However, on block 1 there was only a 7% increase in residual stand damage at the narrower spacing compared to the wider spacing. This occurrence likely influenced the statistical analysis indicating a lack of difference in overall damage between the trail spacing treatments. With such a small sample size it is difficult to explain why the trend in the overall proportion of damage found in blocks 2 and 3 did not continue across block 1 as well, although several possibilities were explored.

From a stand structure perspective, a low residual density might have been associated with lower damage on block 1b (Bruhn 1984, Nichols *et al*. 1994, Hassler *et al*. 1999), but the data do not support this hypothesis. Out of the three blocks treated with the narrower spacing, block 1b had the highest residual density (257 stems$\cdot$ha^{-1}) and the second highest residual basal area (7.6 m$^2\cdot$ha^{-1}; see Table 2.1). Comparing the percent reduction in pre-harvest basal area between the three blocks also reveals that block 1b had the lowest reduction in pre-harvest basal area of the three blocks. From an operational perspective, a lower density of primary skidding trails within block 1b also could have contributed to a lower level of damage; however, comparing the actual density of skid trail area in the three 12.2 m spacing blocks (see Figure 2.4) reveals that block 1b had the highest density of primary trail of the three, which presumably would be associated with a higher portion of residuals damaged. Ostrofksy *et al*. (1986) found significantly lower levels of residual stand damage associated with a narrower trail spacing; however, these results were obtained using a drive-to-tree feller-buncher.

It is likely that the low residual damage on block 1b can be explained by a series of factors not captured in this study that contributed to the operator’s ability to function without excessively damaging residual crop trees (e.g., increased visibility, lower surface roughness, etc.). The spatial distribution of residual stems within the stand also may have influenced the low damage levels on this block. While collecting the residual stem measurements it was noted that a considerable portion of the stems assessed in all six harvest blocks were found just inside the block boundary line all along their perimeters. Although the boundaries were clearly marked it may have been difficult for the feller-buncher operator to determine these trees were inside or outside of the block boundaries. It is possible that these stems largely escaped being damaged by the operation which may also have contributed to both the high residual density and the low damage level.

3.6 CONCLUSIONS

Improvement cutting in a northern hardwood stand using a whole-tree harvest system resulted in average levels of residual stand damage of 32% at a spacing of 36.6 m and 46% at a spacing of 12.2 m. Patterns of residual damage from the operation were similar for the two treatments. The primary question was whether any benefits that were gained by reducing primary skid trail spacing to improve the operational productivity of the harvest were offset by an increase in residual stand damage. The results indicate that there was no increase in residual stand damage when the spacing between primary skid trails was reduced from 36.6 m to 12.2 m. However, damage levels were higher at the narrower spacing in each of the three replicates, and distinct increases in damage levels were found in 2 out of the 3 replicates. Additionally, the lowest level of stand damage resulted from using the wider trail spacing while the highest level of stand damage resulted from using the narrower trail spacing. Had a larger number of replicates been used for this study, stronger evidence may have been developed concerning the relative difference in damage proportions between the two spacings.

An attempt was made to compare the damage level results found in this study with the results of similar studies; however, as Hassler *et al*. (1999) notes, the number of different methodologies used throughout the literature to characterize stand damage is nearly equivalent to the number of studies. The inconsistency among methods along with other differences (e.g., operator ability, site conditions, harvest system, etc.) precludes direct comparisons of the results from this study to those reported in others.

Chapter 4:

AN APPROACH FOR THE APPLICATION OF STATISTICAL PROCESS CONTROL TECHNIQUES FOR PROCESS IMPROVEMENT OF FOREST OPERATIONS

4.1 ABSTRACT

This study presents an approach to understanding, monitoring, and improving the variability of forest operations using statistical process control (SPC). Study data consisted of whole-tree harvest records collected over a period of 20 months from two feller-bunchers and four grapple skidders operating on several tracts throughout Maine. Productivity of each machine was evaluated over the period using Shewhart 3σ control charts. Control chart centerlines were estimated using the overall process mean. Three sets of control limits were calculated and compared for each chart using three estimates of σ including the average moving range, the median moving range, and the overall process standard deviation. Seven runs rules commonly used in statistical quality control of industrial manufacturing processes were applied to each chart to evaluate their performance with the harvesting data.

Control limits calculated using the average moving range and the median moving range provided similar results with slight differences mostly caused by the presence of outliers. Control limits based on the standard deviation proved to be insensitive. The indiscriminant application of runs rules to the data generally did not provide much useful information about each process.

Overall, the approach to understanding harvesting operations using SPC shows great potential. The control charts clearly provided useful information including a lucid depiction of the level of variation that operations managers must attempt to work with on a daily basis. However, many challenges related to how operational data is collected and organized, and how the underlying causes of variation are interpreted, need to be overcome, before SPC can be effectively implemented in forestry operations.

4.2 INTRODUCTION

At the most basic level, a forest harvesting operation is a collection of interacting processes that convert standing trees into primary wood products. Each process consists of a blending of inputs that can generally be categorized as materials, machines, manpower, environment, and methods that result in one or more outputs (Kiemele *et al*. 1997, Oakland 2007). In this regard a forest harvesting operation, particularly one that is fully mechanized, is analogous to an industrial mass-manufacturing plant (Rajala 1993). The major difference is that instead of the raw material input being transported to the factory for processing, the “factory” must move to and through the raw material. This is a considerable disadvantage as a forest operation has very little control over environmental and material inputs. Forest harvesting operations, therefore, must be performed with regard to uncontrolled, fluctuating inputs such as weather conditions, terrain, species composition, and the size, quality, and location of harvestable material, all of which vary hour-to-hour as harvesting progresses over an area (Wackerman *et al*. 1966). The variability of these inputs leads to variations in the output of each process.

The challenge of understanding and dealing with this variation has plagued forest operations for many years. In his classic book, *Cost Control in the Logging Industry*, Matthews (1942) recognized that the extreme variability in the cost of conducting logging operations restricts the ability of managers to predict future costs. He acknowledged that logging costs were subject to a great number of influential conditions such as the nature and density of the stand, the size and nature of the trees or logs, the location and conditions of the logging chance and its relation to spur roads, and the rate of production and flow of materials. Matthews also understood the need to assess the influence of these process inputs on the variable logging cost output.

> "This limitation of accurate cost prediction may not be serious in industries in which the environment of production changes little from month to month or year to year. In the logging industry, however, identical production situations are the exception rather than the rule, and unless the data of costs are broken down, recorded…and correlated with the factors that control their values, they remain merely data…of little use in deciding between alternative procedures."

In essence Matthews was calling for a way of analyzing the process output, in this case cost, in relation to the variable process inputs to make informed management decisions for the future rather than just relying on speculation and intuition.

While industrial mass-manufacturing processes are substantially more controlled and consistent than forest harvesting processes, the economic impact of even small variations in output can be much more severe. Therefore, manufacturing companies have been struggling to understand the variation within their processes in a way that can be used strategically. While working for Bell Telephone Laboratories in the early 1920s, Dr. Walter A. Shewhart developed a scientific approach to quality management, known today as statistical process control (SPC), that attempted to assess the variability of manufacturing processes using basic statistical concepts (Shewhart 1931). The primary objective of SPC is to bring routine processes into a state of statistical control where, according to Shewhart, through the use of past experience, one can predict at least approximately, how the phenomenon may be expected to vary in the future.

The core of SPC theory lies in the differentiation of two sources of variation that contribute to the overall variation within a process over time; *common cause* and *special cause*. Common, or natural, cause refers to the cumulative effect of a multitude of inherent sources of variation that produce chance or random variability within a process and cannot be avoided. This type of variation within a process is what many often refer to as *noise*. Processes that can be characterized by well defined distributions will produce a consistent output that varies randomly within limits as described by statistical measures of central tendency and dispersion. When common causes are the only source of variation present in a process, the process is said to be operating in a state of statistical control. Special, or assignable, causes of variation result in variability beyond expectations in a process that can be traced back to identifiable sources or causes.

Shewhart developed the control chart as a visual means of identifying when a process is in statistical control and to detect the occurrence of special causes of variation. It is a graphical display of a process that has been recorded over time, comprised of a run chart with a time scale plotted chronologically on the horizontal axis and a process measurement variable plotted on the vertical axis (ASTM International 2002). The key components of a process control chart that aid in decision making are the statistically generated centerline (CL), the upper control limit (UCL), and the lower control limit (LCL). The exact placement of these three horizontal lines in relation to the data is what defines the stable running process; therefore, they are positioned objectively with considerable thought, and use of basic statistics.

Because of the similarity between forest operations and industrial manufacturing it is possible that the principles of SPC developed for industrial settings can also be applied as a method of process improvement in forest operations. Generally, those who are involved in overseeing forest harvesting operations have a rough estimate of their average output; however, the challenge is in deciding when to react if the output of the operation strays above or below the norm. How far from the estimated norm does the output have to be before some sort of action should be taken? According to Shewhart, if the deviation of an observed metric is the result of common variation, any efforts made to change the operation would be time wasted on a problem that does not exist, and likely would result in detrimental over-corrections. Likewise, efficiency could be sacrificed when special causes are present but are assumed to be inherent to the system. A process control system in forest operations could benefit managers by providing them with a statistical signal when special causes of variation are present so that corrective action can be taken (Shewhart 1931, Kiemele *et al*. 1997). The system would also prevent the overseer from taking action on inherent variation in the system. Over time an SPC system theoretically could help improve the harvesting process by reducing the variability in the output, increasing its predictability.

For most operations, however, a harvesting process perpetually controlled to a certain output is not the long-term goal, particularly for those who are interested in improving the productive capability of their system. Managers and contractors are constantly trying to implement changes that will improve the harvest output, or reduce the unit cost of production. However, without a basic understanding of the behavior for a harvesting process and a baseline of comparison, it is difficult to know whether a change has led to the desired result. The emphasis of SPC in forest operations, therefore, is the characterization of the process behavior as a starting point for process improvement. Control charts can be used to identify not only the special causes of variability that are detrimental to the system, but also the beneficial sources (i.e., those that cause higher than average production values). By eliminating the sources of variability that drag the productivity down and utilizing those that pull it up, the average productivity can be improved over time. Therefore, in combination with reducing process variability, an SPC system can also aid in raising the average output of a forest harvesting operation over time.

Although widely used in the wood products industry, to the best of our knowledge, very few studies have attempted to apply SPC to forest operations (see Lepage and LeBel 2007). Therefore, this study was designed as an attempt to apply the basic concepts of SPC to forest harvesting processes. The objective of this study was to develop a methodology for successfully applying the standard theories of SPC to actual harvesting data as an approach for process improvement.

4.3 METHODS

4.3.1 Dataset

The dataset used in this study was collected from a single company's records on several pieces of their whole-tree harvest systems and included two feller-bunchers and four grapple skidders. The machines were used in predominantly single-shift, whole-tree harvesting operations on 30 tracts throughout Maine. The operator of each machine filled out a daily shift report recording overall machine performance and daily operating conditions (Appendix B). The date, machine number, operator name, operator shift time, machine shift time, equipment meter reading time, estimated fuel consumption, tract name, terrain, and production were recorded for each machine. An operational summary for each machine can be found in Table 4.1 and Table 4.2.

Operator shift time began when the machine was first started in the morning and ended after the machine was fueled and serviced at the end of each day. The machine shift time included the time when the machine started and stopped moving for the day. The equipment meter reading time was the daily record of operating hours recorded directly from the hour meter on the machine. Dominant terrain conditions were recorded by attribute classes that included wet, rocky, steep, or flat, with each being documented in a binary fashion – either encountered during the shift or not. Therefore, the terrain variable for a single shift can be an individual terrain type or any combination of the four types. Grapple skidder operators also recorded as part of their terrain type whether they were skidding uphill, downhill, or on a hilly site; however, these were not pertinent to every terrain type (e.g., uphill or downhill skidding was not recorded for flat terrain), or

Table 4.1. Operating summary for feller-bunchers.

	Feller-buncher 1	**Feller-buncher 2**
Machine make and model	TIGERCAT 845B	TIGERCAT 822
Year	2002	2003
Equipment hours at beginning of study	5406	429
Number of operators	3	7
Total days of productive operation	310	331
Number of tracts operated on	21	13
Average fuel consumption (liters/shift)	269	256
Average number of bunches cut per shift	70.9	61.2
Average number of operating hours per shift (hh.h)	8.9	9.0
Average equipment hours per shift (hh.h)	8.8	8.3
Average shift time (hh.h)	10.1	10.4
Average utilization rate (%)*	80.6	75.6
Number of terrain types operated on	8	11

* Utilization is calculated by dividing the productive machine hours per shift by the operator shift time.

Table 4.2. Operating summary for grapple skidders.

	Grapple skidder 1	**Grapple skidder 2**	**Grapple skidder 3**	**Grapple skidder 4**
Machine make and model	JOHN DEERE 648GIII	JOHN DEERE 648GIII	JOHN DEERE 648GIII	JOHN DEERE 648GIII
Year	2003	2003	2004	2006
Equipment hours at beginning of study	3624	3295	1637	1
Number of operators	11	11	8	6
Total days of productive operation	375	369	356	237
Number of tracts operated on	16	15	18	12
Average fuel consumption (liters/shift)	138	141	133	142
Average number of twitches yarded per shift	47.3	43.1	42.1	44.3
Average number of operating hours per shift (hh.h)	9.3	9.3	9.0	9.4
Average equipment hours per shift (hh.h)	8.8	9.0	8.5	9.0
Average shift time (hh.h)	10.3	10.4	10.0	10.2
Average utilization rate (%)*	82.9	80.4	79.0	86.6
Number of terrain types operated on	22	23	20	10

* Utilization is calculated by dividing the productive machine hours per shift by the operator shift time.

recorded in combination with each other (e.g., recording uphill and downhill skidding for the same shift).

Production was recorded for each machine as a total count of bunches cut for feller-bunchers, or total hitches yarded for grapple skidders over the entire shift. Productivity was self-reported and operators kept track of their respective counts throughout the shift using tally meters mounted in each machine. Feller-buncher operators also recorded a categorical variable identifying which of five general silvicultural prescriptions were being implemented during each shift; select, group select, overstory removal, clearcut, or right-of-way. Only a single prescription was executed per shift. Right-of-way records were not included in this analysis because a substantial portion of the material harvested was not merchantable and did not count towards production. None of the feller-bunchers were used for clearcutting operations during the period of data collection.

All operators recorded productive delays and nonproductive downtime. Productive delays included any delay ≥ 15 minutes that occurred between the start and stop machine shift times. Nonproductive downtime included any downtime ≥ 15 minutes that occurred between the start and stop operator shift times, but outside the start and stop machine shift times. Both delays and downtime were categorized as mechanical or operational. Mechanical delays or downtime included any nonproductive time resulting from a mechanical issue for that machine, whereas operational delays or downtime included all other nonproductive time.

The daily reports were entered into a separate database for each machine type (i.e., feller-buncher, grapple skidder). The databases included records kept on the machines for just over one and a half years (September 19, 2005 to June 1, 2007), although the time span for individual machines slightly varies. Prior to conducting this study the datasets were evaluated for missing or erroneous entries. The data were not collected for the express purpose of implementing an SPC program and therefore poses several challenges in applying SPC theory.

4.3.2 Defining the process and identifying critical measures

The process analyzed in this study was the harvesting (or skidding) work cycle for individual feller-bunchers (or grapple skidders) over the period of one shift. The feller-buncher harvesting work cycle consisted of the tasks required to produce one bunch of accumulated whole-trees piled on the ground for subsequent skidding. The grapple skidder work cycle consisted of the tasks required to collect and transport one hitch of accumulated bunches to the landing. It is important to note that the units of *bunch* and *hitch* are not identical in many cases as a grapple skidder may accumulate more than one bunch in a single hitch. Therefore, the productivities of the two machines cannot be directly compared.

In order to understand these processes their performance must be evaluated using some sort of measure(s), known as *critical measurements* (Kiemele *et al*. 1997). Typically these reflect one or more outputs of the process. Because variability is always present, the critical measurements can be regarded as random variables characterized by their probability distribution. The distribution parameters of an in-control process are referred to as *control parameters*. Machine productivity was used as the critical measure for this dataset as it is the only output metric recorded, but other metrics such as number of acres harvested, fuel use, or operating cost could also be measured and tracked to assess performance. The productivity variable in this study was defined as the total number of bunches produced by each feller-buncher, or the number of hitches yarded by each grapple skidder over the period of one shift. Because this study assessed productivity, only observations with positive bunch or hitch counts from each database were included in the datasets.

Since the productivity variable is based on discrete data, it provides only a coarse assessment of the actual productivity because the true volume of each bunch or hitch is unknown and likely varies substantially from one to the next. While a continuous variable such as an exact weight or volume measurement (e.g., tonnes per bunch or cubic meters per hitch) would provide a better assessment of the productivity, collecting this data would likely be difficult, costly, and/or excessively impede on the productivity of the operation. The assumption then is that the operators fully utilize the accumulating capacity of their respective machines on each cycle and in doing so produce bunches or hitches of approximately equal size. Under this assumption the bunch and hitch count is assumed to be a suitable enough proxy for the actual volume produced and provide a useful measure of productivity.

In order to compare the individual bunch or hitch counts to one another they must have equally sized *areas of opportunity* (Wheeler and Chambers 1992, Wheeler 2004). In this case the number of productive machine hours (PMH; i.e., the area of opportunity) for each observation is not always the same from shift-to-shift. Therefore a bunch count of 10 cannot be directly compared to a bunch count of 130 when the former was attained after only 2 PMH in one shift and the latter after 11 PMH in another shift. Essentially, because the number of PMH varies from one shift to another it becomes a special cause of variation and must be removed. This is achieved by converting the counts into rates by dividing each count by its area of opportunity (Wheeler and Chambers 1992). The number of PMH for a given shift was obtained by subtracting the total time of any mechanical or operational productive delays from the machine shift time. Each production observation was then divided by the calculated PMH for that shift. As a result the previous definition for the productivity variable based on the period of one shift becomes: the average number of bunches cut by each feller-buncher, or hitches yarded by each grapple skidder per PMH as recorded for each shift. This production variable will be referred to as the *operating productivity* for the remainder of this study. This transformation shifts the analysis question from *how much has the machine produced at the end of each shift?* to *when the machine is running, how productive is it?*

Usually the variation is tracked in the critical output(s) of the process, but in many cases it makes sense to track variation in critical inputs as well, particularly to gain an understanding of the variability in inputs that directly influence the output measures. As an example, because the operating productivity is only a rate, managers may not be happy with one or two PMH per day no matter how high the operating productivity is during that time. While not conducted for this study, the operating productivity would therefore need to be compared to the machine utilization rate (i.e., productive machine hours per shift divided by the operator shift time) to assess the productive operating time per day. Other examples of influential inputs in this study could include tract, machine, operator, terrain type, and prescription variables. Based on previous forest operations research these variables could be expected to influence productivity (Greene *et al*. 1987, Gingras

1988, 1989, Purfürst 2007, Dvořák *et al*. 2008). Therefore, a correlation analysis was conducted of all the variables within each database to identify any influential relationships (Table 4.3 and Table 4.4). Only the operating times (i.e., machine shift time, operator shift time, and meter reading time) and fuel consumption were found to have any substantial correlation to bunch and hitch count variables. Operator, machine, tract, terrain type, and prescription showed little to no correlation to production.

4.3.3 Control charting

The control chart is the tool that allows the practitioner to identify excessive variation, and, when the causes of that variation are identified, to bring the process into a state of statistical control. There are two distinct phases in control charting (Woodall 2000, De Mast and Roes 2004, Chakraborti *et al*. 2009, Montgomery 2009). In Phase I (also referred to as preliminary or retrospective analysis), the aggregate of historical observations from one or more samples of the process variables are retrospectively assessed to determine the natural variation of the process, and to develop control limits to see if the process was in control. In this phase the control chart is used as an analytical tool to explore and understand the process behavior, and to identify the limitations of natural variation within the process. The primary objective of Phase I analysis is to estimate the unknown control parameters of the in-control process (De Mast and Roes 2004). This is achieved through a cyclical procedure of collecting an initial sample of process data, plotting the process critical measurement on a control chart with trial control limits calculated from the data, identifying out-of-control (OOC) observations based on those limits. The procedure continues by attempting to identify the underlying

Table 4.3. Correlation coefficients for feller-buncher variables.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
(1) Tract	1									
(2) Feller-buncher #	0.336	1								
(3) Operator	-0.214	-0.425	1							
(4) Machine shift time	-0.007	0.016	-0.048	1						
(5) Meter reading time	-0.004	-0.119	-0.032	0.849	1					
(6) Operator shift time	-0.020	0.110	-0.065	0.683	0.598	1				
(7) Fuel consumption	0.111	-0.087	-0.047	0.742	0.823	0.518	1			
(8) Terrain	-0.118	0.348	-0.123	0.049	-0.028	0.055	-0.049	1		
(9) Prescription	-0.099	0.070	0.036	-0.068	-0.100	-0.133	-0.060	0.087	1	
(10) Total # of bunches cut	0.012	-0.211	-0.038	0.712	0.805	0.477	0.762	-0.082	-0.120	1

Table 4.4. Correlation coefficients for grapple skidder variables.

		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(1)	Tract	1								
(2)	Grapple skidder #	0.168	1							
(3)	Operator	-0.049	0.251	1						
(4)	Machine shift time	-0.044	-0.015	0.002	1					
(5)	Meter reading time	-0.022	0.006	0.002	0.795	1				
(6)	Operator shift time	-0.030	-0.035	-0.072	0.769	0.684	1			
(7)	Fuel consumption	-0.023	-0.006	-0.052	0.574	0.612	0.523	1		
(8)	Terrain	-0.012	-0.041	0.006	0.003	-0.013	-0.002	0.027	1	
(9)	Total # of hitches yarded	0.014	-0.095	0.067	0.615	0.616	0.509	0.509	-0.015	1

sources of disparity of any OOC observations, correcting OOC observations resulting from the identified cause, recalculating the control limits, collecting new data, and repeating the process (Montgomery 2009, Chakraborti *et al*. 2009). This process is repeated until at some point the plotted data fall within the most recently calculated control limits, exhibiting only the natural variation of the process (Chakraborti *et al*. 2009). It is important to emphasize that not only is the data adjusted to be in-control through this process, but the harvesting process itself must also be systematically controlled through engineering and operating personnel before entering Phase II (Montgomery 2009). Therefore, as special causes are identified during each iteration of Phase I analysis they are not only eliminated from the data but also from the process.

The success of Phase II is critically dependent on a careful Phase I assessment. Inappropriately or inadequately isolating the true natural variation of the process and using the associated parameters to calculate the control limits for Phase II analysis would result in developing a faulty standard to evaluate the process, potentially causing management errors with serious economic consequences. Therefore, the greatest challenge in Phase I analysis is to estimate control parameters based on the observations in the initial sample that are robust enough to identify the presence of out of control observations within the initial sample (Boyles 1997, Bryce *et al*. 1997, De Mast and Roes 2004). Once the process has been brought into a state of control, the limits based on the control parameters become the definition of statistical control for that process.

Phase II (or prospective analysis) then, is the monitoring phase that uses the parameters established in Phase I from the in-control data (also called reference data; Chakroborti *et al*. 2009) to analyze the behavior of the process in comparison to the control baseline as future records are collected. Unlike Phase I analysis which is concerned with the entire initial data sample, Phase II is only concerned with analyzing individual values for special causes as they are collected to verify whether the process is still in statistical control. The emphasis in this phase is quick and accurate identification of special causes of variation in the active process so that corrective action can be taken to prevent economic loss. Equally important is the prevention of economic loss associated with taking action on natural process variation.

As special causes are removed and the process is brought in-control during Phase I, the form of the underlying probability distribution becomes more important in determining the appropriate approach to calculating control limits for Phase II (Woodall 2000). This is because the control chart in Phase II takes on more of a theoretical design, as opposed to the analytical design in Phase I. Because control parameters are assumed to be known in Phase II the control chart can be used like a series of consecutive hypothesis tests (Woodall 2000). Normality is not a requirement in Phase I analysis. There is an important discussion on normality and the empirical rule that Wheeler (2004) addresses. The basic point he makes is that the empirical rule can be applied fairly well to other distributions as well. Due to the broad differences in theoretical backgrounds of Phase I and II, analysis this study will only focus on applying the theories of Phase I SPC to the forest harvesting dataset[5].

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[5] For more information on Phase II analysis see Montgomery (2009).

4.3.4 Types of charts

Several adaptations of Shewhart's original control chart have been developed to conform to various circumstances. Selection of a specific chart type will depend on the nature of the data being plotted. In most cases control charts are based on measurement data where observations are collected from an infinitely divisible continuum (i.e., heights, weights, temperature, and time). However, as previously discussed, the productivity variable in this study consists of discrete data based on counts. The *p*, *np*, *c*, and *u* control charts are widely used in the field of SPC for control charting of attribute data (Woodall 1997). However, these charts were developed primarily for quality control purposes and focus on monitoring the fraction of non-conforming products or non-conformities within a product. Conformity is typically based on strict specification limits. Therefore, the concepts of these charts are difficult to apply to a forest operations setting where the focus is on increased production.

Typically the configuration of a process may suggest rational subgroups (i.e., observations carefully combined to form groups of size $n > 1$) [6] of relatively homogeneous data, or the process is sampled ($n > 1$) at regular intervals. In these cases mean-charts ($\bar{x}$-charts) are usually employed where the means of the subgroups ($\bar{x}$) are plotted on the y-axis at each time interval (ASTM International 2002, De Mast and Roes 2004). However, the data used in this study only has individual production observations ($n = 1$) recorded for each time interval (i.e., total number of bunches cut or hitches yarded per shift). Each observation ($X_1, X_2, \ldots, X_m$) is the result of a unique, heterogeneous combination of day-to-day operating conditions (i.e., operator, tract, terrain, machine,

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[6] For detailed information on subgrouping see Grant and Leavenworth (1996) and Wheeler (2004).

prescription, etc.). Subgrouping of these X values would combine measures that were likely obtained under very different conditions. If rational subgroups are formed, the conditions under which the data were collected must be essentially the same and the subgrouped values need to be as homogeneous as possible so that if special causes are present they show up as differences between subgroups rather than differences between the members of a subgroup (Duncan 1986, Wheeler 2004, Montgomery 2009). Therefore, no rational subgroups of the values were formed for the productivity variable in this study and the individual values were used.

Control charts for individual observations, known as individuals charts (also, Shewhart X-charts or i-charts), were used in this study to evaluate the operating productivity of each machine over time. Individuals charts are often used to monitor processes where little data are available or where it does not make sense to sub-group measurements (Montgomery 2009). Although the individuals chart was originally introduced as a charting technique for continuous measurement data, its use with the count data of this study does not present a problem as long as each observation has an equal area of opportunity (Gitlow 1989, Wheeler and Chambers 1992). Individuals charts show a running display of only a single observation per time interval. As a result, they tend to be much more variable than $\bar{x}$-charts and therefore less sensitive to shifts in the critical measures (Oakland 2007).

Additional control charts are often constructed to monitor the variation of observations. In the case of sampled or sub-grouped data, the variability of the observations is monitored within each subgroup using a range chart (*R*-chart)[7]. *R*-charts display the dispersion of the sample data in the $\bar{x}$-chart, plotting the range (i.e., the absolute difference between the highest and lowest observation) of each sample per time interval. But, because it is impossible to calculate the within-sample variation when the sample size equals one, the range chart does not work with individuals data. Traditionally, the process control procedure for individual observations utilizes the moving range (*MR*) chart in conjunction with the *X*-chart as the counterpart of the *R*-chart (Duncan 1986, Wheeler and Chambers 1992, Wetherill and Brown 1991, Montgomery 2009). *MR*-charts track the range of successive groups of individual observations as a means of identifying changes in the process standard deviation. Recently the practice of plotting the moving range has been shown to be inefficient for the purpose of identifying parameter shifts and several researchers believe that its use should be discontinued. (Nelson 1990, Rigdon *et al*. 1994, Sullivan and Woodall 1996, Woodall 2000, Trip and Wieringa 2006). Nelson (1982) and Roes *et al*. (1993) argued that the *X*-chart essentially contains the same information, the *MR*-chart is difficult to interpret due to the serial correlation of the successive points, and that the probability of the *MR*-chart signaling given that the *X*-chart did not, is very small. Therefore, *MR*-charts were not included in this study.

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[7] For more information on mean and range charts refer to Wheeler and Chambers (1992), Ryan (1989), Oakland (2007), and Montgomery (2009).

4.3.5 Determining the centerline and control limits

Traditional symmetrical Shewhart (1931) control limits are calculated using the formula

$$\mu \pm t\sigma \tag{1}$$

Where μ denotes the in-control process mean, and σ denotes the in-control process standard deviation. The CL, represented by the chart parameter μ, is an estimate of the center of the actual population distribution for the critical measurement. The chart parameter t denotes the distance of the control limits from the CL, as a rule taken to be 3 to give the traditional Shewhart three sigma limits, and a total of six sigma. Therefore, control charts are based on the premise that if a process is affected only by common causes, then observations from that process will almost always fall between $\mu \pm 3\sigma$. Observations exceeding these limits are considered excessive and likely the result of a special cause. Shewhart assumed that symmetrical control limits set at $t = 3$ were an acceptable economic value (Shewhart 1931) and over time, empirical evidence has shown the three sigma limits to be very effective in practice at minimizing the economic consequences of either interpreting natural variation as a signal (Type I error) or missing a signal altogether (Type II error; Shewhart 1931, Wheeler 2004)[8].

In Phase I analysis the control parameters μ and σ of the process are not known and must be estimated. This situation is referred to as the *standards unknown case*, or *case U* (as compared to the *standards known case* or *case K* of Phase II; Chakraborti *et al*. 2009). Rigdon *et al*. (1994) and Quesenberry (1993) stated that in order to achieve a suitable estimate of the process control parameters and establish trial limits, an initial

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[8] For a more detailed discussion of 3σ limits see chapter 5 of Wheeler (2004).

sample size of at least n =100 is required. Sample sizes for this study ranged from n =237 to n =375 for each machine.

Since the process is likely to initially contain special causes it is necessary to use robust methods of estimating the control parameters. In most cases μ can be effectively estimated using either the mean, $M(X_k)$, or median, $Med(X_k)$, of the initial sample data (Roes *et al*. 1993). For this study $M(X_k)$ was used to estimate μ as it is more commonly used within the peer review literature. An abundance of methods used to estimate σ for individual observations have been proposed throughout the literature (Braun and Park 2008). However, studies have shown that no single method of estimation out-performs the others under all special-cause scenarios (Boyles 1997, Braun and Park 2008). Three methods of estimating σ commonly used in Phase I analysis were considered in this study.

The standard method to estimate σ for a continuous process is to use the average of the moving range, $\overline{MR}\ (X_k)$, typically of span size n =2, (Nelson 1982, Duncan 1986, Wadsworth *et al*. 1986, Cryer and Ryan 1990, Wadsworth 1998, Wheeler and Chambers 1992, Rigdon *et al*. 1994, Grant and Leavenworth 1996, Stroumbos and Reynolds 2000, Vermatt *et al*. 2003, Braun and Park 2008, Montgomery 2009) where the moving range of span 2 at time t for sample X_k of size m is defined as

$$MR_t(X_k) = \left|\left(X_t - X_{t-1}\right)\right| \quad \text{for } (t = 2, 3, \dots, m) \tag{2}$$

and the mean of the moving ranges for sample X_k as

$$\overline{MR}(X_k) = \frac{\sum_{t=2}^{m} \mathrm{MR}_t}{m-1} \tag{3}$$

Essentially this method of estimating σ depends on arbitrarily creating small subgroups to capture the short-term variability. Although other group sizes ($n > 2$) can be used, using the moving ranges of span size =2 to estimate sigma is justified as representing the short-term process variation, as a sample or rational subgroup would, while also preventing the estimate from being influenced by a lack of control in the data due to special causes (Nelson 1982, Duncan 1986, Wadsworth *et al.* 1986). The control limits are calculated using

$$M(X_k) \pm \frac{3\overline{MR}(X_k)}{d_2(2)} \tag{4}$$

Where X_k – Denotes the initial sample
$M(X_k)$ – Denotes the mean of the initial sample
$\overline{MR}(X_k)$ – Denotes the mean of the moving ranges (of span size =2)
$d_2(2)$ – Is a constant[9] based on moving range span size that makes $\overline{MR}\ (X_k)$ an unbiased estimator of σ (1.128 for span size =2). The value $^3/d_2$ is sometimes replaced by the constant E_2 (2.6595 for span size =2)

Because the moving ranges are averaged, large special cause observations can still inflate the estimate $\overline{MR}\ (X_k)$ to some degree (Bryce *et al.* 1997). This is due to the fact that each observation comprises two moving ranges, allowing large isolated outliers to overly influence the estimate of σ (De Mast and Roes 2004). Because of this several authors have instead proposed using the median rather than the mean of the moving range (Ferrell 1953, Clifford 1959, Bryce *et al.* 1997, Wheeler 2000, De Mast and Roes 2004).

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[9] Constant factors for computing control chart limits for various sample sizes are listed in the ASTM manual on presentation of data and control chart analysis (Table 49, ASTM International 2002).

Control limits using the median moving range estimator for σ are given by

$$M(X_k) \pm \frac{3MMR(X_k)}{0.954} \tag{5}$$

Where X_k – Denotes the initial sample
$M(X_k)$ – Denotes the mean of the initial sample
$MMR(X_k)$ – Denotes the median of the moving ranges (of span size =2)
0.954 – Is a constant used to render $MMR(X_k)$ an unbiased estimator of σ

When using the moving range to calculate the control limits, we assume that the process is continuous throughout the time span of the dataset. In other words, the moving range could include the absolute difference between consecutive observations that were obtained either on two separate tracts or before and after a break in operations (i.e., weekends, mud season, holidays, long-term repairs, etc.), or both. In the case of feller-bunchers, it also assumes that the harvesting process remains largely unchanged when implementing different prescriptions. It is possible that these assumptions may inflate the moving range (and thus the estimations of σ), as differences between operations on two tracts or before and after a break could be drastically different, and therefore excessively influence the operating productivity. Further research will be required to identify the impact of these assumptions on the analysis and to identify alternative methods of handling these situations.

A third control limit formula advocated by Ryan (1989), and Cryer and Ryan (1990) for in-control processes uses the standard deviation of the initial dataset to estimate σ. The control limits in this case are calculated as

$$M(X_k) \pm \frac{3S(X_k)}{c_4(K)} \tag{6}$$

Where X_k – Denotes the initial sample
$M(X_k)$ – Denotes the mean of the initial sample
$S(X_k)$ – Denotes the standard deviation of the combined individual observations in the initial sample
$c_4(k)$ – Is a constant based on the total number of individual observations in the initial sample that makes $S(X_k)$ an unbiased estimator of σ (given by $\left(\frac{4n-3}{4n-4}\right)$ for n >25)

The standard deviation is a long term estimate of variability since it measures the dispersion of every observation within the initial sample over the entire time interval (Rigdon *et al*. 1994, Bryce *et al*. 1997). It is more sensitive to special causes in the data than formulas (4) and (5) because the required squaring of the individual values deviations causes outliers to substantially inflate the estimate of σ (Rigdon *et al*. 1994, Bryce *et al*. 1997, Montgomery 2009). As a result, Shewhart (1931) determined that the standard deviation of the individual observations results in control limits that are unnecessarily wide. Rigdon *et al*. (1994) recommended using the control limits based on formula (4) rather than the limits based on formula (5) for Phase I analysis. Cryer and Ryan (1990) recommended that both control limits (4) and (6) be calculated and compared for a given series of observations. If both control limits agreed reasonably well they felt that the practitioner could be fairly confident that the series was in control. However, if the process was not in control, then the $\frac{\mathrm{S(X_k)}}{\mathrm{c_4(k)}}$ estimate would be substantially inflated, and consequently, the control limits would be much wider than they should be (Braun and Park 2008). In this study all three sets of control limits were calculated based on formulas (4), (5) and (6). The limits were compared to one another to assess their performance and to identify if special causes exist within the dataset; however, OOC observations were identified using the limits based on formula (5).

4.3.6 Runs Rules

If a process is in control, then nearly all of the observations should fall between the upper and lower control limits and only exhibit random variation. In some cases “in-control” data may fluctuate in systematic, non-random patterns indicating the presence of special variation. While control limits are useful in detecting obvious deviations from randomness (i.e., outliers) they are less useful in identifying sustained shifts in the mean of the process or repetitive trends in the observations. Several decision rules known as *runs rules* or *sensitizing rules* have been developed to objectively identify non-random patterns and sustained shifts on control charts. The most widely cited runs rules were first published in the Western Electric Handbook (1956) with later improvements by Nelson (1984). These rules partition the spaces above and below the CL each into three equal zones (A, B, and C) one sigma in width (Figure 4.1). For this reason these charts are often referred to as *zoned* control charts. These runs rules are applicable to individuals control charts assuming that the data can be reasonably described by means of the normal distribution (Nelson 1984, Albin *et al*. 1997, De Mast and Roes 2004). Unnatural patterns are identified using the following rules

(1) A single point falls outside of the 3 sigma limit (beyond zone A)
(2) Eight points in a row in zone C or beyond
(3) Six consecutive points in a row steadily increasing or decreasing
(4) Fourteen points in a row alternating up and down

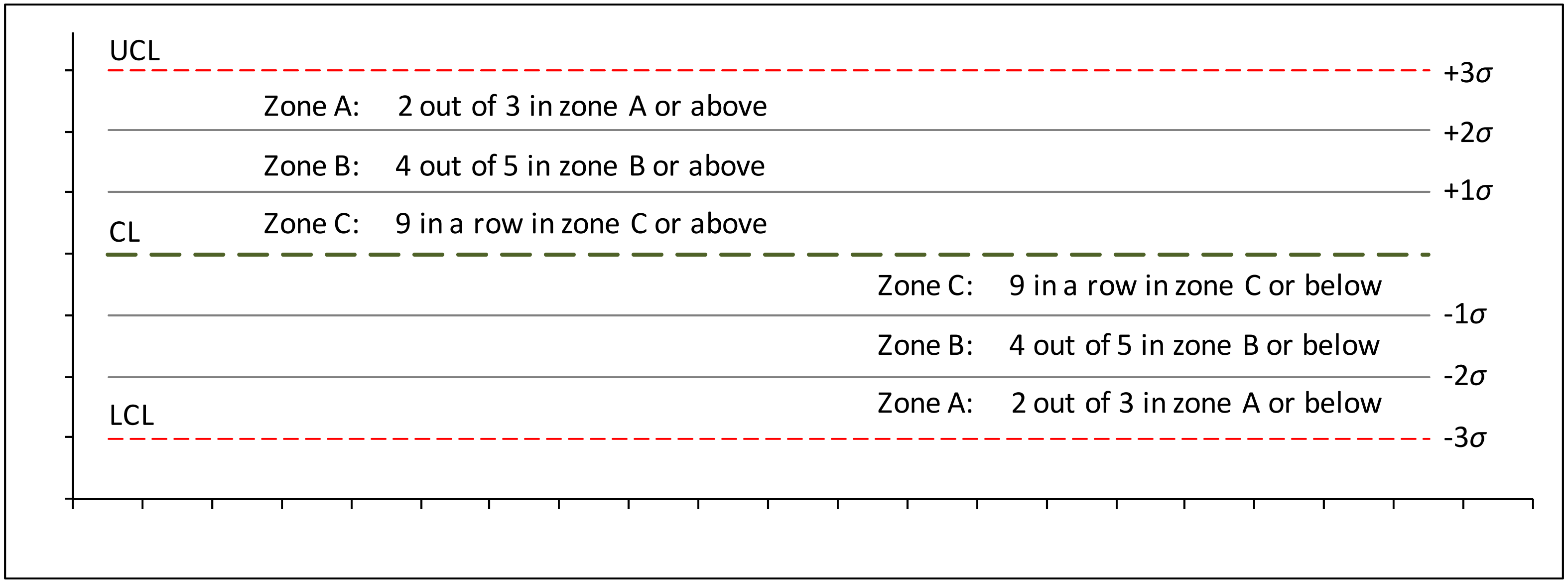


Figure 4.1. Visual summary of rules for identifying unnatural control chart patterns. Rules 2, 5, and 6 are listed in their respective zones (redrawn from the Western Electric Handbook (1956)).

(5) Two out of three successive points fall in zone A or beyond

(6) Four out of five successive points fall in zone B or beyond

(7) Fifteen or more consecutive points in a row in zone C on both sides of the centerline

(8) Eight consecutive points on both sides of the centerline with non in zone C

Runs rules 1, 2, 5, and 6 are applied to the upper and lower halves of the chart separately (Figure 4.1), while rules 3, 4, 7, and 8 are applied to the whole chart. The first rule is the standard 3σ control limit rule for identifying individual OOC observations. The last observation in each run is marked to indicate the presence of a pattern (Western Electric 1956, Nelson 1984). According to the Western Electric Handbook (1956) a single observation can be assessed with more than one runs rule. Likewise, because a run can be formed from any combination of observations meeting the rule criteria, an individual observation can also be assessed with the same rule multiple times.

Runs rules are commonly used to improve the sensitivity to patterns and shifts, but often result in an increased false alarm rate, in some cases with no added detection benefit. For example, several researchers have shown that rule 3 is ineffective in detecting a trend in the process and increases the false-alarm rate (Woodall 2000, Montgomery 2009). They recommend that it not be used as a supplementary rule. Consequently, for this study, only rules 1 – 2 and 4 – 8 were applied to the control charts to assess their applicability and usefulness on the forest operations data.

4.4 RESULTS AND DISCUSSION

4.4.1 Phase I analysis

As noted earlier, the goal of Phase I analysis is to 1) ensure that the process is operating at or near an acceptable level under only natural causes of variation, with no special causes present, and 2) estimate the parameters of the in-control process. As an initial step of this process, X-charts of the operating productivity variable were developed for each machine (Figure 4.2) using the methodology previously outlined. A summary of the estimated control limits for the data are listed in Table 4.5.

The control charts, specifically the control chart limits, clearly express the level of variation operations managers must attempt to work with on a daily basis. All six charts are characterized by frequent spikes, both up and down, in operating productivity. There are few examples where the felling or skidding process exhibits stable, consistent output over any substantial period of time. In all six cases, the control limits calculated using formula (5) had the narrowest range, while the limits based on formula (6) had the widest. The disparity between the control limits calculated using formulas (4) and (6) in all six control charts clearly indicate the presence of special causes of variation within the datasets. Differences between control limits based on formulas (4) and (5) were only minor and most likely the result of formula (4) being more sensitive to the many outliers within the datasets. It is important to note that although the data used to compute the control limits may be OOC, the formula (4) and (5) limits obtained are still robust enough to detect that lack of control within individual observations.

The feller-buncher control charts indicate that on average the operating productivity of feller-buncher 1 (FB1) was greater than feller-buncher 2 (FB2), across all

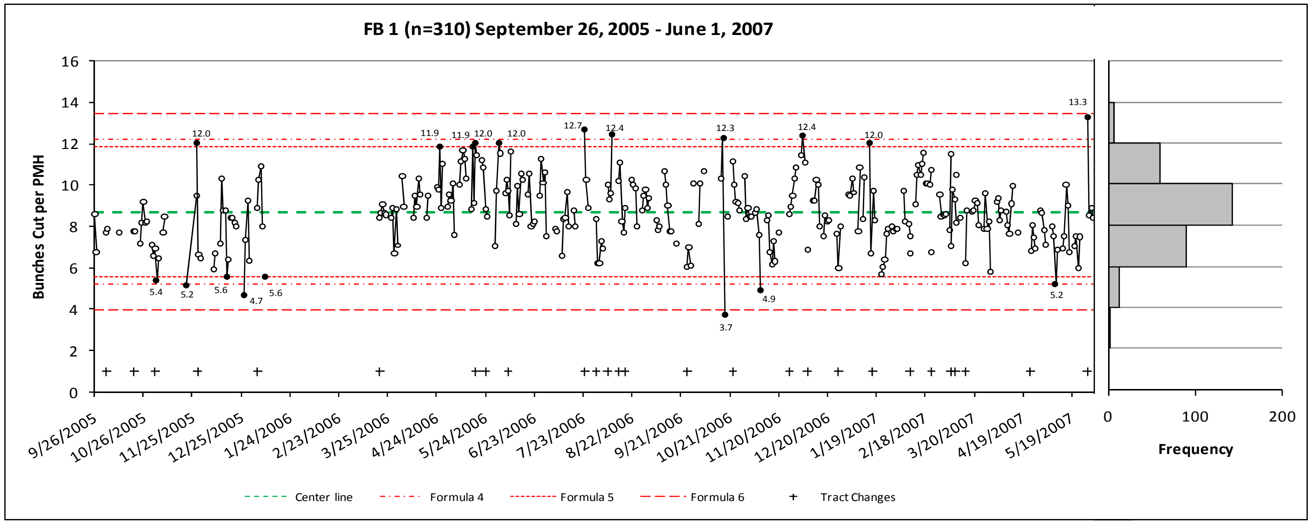
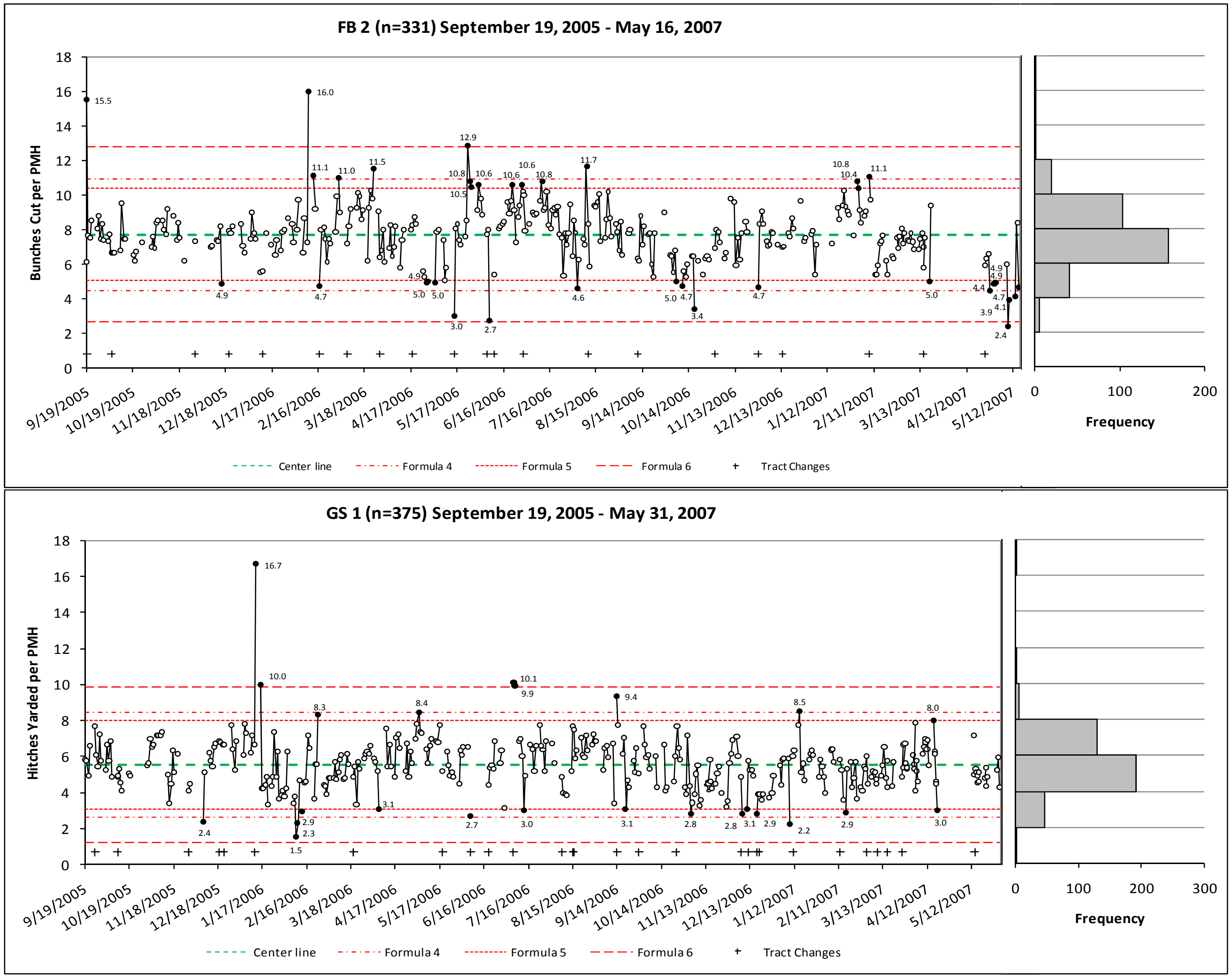


Figure 4.2. Individuals control chart of operating productivity by machine with control limits calculated using formulas (4), (5) and (6). Rule-1 OOC observations have been identified based on formula (5) control limits. A frequency distribution of the data is included on the right. Indications of tract changes (+) are also included. The title of each figure denotes the machine (feller-buncher 1 (FB 1), feller-buncher 2 (FB 2), grapple skidder 1 (GS 1), grapple skidder 2 (GS 2), grapple skidder 3 (GS 3), or grapple skidder 4 (GS4)), the total number of observations, and the observation period.



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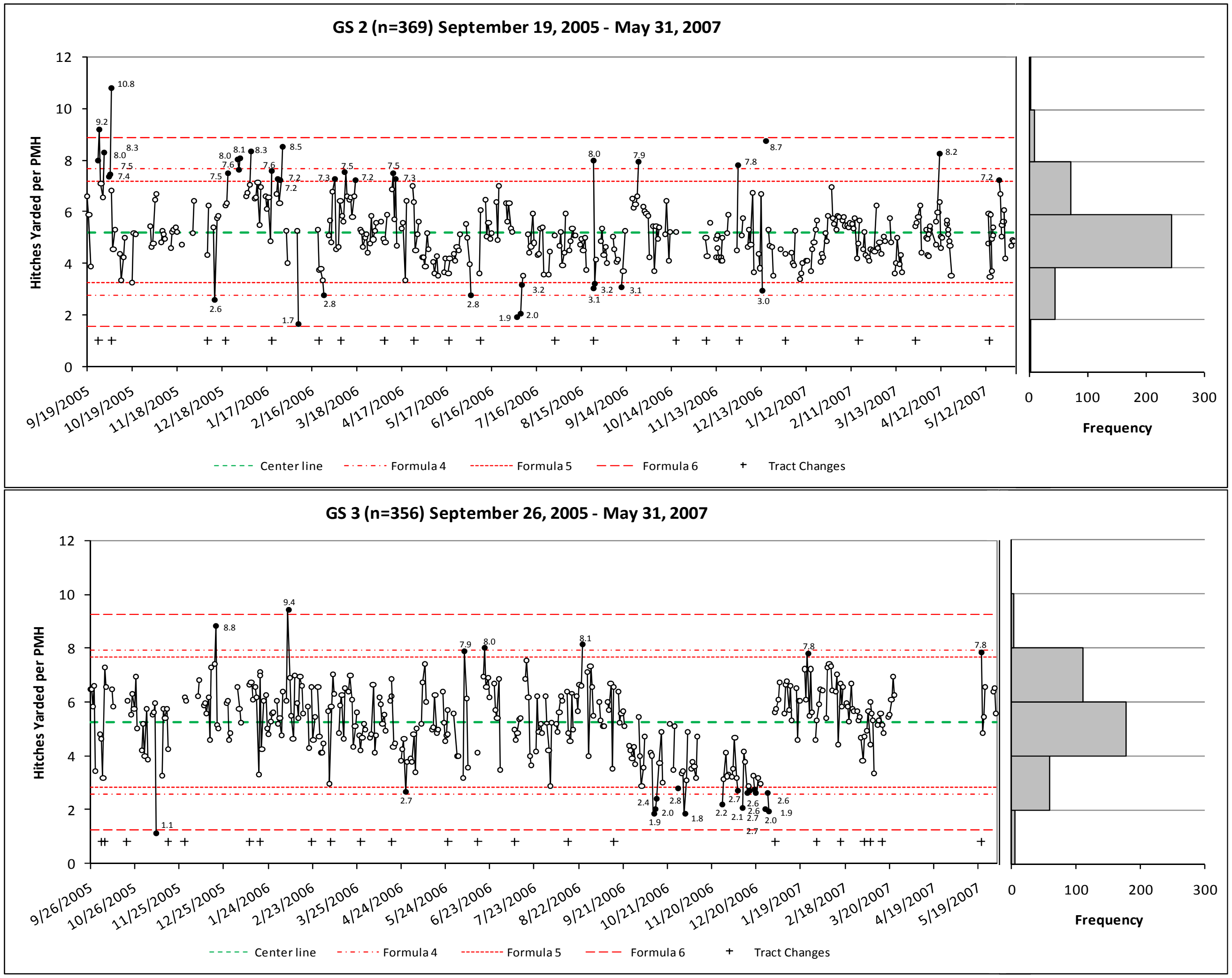

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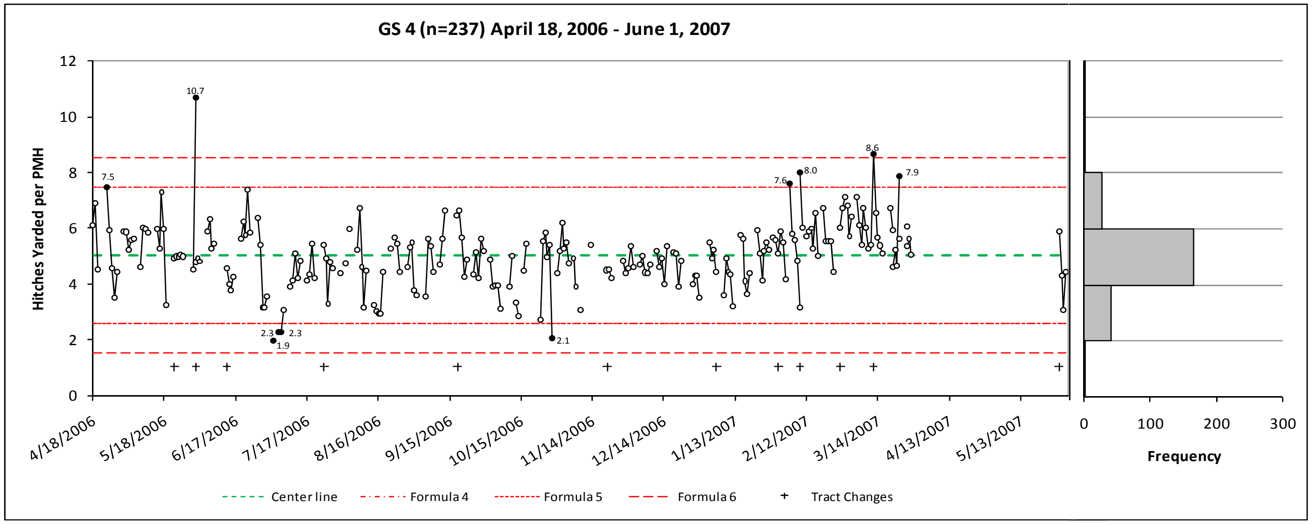


(Figure 4.2. Continued)

Table 4.5. Summary of control chart line values by machine, including the estimated value of σ based on formulas (4), (5), and (6).

	Mean/ CL	Median	Overall Range	Standard Deviation*	Formula 4			Formula 5			Formula 6		
					σ	UCL	LCL	σ	UCL	LCL	σ	UCL	LCL
Feller-buncher 1	8.70	8.59	9.5	1.6	3.5	12.21	5.20	3.1	11.85	5.56	4.8	13.46	3.95
Feller-buncher 2	7.71	7.71	13.6	1.7	3.2	10.94	4.48	2.7	10.37	5.05	5.1	12.77	2.65
Grapple skidder 1	5.56	5.52	15.1	1.4	2.9	8.45	2.66	2.4	8.00	3.11	4.3	9.86	1.25
Grapple skidder 2	5.21	5.11	9.1	1.2	2.4	7.65	2.77	2.0	7.17	3.25	3.6	8.85	1.57
Grapple skidder 3	5.24	5.41	8.3	1.3	2.7	7.92	2.57	2.4	7.67	2.82	4.0	9.24	1.25
Grapple skidder 4	5.02	5.04	8.7	1.2	2.5	7.47	2.56	2.4	7.45	2.58	3.5	8.50	1.53

* Actual standard deviation of the initial sample data.

tracts, terrain types, operators, and prescriptions. Based on the actual standard deviation of the data for each machine, the variation of the operating productivity variable for both machines was generally similar. However, the overall range in values for FB2 was greater than FB1, a result of the large outliers in the FB2 data. The control limits based on formula (5) identified 19 OOC observations (based on rule-1) for FB1 and 36 for FB2.

For the skidders, the control charts indicate that on average the operating productivity of grapple skidder 1 (GS1) was the greatest, followed by grapple skidder 3 (GS3) than grapple skidder 2 (GS2), with grapple skidder 4 (GS4) having had the lowest average operating productivity. However, the mean of GS1 is substantially inflated by the OOC observation occurring on 1/13/06 (16.7 hitches·PMH^{-1}). Because of this, GS1 also exhibited both the highest variability and the largest range in operating productivity values. Of the remaining three skidders, the operating productivity of GS4 was the least variable while GS3 was the most. The range in productivity values was the greatest for GS2 and the least for GS3. The formula (5) control limits identified 24 OOC observations (based on rule-1) for GS1, 37 for GS2, 24 for GS3, and 10 for GS4. A summary for each rule-1 OOC observation was produced from the datasets and includes the record number, date, data value, operator, prescription (in the case of feller-bunchers), terrain type, number of PMH, utilization rate, tract name, as well as a description and total time of any productive or nonproductive delays or downtime (excluding regular breaks and minor maintenance; Appendix C).

Based on the limited amount of data collected on each machine and the vast number of potential input variables that could have affected the performance of individual records it was difficult to determine underlying special causes for many of the

OOC observations. Several of the OOC observations that fell below the LCL had recorded notes that could at least help to explain why the productivity was low (e.g., unfavorable operating conditions, or working on unproductive tasks). It is important to emphasize, however, that while many of the downtime and delay details may help to explain that shift's utilization rate it does little to explain the productivity of the machine when operating, which is the charted variable of interest. For example, a broken hydraulic hose does not explain the productivity of the machine while it was operating. In many instances sustained drops in machine productivity could be linked to particular tracts. For example, FB2 had a noticeable reduction in operating productivity after moving to a different tract on 4/24/07 and conducting an OSR on rocky/flat terrain. Notes indicate several mechanical problems throughout this time and poor utilization rates, particularly on the latter OOC shifts. Although none of the observations signaled, operating productivity values for GS2 were consistently below average from 4/25/06 to 5/15/06 while operating on a single tract with rocky/hilly terrain. A sustained reduction in productivity with several signals occurred for grapple-skidder 3 from 9/15/06 to 1/2/07 and was identified as resulting from a tract with a long yard distance.

For observations that exceeded the UCL there was less obvious information about the operating methods and conditions that could be used to identify what contributed to the increased operating productivity. Surprisingly, several of the operating productivities exceeding the UCL were associated with very low utilization rates (e.g., record no. 5, 151, 328, 762, 888, 1015, 1073, 1311, 1356, 1512, 1633, and 1862). Several cases were again identified where higher productivities occurred on a particular tract. While none of the observations signaled, FB1 had higher than average productivity on a tract from

2/9/07 to 2/22/07 while conducting an OSR on flat terrain. Productivity for FB2 was also consistently higher on a single tract from 6/10/06 to 6/29/06 while conducting an OSR on terrain generally classified as wet/rocky/flat. The control chart for GS2 indicated two tracts with high operational productivity values, several of which exceeded the UCL. The first occurred from 9/26/05 to 10/5/06 while skidding uphill on wet terrain, and the second from 12/20/05 to 1/19/06 on wet/flat terrain.

A special cause of variation identified by the OOC summary data was the presence of several estimated production values (e.g., record no. 345, 364, 485, 890, 911, and 1458). All but one of these estimations resulted in operating productivity values that exceeded the UCL. The extremely high operating productivity value of 16.7 hitches per PMH on 1/13/06 for GS1 (record no. 345) was found to be a poorly estimated value. As part of the Phase I analysis all estimations of productivity should be excluded from the dataset as they do not accurately reflect the actual process behavior and bias the control parameter estimates. Because of the structure of the dataset used in this study, there was no way of easily filtering out these estimated values.

While the charts identified several OOC observations, the distinction between common causes and special causes of variation remains largely context dependent. Applying the strict SPC definitions of natural and special cause variation can result in some confusion in the context of forest operations. For example, in the FB1 records for the OOC observation occurring on 12/27/05 (record no. 221) the operator noted that “snow covered the trees.” This would likely explain the OOC operating productivity of 4.7 bunches per PMH for that shift. In the strict sense this should probably be considered a special cause of variation. However, snow in Maine is a natural and uncontrollable environmental input that occurs each winter. Even if it is considered a special cause there is little that can be done to eliminate the effects of a deep snow on feller-buncher productivity. The challenge is in deciding how to address the situations where extraneous sources that cannot be controlled cause local shifts to occur, as the entire purpose is to prevent taking action on uncontrollable process variation.

4.4.2 Runs rules

Runs rules 1 – 2, and 4 – 8 were charted on zoned control charts (based on formula (5) control limits) that display the signaled runs for each machine (Figure 4.3). A summary of the number of runs identified by each rule can be found in Table 4.6. Generally, non-random patterns as indicated by rules 4, 7, and 8 were not found. However, rules 2, 5, and 6 identified an excessively large number of runs within the data. Clearly the rules find evidence of shifts in the data, but little information is obtained as to the number of shifts or the time instants on which they occur, even when the rules are applied individually to the chart. It is clear that the runs rules developed for manufacturing processes do not work as well with the type of variation included in the harvesting data.

Most of the trouble likely arises from our assumption that the process is continuous over all tracts. As indicated earlier, distinct shifts in the mean operating productivity were found to occur as the machines moved from one operation to the next. Because the estimates of σ used in this study absorb these shifts, the resulting generalized control limits are blind to them. Runs rules 4, 7, and 8 are also somewhat blind to these shifts because they are concerned with changes in long strings of continuous process data.

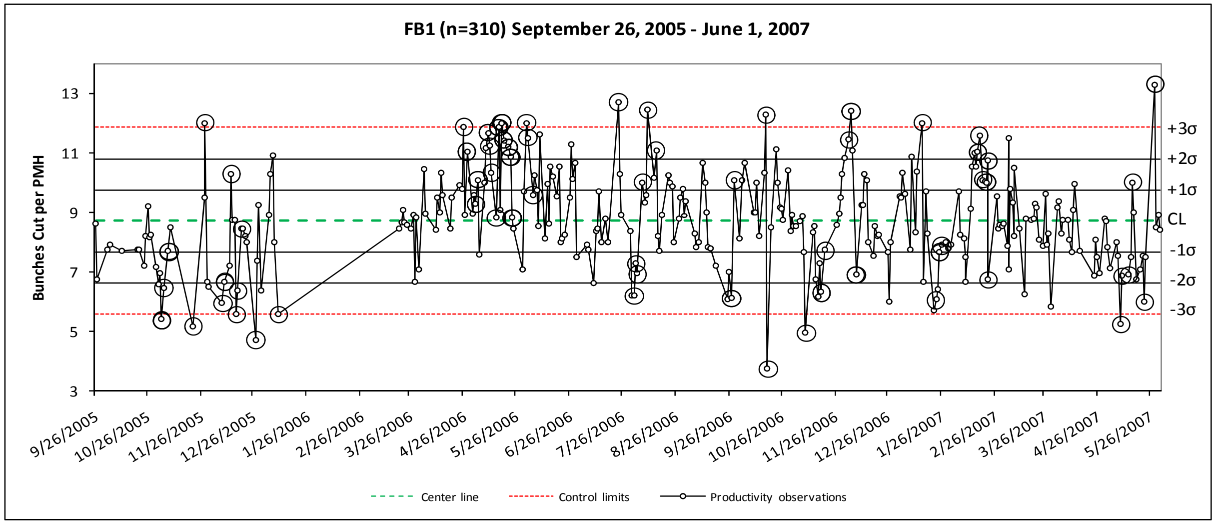
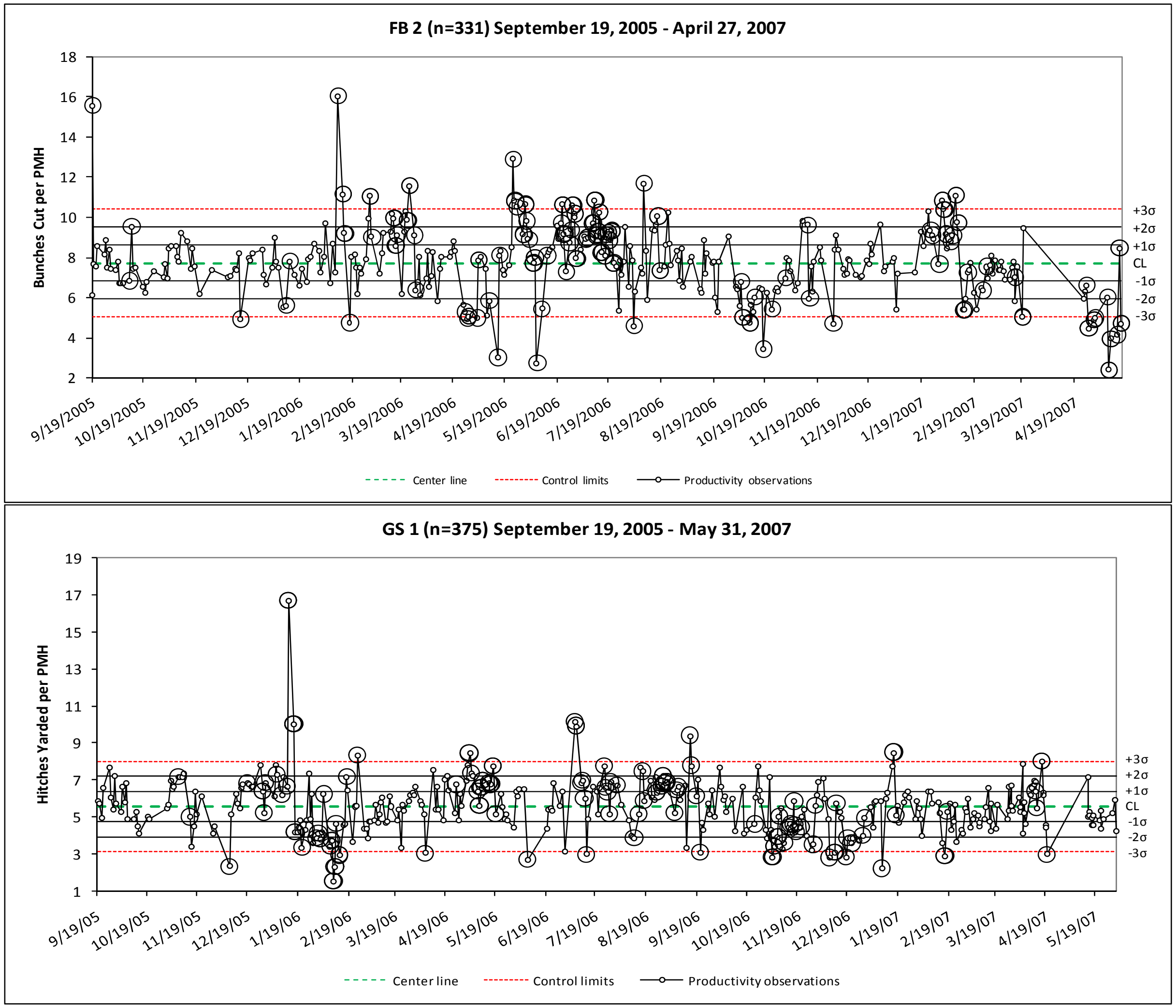


Figure 4.3. Zoned control chart of operating productivity by machine with control limits calculated using formula (5). Run rules 1 – 2, and 4 – 8 were used to identify patterns in the data. The last observation in each run is circled. Circled observations may be identified as out-of-control by one or more runs rules. The title of each figure denotes the machine (feller-buncher 1 (FB 1), feller-buncher 2 (FB 2), grapple skidder 1 (GS 1), grapple skidder 2 (GS 2), grapple skidder 3 (GS 3), or grapple skidder 4 (GS4)), the total number of observations, and the observation period. Note: Although the run line is un-segmented observations are not necessarily collected from consecutive operating days, refer to Figure 4.2.



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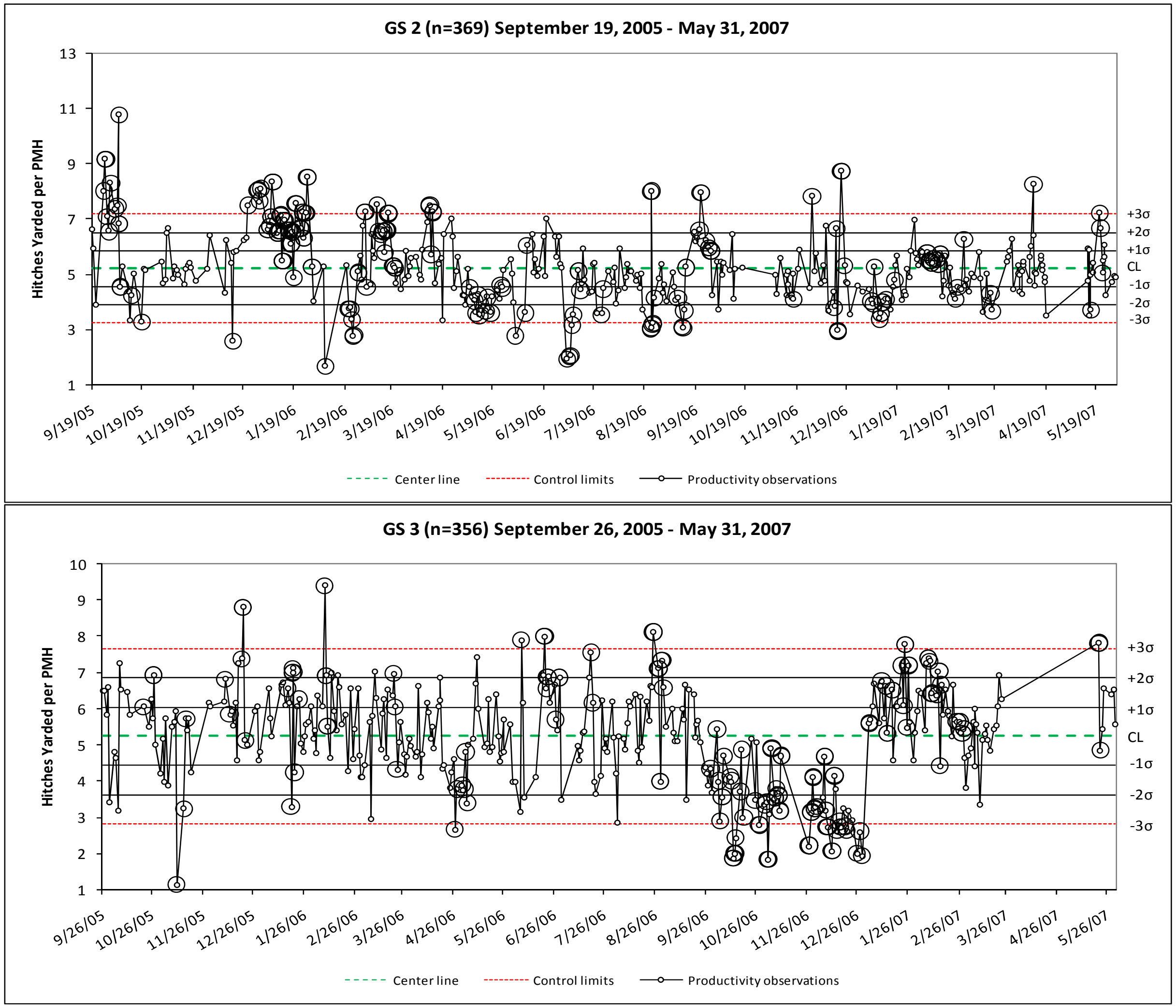

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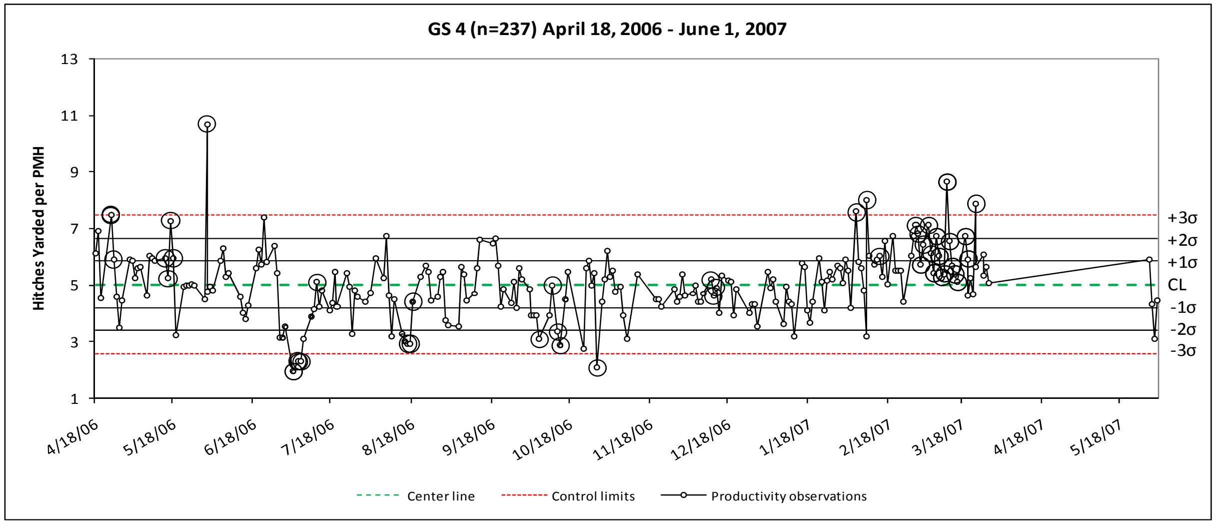

(Figure 4.3. Continued)

Table 4.6. Counts of out-of-control runs identified by runs rules for each machine based on Formula (5) control limits.

	Rule 1	Rule 2	Rule 4	Rule 5	Rule 6	Rule 7	Rule 8	Total Runs*
Feller-buncher 1	19	18	1	27	29	0	0	64
Feller-buncher 2	36	34	0	49	45	1	0	103
Grapple skidder 1	24	26	0	34	54	0	0	99
Grapple skidder 2	37	54	4	56	56	0	0	124
Grapple skidder 3	24	24	0	44	67	0	0	107
Grapple skidder 4	10	24	0	13	22	3	0	50

* Net count of runs identified by one or more run rules.

Rules 2, 5 and 6 are better suited for identifying prolonged shifts within the data and are likely reflecting some of the tract differences. A more suitable approach to this data complication may require incorporating change point analysis as outlined by Sullivan and Woodall (1996), Turner *et al*. (2001), and De Mast and Roes (2004). This approach uses a maximum likelihood function to partition the historical data into all possible subgroups with consistent means and variance.

4.5 CONCLUSIONS

Statistical process control has the potential to be used as an approach to understanding and reducing the variability of forest harvesting operations. The long-term focus of an SPC approach to process improvement offers a means of understanding harvesting processes that cannot be easily achieved through traditional case study approaches to forest operations research. Organizations that understand the behavior of the variations within their harvesting processes will be in a better position to improve their operations. As this study has shown, SPC principles can be applied to a forest harvesting operation, and provide useful information; however, there are many challenges that still need to be addressed.

Data collection on forest harvesting machinery is often limited by high collection costs as well as the degree of intrusion on the operation. Because of this, performance data is often limited to counts or other attribute data as they are fast and inexpensive to collect. Operations taking a SPC approach to analyzing their harvesting systems should strive to employ efficient technologies for collecting continuous measurement data that more accurately reflect the performance of their processes. Data should be collected in a way that would allow the formation of rational subgroups thus eliminating the loss of sensitivity associated with using individuals control charts. This approach would require collecting data on finer time scales than the per-shift interval used in this study. Doing so would also remove the need to use rates of productivity in place of the production of the process, if the time intervals were consistent from one to the next. Detailed data collection should also be expanded to the conditions in which the machines are operating since the environmental and material inputs (i.e., topography, weather, forest composition and arrangement, silvicultural objectives) also influence the harvesting process. Integrated data collection systems that can consistently track standard information on material as it flows throw the system from stump to road-side should also be developed.

Based on the control limit comparison conducted in this study there appears to be little advantage in using the median of the moving ranges over the more commonly used mean of the moving ranges for Phase I analysis. Differences between the two control limits were mostly the result of outliers within the datasets, many of which would be removed due to their association with special causes.

The commonly used control chart runs rules designed to detect patterns and small shifts in the mean or standard deviation of processes are more applicable to quality control management where the goal is to reduce the variation as much as possible and consistently produce the same output. These rules do not necessarily work well when indiscriminately applied directly to the process data used in this study. Future research should focus on modifying existing rules, developing new rules more aptly suited to forest operations, and incorporating more appropriate control limit methods to better detect process shifts and trends.

Another major challenge in applying the principles of SPC to a harvesting operation is the inability to control influential inputs. Whereas a manufacturing process can operate rather consistently in a controlled environment with regulated input materials, a forest harvesting process must be constantly changing and adapting to external variations. Therefore, forest operations applications pose several challenges to the basic SPC definitions for the two sources of variation. Many of the “special” causes of variation that a SPC control chart may identify could in fact be natural variation uncontrollable by the operation. By definition, if a cause of variation cannot be removed without fundamentally changing the process itself then it is a natural cause. Because of the variation that environmental and material inputs impose on a harvesting system there may be many more false alarms in a forest operations SPC system. The focus of future research in applying SPC to forest operations should be on developing a methodology that will consistently yield useful results for improving the harvesting process.

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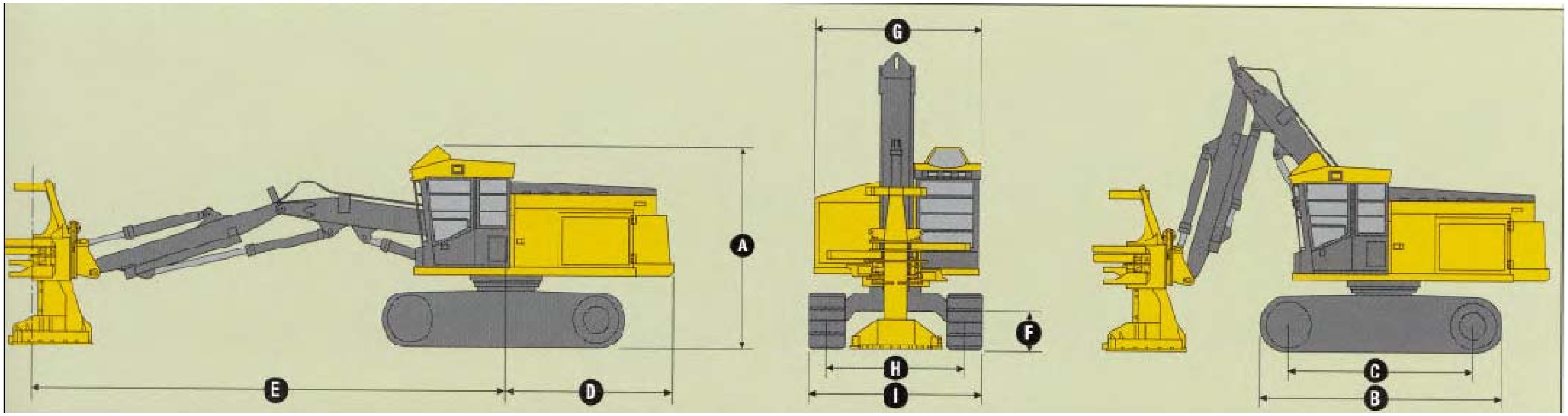
APPENDICES

Appendix A

FELLER BUNCHER DIMENSIONS



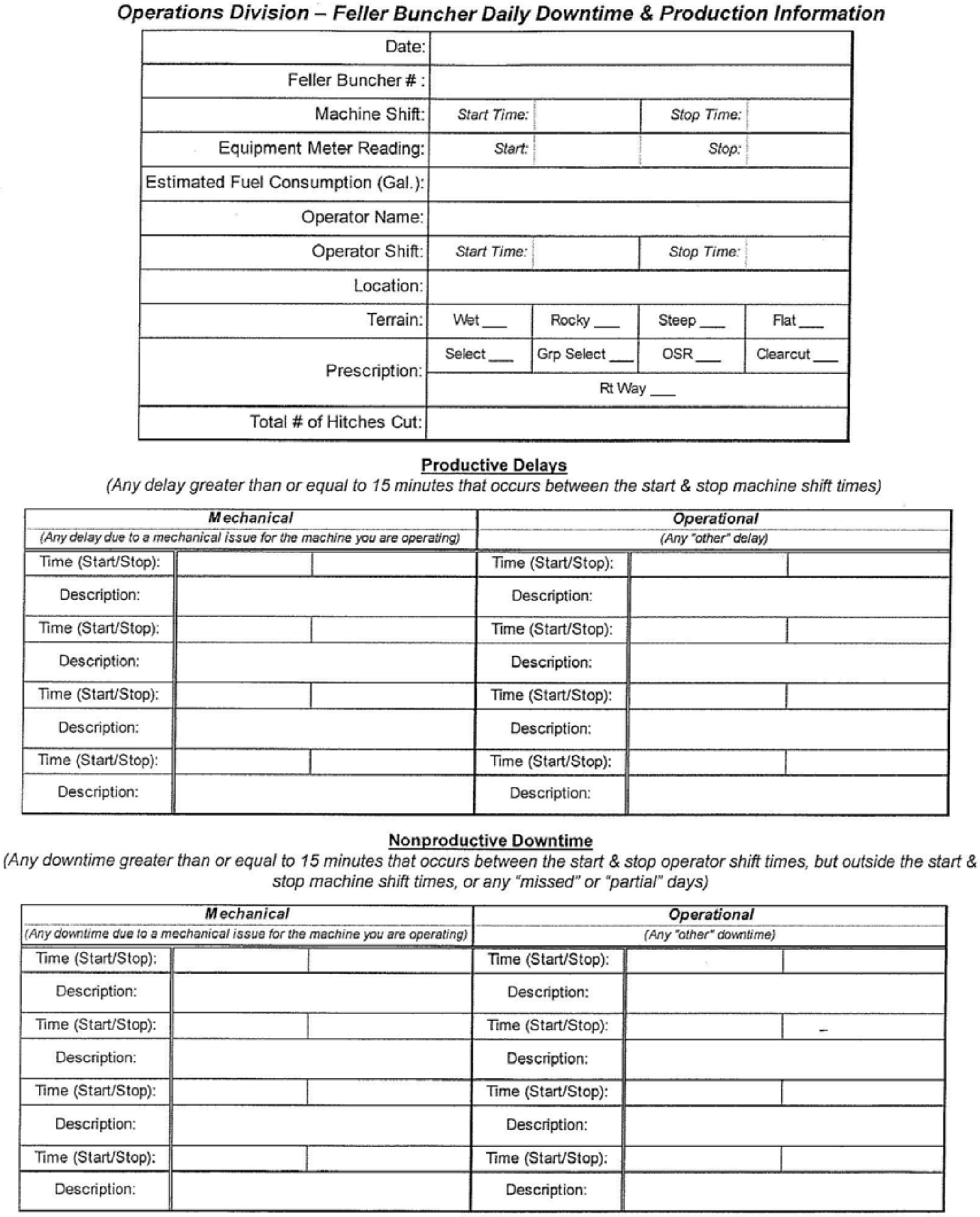
John Deere Feller-buncher, Model No. 853G, with FS22 felling head
Dimensions:

	(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)
Meters	3.78	4.42	3.35	3.00	8.20	0.007	2.97	2.54	3.15
Feet	12.41	14.50	11.00	10.00	26.91	2.42	9.75	8.33	10.33

Figure A.1. Dimensions of John Deere feller-buncher from manufacturer’s specifications.

Appendix B

DAILY DOWNTIME AND PRODUCTION RECORD SHEETS



Operations Division – Feller Buncher Daily Downtime & Production Information

Date:				
Feller Buncher # :				
Machine Shift:	*Start Time:*		*Stop Time:*	
Equipment Meter Reading:	*Start:*		*Stop:*	
Estimated Fuel Consumption (Gal.):				
Operator Name:				
Operator Shift:	*Start Time:*		*Stop Time:*	
Location:				
Terrain:	Wet ___	Rocky ___	Steep ___	Flat ___
Prescription:	Select ___	Grp Select ___	OSR ___	Clearcut ___
	Rt Way ___			
Total # of Hitches Cut:				

Productive Delays

(Any delay greater than or equal to 15 minutes that occurs between the start & stop machine shift times)

Mechanical			***Operational***		
(Any delay due to a mechanical issue for the machine you are operating)			*(Any "other" delay)*		
Time (Start/Stop):			Time (Start/Stop):		
Description:			Description:		
Time (Start/Stop):			Time (Start/Stop):		
Description:			Description:		
Time (Start/Stop):			Time (Start/Stop):		
Description:			Description:		
Time (Start/Stop):			Time (Start/Stop):		
Description:			Description:		

Nonproductive Downtime

(Any downtime greater than or equal to 15 minutes that occurs between the start & stop operator shift times, but outside the start & stop machine shift times, or any "missed" or "partial" days)

Mechanical			***Operational***		
(Any downtime due to a mechanical issue for the machine you are operating)			*(Any "other" downtime)*		
Time (Start/Stop):			Time (Start/Stop):		
Description:			Description:		
Time (Start/Stop):			Time (Start/Stop):		
Description:			Description:		
Time (Start/Stop):			Time (Start/Stop):		
Description:			Description:		
Time (Start/Stop):			Time (Start/Stop):		
Description:			Description:		

Operations Division – Grapple Skidder Daily Downtime & Production Information

Date:				
Grapple Skidder # :				
Machine Shift:	*Start Time:*		*Stop Time:*	
Equipment Meter Reading:	*Start:*		*Stop:*	
Estimated Fuel Consumption (Gal.):				
Operator Name:				
Operator Shift:	*Start Time:*		*Stop Time:*	
Location:				
Terrain:	Wet ___	Rocky ___	Steep ___	Flat ___
	Dow nhill ___	Hilly ___	Uphill ___	
Total # of Hitches:				

Productive Delays

(Any delay greater than or equal to 15 minutes that occurs between the start & stop machine shift times)

Mechanical			***Operational***		
(Any delay due to a mechanical issue for the machine you are operating)			*(Any "other" delay)*		
Time (Start/Stop):			Time (Start/Stop):		
Description:			Description:		
Time (Start/Stop):			Time (Start/Stop):		
Description:			Description:		
Time (Start/Stop):			Time (Start/Stop):		
Description:			Description:		
Time (Start/Stop):			Time (Start/Stop):		
Description:			Description:		

Nonproductive Downtime

(Any downtime greater than or equal to 15 minutes that occurs between the start & stop operator shift times, but outside the start & stop machine shift times, or any "missed" or "partial" days)

Mechanical			***Operational***		
(Any downtime due to a mechanical issue for the machine you are operating)			*(Any "other" downtime)*		
Time (Start/Stop):			Time (Start/Stop):		
Description:			Description:		
Time (Start/Stop):			Time (Start/Stop):		
Description:			Description:		
Time (Start/Stop):			Time (Start/Stop):		
Description:			Description:		
Time (Start/Stop):			Time (Start/Stop):		
Description:			Description:		

Appendix C

OPERATIONAL SUMMARY OF OUT-OF-CONTROL DATA

Table C.1. Operational summary of rule-1 out-of-control observations based on daily downtime and production reports. Data in bold represent observations that exceed the upper control limit, all other observations fall below the lower control limit. Control limits are based on formula 5. PMH based on machine shift time minus productive delays.

Rec. No.	Date	Value	Notes
FELLER-BUNCHER 1 **(n=19 (6.1% of all observations), 11 > UCL, 8 < LCL)**			
89	11/3/2005	5.4	• Operator 14, OSR on rocky steep terrain, 7.3 PMH, utilization 76% – 30305 tract • Blew hose on saw head (-1:30)
140	11/21/2005	5.2	• Operator 14, select cutting on steep terrain, 7.8 PMH, utilization 82% – 30305 tract • NO UNUSUAL DOWNTIME OR DELAYS RECORDED (-0:00)
151	**11/28/2005**	**12.0**	• **Operator 14, select cutting on steep/flat terrain, 1.3 PMH, utilization 25% – 22414 tract** • **Moved from Greenfield to Amherst (-3:30)**
193	12/16/2005	5.6	• Operator 14, OSR on flat terrain, 9.0 PMH, utilization 90% – 22414 tract • NO UNUSUAL DOWNTIME OR DELAYS RECORDED (-0:00)
221	12/27/2005	4.7	• Operator 14, OSR on flat terrain, 8.5 PMH, utilization 81% – 22414 tract • Snow covered trees • Blew hose in valve bank (-1:00)
478	**4/26/2006**	**11.9**	• **Operator 14, OSR on rocky/steep terrain, 7.0 PMH, utilization 67% – 23608 tract** • **Blew hose on head (2:45)**
508	**5/16/2006**	**11.9**	• **Operator 14, OSR on rocky terrain, 6.8 PMH, utilization 68% – 23608 tract** • **Blew main cylinder hose, went to garage and got one, replaced (-3:00)**
510	**5/18/2006**	**12.0**	• **Operator 14, OSR on flat terrain, 9.8 PMH, utilization 93% – 31604 tract**
531	**6/1/2006**	**12.0**	• **Operator 14, group select on steep terrain, 8.5 PMH, utilization 77% – 20900 tract** • **Tightened heater blower motor (-1:15)**
616	**7/24/06**	**12.7**	• **Operator 14, OSR on flat terrain, 7.3 PMH, utilization 69% – 22602 tract** • **Figured out cut blocks with Kevin (-2:30)**
640	**8/10/2006**	**12.4**	• **Operator 14, OSR on flat terrain, 9.5 PMH, utilization 90% – 22602 tract**
740	10/18/2006	3.7	• Operator 14, group select on steep terrain, 3.8 PMH, utilization 83% – 20606 tract • Too wet (-4:00)
771	11/09/2006	4.9	• Operator 22, OSR on rocky terrain, 9.5 PMH, utilization 79% – 23608 tract • Worked on LSK8--blew an O-ring (-2:00)
810	**12/5/2006**	**12.4**	• **Operator 14, OSR on flat terrain, 10.5 PMH, utilization 91% – 32102 tract**
870	**1/15/2007**	**12.0**	• **Operator 14, OSR on flat terrain, 6.0 PMH, utilization 57% – 12910 tract** • **Broke track pin, went to garage to gather what I needed (-4:00)**
1046	4/13/2007	5.2	• Operator 14, select cutting on flat terrain, 8.3 PMH, utilization 88% – 27400 tract • Brushing back right of way (-4:00)

Table C.1. (Continued)

Rec. No.	Date	Value	Notes
1034	5/9/2007	5.2	- Operator 14, OSR on rocky/flat terrain, 5.2 PMH, utilization 47% – 23608 tract - Blew hose, had hard time finding it. Went to Carquest and replaced it (-4:00) - Helped LFB6 operator find leak on LFB6 (1:00)
739	**10/17/06**	**12.3**	- **Operator 14, group select on steep terrain, 7.8 PMH, utilization 74% – 20606 tract** - **Blew hose on stick boom (-2:00)**
1075	**5/29/2007**	**13.3**	- **Operator 14, OSR on flat terrain, 5.5 PMH, utilization 50% – 31604 tract** - **Changed oil and filters, and replaced door handle (-2:30)** - **Move to T3 ND (-2:30)**
FELLER-BUNCHER 2 **(n=36 (10.9% of all observations), 16 > UCL, 20 < LCL)**			
5	**5/19/2005**	**15.5**	- **Operator 8, select cutting on flat terrain, 1.4 PMH, utilization 31% – 20606 tract** - **Moved from T39 to Clifton (-3:00)**
198	12/15/2005	4.9	- Operator 8, select cutting on flat terrain, 4.5 PMH, utilization 38% – 20606 tract - No work, stuck in mud (-4:00)
328	**2/10/2006**	**16.0**	- **Operator 14, group select on flat terrain, 3.8 PMH, utilization 39% – 75500 tract** - **Machine would not start (too cold) (-5:00)**
339	**2/13/2006**	**11.1**	- **Operator 14, group select on flat terrain, 5.8 PMH, utilization 61% – 75500 tract** - **Turned saw teeth (-1:00)** - **Replaced steel line on stick boom cylinder (-2:00)**
342	2/17/2006	4.7	- Operator 3, select cutting on flat terrain, 5.5 PMH, utilization 73% – 22026 - Met Kevin to review cut site (-1:30)
372	**3/1/2006**	**11.0**	- **Operator 3, OSR on flat terrain, 10.3 PMH, utilization 93% – 22026 tract**
419	**3/24/2006**	**11.5**	- **Operator 3, OSR on flat terrain, 8.8 PMH, utilization 92% – 79366 tract**
484	4/27/2006	4.9	- Operator 6, select cutting on rocky terrain, 6.5 PMH, utilization 65% – 23608 tract - Kevin estimated everything - Tighten pad bolts (-0:45)
485	4/28/06	5.0	- Operator 6, select cutting on rocky terrain, 7.2 PMH, utilization 72% – 23608 tract - Kevin estimated everything - Walked machine to a new yard (-0:20)
493	5/3/2006	5.0	- Operator 10, group select on rocky terrain, 8.7 PMH, utilization 87% – 23608 tract - NO UNUSUAL DOWNTIME OR DELAYS RECORDED (-0:00)
512	5/15/2006	3.0	- Operator 10, OSR on flat terrain, 5.7 PMH, utilization 52% – 31604 tract - Broke hose (-2:00) - Moved from garage to T3ND (-3:00)
524	**5/24/2006**	**12.9**	- **Operator 10, group select on steep terrain, 9.2 PMH, utilization 83% – 31604 tract** - **Hydro. Leak; o-ring (-1:00)**
525	**5/25/2006**	**10.8**	- **Operator 10, OSR on flat terrain, 8.3 PMH, utilization 83% – 31604 tract**
526	**5/26/2006**	**10.5**	- **Operator 10, OSR on steep rocky/flat terrain, 7.9 PMH, utilization 79% – 31604 tract** - **Tracked machine to new yard (-1:00)**

Table C.1. (Continued)

Rec. No.	Date	Value	Notes
535	**5/31/2006**	**10.6**	• **Operator 10, OSR on rocky terrain, 9.4 PMH, utilization 86% – 31604 tract**
545	6/7/2006	2.7	• Operator 10, select cutting on wet terrain, 7.3 PMH, utilization 64% – 22225 tract • Repair skidder trails (-3:00)
567	**6/22/2006**	**10.6**	• **Operator 10, OSR on rocky/flat terrain, 10.1 PMH, utilization 81% – 11105 tract** • **Tighten pads (-1:00)** • **Talk with forester (-0:15)**
577	**6/28/2006**	**10.6**	• **Operator 10, OSR on wet/rocky terrain, 9.8 PMH, utilization 79% – 11105 tract** • **O-rings and tighten pads (-1:00)** • **O-ring (-0:20)**
611	**7/11/2006**	**10.8**	• **Operator 10, OSR on wet/steep terrain, 11.1 PMH, utilization 89% – 22224 tract**
635	8/3/2006	4.6	• Operator 10, group select on wet/rocky/steep terrain, 1.8 PMH, utilization 21% – 22224 • Teeth – hit rock (-3:00) • Move to other yard (-1:00) • Wait for place to cut (-2:30)
644	**8/9/2006**	**11.7**	• **Operator 10, OSR on rocky terrain, 11.6 PMH, utilization 86% – 22225 tract** • **60 hitches from ROW** • **Moved to ROW (-0:40)**
726	10/6/2006	5.0	• Operator 10, group select on rocky/steep terrain, 7.4 PMH, utilization 82% – 30305 tract • Scout hill for trails (-0:20)
732	10/10/2006	4.7	• Operator 10, group select on rocky/steep terrain, 8.5 PMH, utilization 81% – 30305 tract • Tighten pads (-0:25)
745	10/18/2006	3.4	• Operator 10, group select on wet/rocky/steep terrain, 3.5 PMH, utilization 78% – 30305 • Too wet (-4:00)
805	11/28/2006	4.7	• Operator 10, group select on wet/rocky terrain, 4.9 PMH, utilization 43% – 32102 tract • Blown hose (-3:30) • Foresters (-2:45)
888	**1/31/2007**	**10.8**	• **Operator 14, group selection on steep terrain, 2.5 PMH, utilization 25% – 75500 tract** • **Put starter on, traced wire, found burnt wire, replaced – warning light came on (-7:30)**
889	**2/1/2007**	**10.4**	• **Operator 14, group select on steep terrain, 6.8 PMH, utilization 61% – 75500 tract** • **Fire suppression system discharged, blew hose on valve bank – went to Oakfield, got new one and replaced (-3:30)**
911	**2/8/2007**	**11.1**	• **Operator 2, group select on flat terrain, 3.3 PMH, utilization 27% – 22225 tract** • **Operator did not fill out d&p sheets. Data taken from the operator's time card** • **Work on machine @ Garage (-6:00)** • **Move from Garage to Seboeis (-2:30)**
976	3/19/2007	5.0	• Operator 20, select cutting on rocky/flat terrain, 9.0 PMH, utilization 90% – 22026 tract • NO UNUSUAL DOWNTIME OR DELAYS RECORDED (-0:00)
1071	4/27/07	4.4	• Operator 20, OSR on rocky/flat terrain, 6.8 PMH, utilization 79% – 23608 tract • NO UNUSUAL DOWNTIME OR DELAYS RECORDED (-0:00)

Table C.1. (Continued)

Rec. No.	Date	Value	Notes
1027	4/30/2007	4.9	• Operator 20, OSR on rocky/flat terrain, 9.3 PMH, utilization 84% – 23608 tract • Broke exhaust clamp (-0:30)
1028	5/1/2007	4.9	• Operator 20, OSR on rocky/flat terrain, 9.5 PMH, utilization 86% – 23608 tract • Replaced exhaust clamp (-0:30)
1039	5/9/2007	2.4	• Operator 20, OSR on rocky/flat terrain, 3.8 PMH, utilization 34% – 23608 tract • Blown o-ring. Went to get new fitting in Bangor (-6:30)
1040	5/10/2007	3.9	• Operator 20, OSR on rocky/flat terrain, 4.3 PMH utilization 41% – 23608 tract • Check oil in final drives. Talked to Frank Martin (-1:40) • Turned teeth (-0:45) • Blown o-ring & 2 broken motor mounts (-3:00)
1007	5/14/2007	4.1	• Operator 20, select cutting on rocky/flat terrain, 5.3 PMH, utilization 48% – 23608 tract • Hole in hose on air intake. Taped and wrapped it. (-1:10) • Looking for hose (-3:00) • Talked w/ Kevin (-0:30)
1009	5/16/2007	4.7	• Operator 20, select cutting on rocky/flat terrain, 3.4 PMH, utilization 43% – 23608 tract • Blown motor (-5:15)
GRAPPLE SKIDDER 1 **(n=24 (6.4% of all observations), 9 > UCL, 15 < LCL)**			
232	2/8/2005	2.4	• Operator 27 skidding downhill on wet/rocky/steep terrain, 4.3 PMH, utilization 85% – 20606 tract • No work: too wet (-3:30)
345	**1/13/2006**	**16.7**	• **Operator 27 skidding on flat terrain, 3.0 PMH, utilization 33% – 25200 tract** • **I just put in a number for hitches until Rory gets back** • **Greased/Fixed chains (-1:45)** • **Walked machines (-1:00)** • **Working on limber (-2:30)**
364	**1/16/2006**	**10.0**	• **Operator 27 skidding on flat terrain, 4.0 PMH, utilization 36% – 25200 tract** • **No hitches listed, est. all week** • **Waiting for limber (-6:00)**
435	2/9/2006	1.5	• Operator 27 skidding on flat terrain, 6.5 PMH, utilization 62% – 25200 tract • 500 hours filters (-2:00) • Fixed chains (-1:00)
436	2/10/2006	2.3	• Operator 27 skidding on flat terrain, 6.5 PMH, utilization 68% – 25200 tract • Worked on harvester (-2:00)
454	2/13/2006	2.9	• Operator 27 skidding on flat terrain, 9.5 PMH, utilization 90% – 25200 tract • NO UNUSUAL DOWNTIME OR DELAYS RECORDED (-0:00)
480	**2/24/2006**	**8.3**	• **Operator 27 skidding on flat terrain, 6.8 PMH, utilization 71% – 25200 tract** • **U-joint (-1:45)**
601	4/6/2006	3.1	• Operator 27 skidding on flat terrain, 6.5 PMH, utilization 81% – 23608 tract • O-ring (-0:30)
686	**5/3/2006**	**8.4**	• **Operator 6 skidding on rocky/flat terrain, 8.4 PMH, utilization 84% – 23608 tract** • **Talked with Kevin and Tim (-0:20)**

Table C.1. (Continued)

Rec. No.	Date	Value	Notes
788	6/7/2006	2.7	• Operator 6 skidding on wet/flat terrain, 8.5 PMH, utilization 89% – 22224 tract • NO UNUSUAL DOWNTIME OR DELAYS RECORDED (-0:00)
889	**7/6/2006**	**9.4**	• **Operator 6 skidding on flat terrain, 6.4 PMH, utilization 80% – 22224 tract** • **Ran LSK10 (-3:00)** • **Drive from Lakeview to Seboeis (-0:45)**
890	**7/7/2006**	**9.9**	• **Operator 6 skidding on flat terrain, 5.3 PMH, utilization 72% – 22224 tract** • **Sheet estimated** • **OP#16 had Dr. app. at 8:30am. OP#6 limbed wood & ran skidder from 9:30am to 12:00pm.** • **Ran LDL5 (half of OP#6 time from 8:30am to 12:00pm allocated to LDL5) (-1:45)**
909	7/13/2006	3.0	• Operator 6 skidding on wet/rocky/flat terrain, 10.0 PMH, utilization 87% – 22224 tract • NO UNUSUAL DOWNTIME OR DELAYS RECORDED (-0:00)
1073	**9/14/2006**	**10.1**	• **Operator 6 skidding on flat terrain, 2.7 PMH, utilization 28% – 21201 tract** • **Moved from Haynesville/T3R3 to Mattawankeag-T (-4:00)** • **Worked on LDL6: changed staffer motor (-3:00)**
1092	9/20/2006	3.1	• Operator 16 skidding on wet/rocky/hilly terrain, 4.5 PMH, utilization 100% – 21201 • Ran LDL5 – LSK8 Operator out sick (-2:00) • Pushed out yard space, moved rocks and stumps (-1:45)
1218	11/3/2006	2.8	• Operator 16 skidding on rocky terrain, 8.5 PMH, utilization 77% –23608 tract • Long yard • No start – repaired wires (-1:30)
1329	12/8/2006	2.8	• Operator 16 skidding on wet terrain, 6.8 PMH, utilization 61% – 30305 tract • LSK8 was yarding to LDL8 • Helped put chains on LSK10 (-3:00)
1346	12/11/2006	3.1	• Operator 16 skidding on wet terrain, 9.0 PMH, utilization 86% –30305 tract • Long yard
1367	12/18/2006	2.9	• Operator 16 skidding uphill on wet terrain, 7.0 PMH, utilization 74% – 30305 tract • Long yard • Pulled out LSK10 (-1:30)
1432	1/9/2007	2.2	• Operator 16 skidding downhill on wet terrain, 6.8 PMH, utilization 61% – 20606 tract • Move logs (-2:45)
1458	**1/16/2007**	**8.5**	• **Operator 16 skidding on flat terrain, 11.7 PMH, utilization 90% – 12910 tract** • **All hitches "York"**
1546	2/16/2007	2.9	• Operator 16 skidding on flat terrain, 7.3 PMH, utilization 91% –11207 tract • Changed fuel filters (-0:15)
1838	**4/16/2007**	**8.0**	• **Operator 4 skidding on wet/flat terrain, 8.3 PMH, utilization 83% – 27400 tract**
1841	4/19/2007	3.0	• Operator 4 skidding on wet/flat terrain, 6.0 PMH, utilization 67% – 27400 tract
			GRAPPLE SKIDDER 2
			(n=37 (10.0% of all observations), 26 > UCL, 11 < LCL)
18	**9/26/05**	**8.0**	• **Operator 9 skidding uphill on wet terrain, 7.3 PMH, utilization 73% – 20606 tract** • **Moved LDL6 to Clifton (-2:00)**

Table C.1. (Continued)

Rec. No.	Date	Value	Notes
19	**9/27/2005**	**9.2**	• **Operator 9 skidding uphill on wet/flat terrain, 6.0 PMH, utilization 86% – 20606 tract** • **Ran LDL6 (-3:30)**
22	**9/30/2005**	**8.3**	• **Operator 9 skidding uphill on wet/flat terrain, 7.0 PMH, utilization 74% – 20606 tract** • **Work on chains (-1:15)**
43	**10/3/2005**	**7.4**	• **Operator 9 skidding uphill on wet/flat terrain, 9.3 PMH, utilization 88% – 20606 tract**
44	**10/4/2005**	**7.5**	• **Operator 9 skidding uphill on wet/flat terrain, 9.3 PMH, utilization 88% – 20606 tract**
45	**10/5/2005**	**10.8**	• **Operator 9 skidding uphill on wet/flat terrain, 3.3 PMH, utilization 65% – 20606 tract** • **Yarded brush and cleaned yard (-1:15)**
263	12/13/2005	2.6	• Operator 9 skidding downhill on wet terrain, 1.2 PMH, utilization 11% – 20606 tract • Worked on skidder, wouldn't start (-4:30) • Went to get oil and pickup to start skidder (-3:35) • Changed oil & filter, put in 0W30 oil (-1:15)
286	**12/22/2005**	**7.5**	• **Operator 9 skidding on wet/flat terrain, 5.1 PMH, utilization 54% – 24907 tract** • **Safety meeting at office (-3:30)**
305	**12/28/2005**	**8.0**	• **Operator 9 skidding on wet/flat terrain, 8.1 PMH, utilization 73% – 24907 tract** • **Waiting for road to be plowed (-1:30)**
306	**12/29/2005**	**7.6**	• **Operator 9 skidding on wet/flat terrain, 8.9 PMH, utilization 85% –24907 tract**
307	**12/30/2005**	**8.1**	• **Operator 9 skidding on wet/flat terrain, 7.4 PMH, utilization 71% – 24907 tract**
328	**1/6/2006**	**8.3**	• **Operator 9 skidding on wet/flat terrain, 7.0 PMH, utilization 73% – 24907 tract** • **Greased/Tightened chains (-1:03)**
375	**1/20/2006**	**7.6**	• **Operator 9 skidding on wet/flat terrain, 6.4 PMH, utilization 67% –75500 tract** • **Worked front chains (-1:40)**
394	**1/24/2006**	**7.2**	• **Operator 9 skidding on wet/flat terrain, 9.0 PMH, utilization 82% –75500 tract** • **Talked to Kevin (-0:20)**
396	**1/26/2006**	**7.2**	• **Operator 9 skidding on wet/flat terrain, 9.0 PMH, utilization 86% –75500 tract**
397	**1/27/2006**	**8.5**	• **Operator 9 skidding on wet/flat terrain, 6.6 PMH, utilization 69% – 75500 tract** • **Blew o-ring/Greased/Fix front chain (-1:20)**
439	2/7/2006	1.7	• Operator 23 skidding on wet/flat terrain, 9.0 PMH, utilization 86% – 75500 tract • NO UNUSUAL DOWNTIME OR DELAYS RECORDED (-0:00)
485	2/24/06	2.8	• Operator 1 skidding on flat terrain, 1.1 PMH, utilization 14% – 22026 tract • Kevin had to est fuel consumption and # of hitches • Blown radiator hose. Down the rest of the day. (-6:25)
508	**3/3/2006**	**7.3**	• **Operator 1 skidding on flat terrain, 8.0 PMH, utilization 80% – 22026 tract** • **Water in fuel filter – changed (-0:30)** • **Fixed tire chain (-0:15)**
528	**3/10/2006**	**7.5**	• **Operator 1 skidding on hilly terrain, 8.3 PMH, utilization 92% – 79366 tract**
549	**3/17/2006**	**7.2**	• **Operator 1 skidding on hilly terrain, 6.7 PMH, utilization 70% – 79366 tract** • **Helped Steve on DL6 (-1:50)**

Table C.1. (Continued)

Rec. No.	Date	Value	Notes
628	**4/11/2006**	**7.5**	• **Operator 12 skidding on flat terrain, 7.8 PMH, utilization 91% – 27400 tract** • **No counter – estimated by Kevin**
630	**4/13/2006**	**7.3**	• **Operator 12 skidding on flat terrain, 7.8 PMH, utilization 91% – 27400 tract** • **No counter – estimated by Kevin** • **Waiting for trucks to load/wash windows (-1:45)**
775	6/2/06	2.8	• Operator 1 skidding on flat terrain, 10.5 PMH, utilization 95% – 31604 tract • NO UNUSUAL DOWNTIME OR DELAYS RECORDED (-0:00)
891	7/3/2006	1.9	• Operator 16 skidding uphill on rocky/steep terrain, 8.8 PMH, utilization 88% – 31704 tract • NO UNUSUAL DOWNTIME OR DELAYS RECORDED (-0:00)
893	7/5/2006	2.0	• Operator 16 skidding uphill on rocky/steep terrain, 8.8 PMH, utilization 88% – 31704 tract • NO UNUSUAL DOWNTIME OR DELAYS RECORDED (-0:00)
894	7/6/2006	3.2	• Operator 1 skidding uphill on rocky/steep terrain, 8.3 PMH, utilization 79% – 31704 tract • Warm up and replaced four shackles (-1:00)
1014	8/23/2006	3.1	• Operator 1 skidding on flat terrain, 4.9 PMH, utilization 66% – 22602 tract • Wait for lowbed and loading machine (-2:30)
1015	**8/23/2006**	**8.0**	• **Operator 1 skidding on hilly terrain, 0.8 PMH, utilization 19% – 21201 tract** • **Move from Woodville to Mattawankeag (-1:00)** • **Wait for delimber to arrive at job (sheet is not clear?) (-2:00)**
1016	8/24/2006	3.2	• Operator 1 skidding on hilly terrain, 9.7 PMH, utilization 88% – 21201 tract • NO UNUSUAL DOWNTIME OR DELAYS RECORDED (-0:00)
1075	9/11/2006	3.1	• Operator 1 skidding on flat terrain, 6.8 PMH, utilization 62% – 21201 tract • LDL6 has bad leak – needs to be fixed (-3:05)
1099	**9/22/2006**	**7.9**	• **Operator 1 skidding on flat terrain, 6.2 PMH, utilization 69% - 21201 tract** • **Greased and worked on LSK9 (LDL6 down) (-1:45)**
1311	**11/28/2006**	**7.8**	• **Operator 1 skidding on flat terrain, 5.3 PMH, utilization 48% – 32102 tract** • **yarded right of way wood** • **Fixed bent brush guard, 4 broken wires, and steering bumper (-1:15)** • **Move from T2R8 to T39 (-4:00)**
1354	12/14/2006	3.0	• Operator 1 skidding on wet/flat terrain, 10.5 PMH, utilization 88% – 32102 tract • NO UNUSUAL DOWNTIME OR DELAYS RECORDED (-0:00)
1356	**12/16/2006**	**8.7**	• **Operator 1 skidding on wet/flat terrain, 2.8 PMH, utilization 42% – 32102 tract** • **Installed 2 cylinders that were rebuilt (-2:30)**
1862	**4/11/2007**	**8.2**	• **Operator 1 skidding on flat terrain, 4.3 PMH, utilization 43% – 27400 tract** • **LDL6 grab arm wouldn't work (-3:15)** • **replaced muffler due to a rust hole in it (-2:00)**
1765	**5/21/2007**	**7.2**	• **Operator 1 skidding on flat terrain, 6.3 PMH, utilization 57% – 23608 tract** • **Wash LSK9 (-0:30)** • **Prepared yard, moved rocks, while waiting for delimber (-2:45)**
GRAPPLE SKIDDER 3 **(n=24 (6.7% of all observations), 7 > UCL, 17 < LCL)**			
155	11/10/2005	1.1	• Operator 3 skidding on flat terrain, 3.5 PMH, utilization 33% – 23608 tract • Cut pine logs with chainsaw (-6:30)
268	**12/20/2005**	**8.8**	• **Operator 3 skidding on flat terrain, 7.5 PMH, utilization 68% – 22414 tract** • **Changed oil (-2:15)**
421	**2/7/2006**	**9.4**	• **Operator 23 skidding on wet/flat terrain, 9.3 PMH, utilization 88% – 75500 tract**

Table C.1. (Continued)

Rec. No.	Date	Value	Notes
657	4/27/2006	2.7	• Operator 17 skidding on rocky/hilly terrain, 2.3 PMH, utilization 26% – 23608 tract • No work: Out of wood because Jacques quit (-6:00)
777	**6/6/2006**	**7.9**	• **Operator 17 skidding on rocky/flat terrain, 9.8 PMH, utilization 89% – 20900 tract**
837	**6/20/06**	**8.0**	• **Operator 17 skidding on wet terrain, 9.3 PMH, utilization 84% – 11105 tract** • **Put LDL8 chain sprocket back together (-0:30)**
1003	**8/25/2006**	**8.1**	• **Operator 4 skidding on wet/rocky/flat terrain, 8.3 PMH, utilization 87% - 72404 tract**
1142	10/12/2006	1.9	• Operator 4 skidding uphill on wet/rocky terrain, 3.8 PMH, utilization 50% – 30305 tract • Long yard • Cut logs with chainsaw for wood buyer (-3:00) • Too wet (-1:00)
1143	10/13/2006	2.0	• Operator 4 skidding uphill on wet/rocky terrain, 7.5 PMH, utilization 71% – 30305 tract • Long yard • Walking in woods with Kevin (-1:00) • Putting lag on 608 (-1:00)
1144	10/14/2006	2.4	• Operator 4 skidding uphill on wet/rocky terrain, 8.3 PMH, utilization 87% – 30305 tract • Long yard
1184	10/28/2006	2.8	• Operator 4 skidding downhill on wet terrain, 5.8 PMH, utilization 72% – 30305 tract • Long yard • Water bars (-0:30)
1205	11/2/2006	1.8	• Operator 4 skidding downhill on wet/rocky terrain, 9.3 PMH, utilization 84% – 30305 tract • Long yard • On all long yard while trucks were stuck
1295	11/27/2006	2.2	• Operator 4 skidding on wet/rocky/hilly terrain, 9.5 PMH, utilization 86% – 30305 tract • Long yard
1319	12/8/2006	2.7	• Operator 4 skidding uphill on wet/rocky terrain, 6.3 PMH, utilization 57% – 30305 tract • Long yard • Put new chains on (-3:00)
1335	12/11/2006	2.1	• Operator 4 skidding downhill on wet/rocky terrain, 8.8 PMH, utilization 83% – 30305 tract • Long yard
1338	12/14/2006	2.6	• Operator 4 skidding downhill on wet/rocky terrain, 8.8 PMH, utilization 83% – 30305 tract • NO UNUSUAL DOWNTIME OR DELAYS RECORDED (-0:00)
1340	12/16/2006	2.7	• Operator 18 skidding uphill on wet/rocky terrain, 7.0 PMH, utilization 88% – 30305 tract • Hitches estimated @ weeks weighted average because of long turn times • Royce ran LSK10 to pre-yard wood. No delimbing
1358	12/19/2006	2.7	• Operator 4 skidding downhill on wet terrain, 8.8 PMH, utilization 83% – 30305 tract • Long yard
1359	12/20/2006	2.6	• Operator 4 skidding downhill on wet terrain, 8.8 PMH, utilization 83% – 30305 tract • Long yard

Table C.1. (Continued)

Rec. No.	Date	Value	Notes
1380	12/26/2006	2.0	• Operator 4 skidding uphill on wet/rocky terrain, 4.0 PMH, utilization 44% – 30305 tract • Long yard • Stuck in mud (grease machine while waiting for LSK8 to arrive. LSK8 helped LSK10 get out of the mud) (-4:00)
1382	12/20/2006	2.6	• Operator 4 skidding uphill on wet terrain, 5.8 PMH, utilization 55% – 30305 tract • Long yard • Put in water bars (-3:00)
1383	12/29/2006	1.9	• Operator 4 skidding uphill on wet/rocky terrain, 6.8 PMH, utilization 68% – 30305 tract • Long yard • Put in water bars (-1:30)
1481	**1/24/2007**	**7.8**	• **Operator 4 skidding on hilly terrain, 8.8 PMH, utilization 83% – 24907 tract**
1750	**5/21/2007**	**7.8**	• **Operator 4 skidding uphill on wet/rocky terrain, 5.5 PMH, utilization 55% – 31704 tract** • **Moved LSK10 to T7 SD (-3:30)**
GRAPPLE SKIDDER 4 **(n=10 (4.2% of all observations), 6 > UCL, 4 < LCL)**			
659	**4/24/2006**	**7.5**	• **Operator 27 skidding on rocky/flat terrain, 9.5 PMH, utilization 90% – 23608 tract**
762	**5/31/2006**	**10.7**	• **Operator 27 skidding uphill, 0.8 PMH, utilization 25% – 31604 tract** • **Waiting for lowbed (-2:00)**
881	7/3/2006	1.9	• Operator 6 skidding on rocky/hilly terrain, 8.8 PMH, utilization 88% – 31704 tract • NO UNUSUAL DOWNTIME OR DELAYS RECORDED (-0:00)
883	7/5/2006	2.3	• Operator 6 skidding on rocky/hilly terrain, 8.8 PMH, utilization 88% – 31704 tract • NO UNUSUAL DOWNTIME OR DELAYS RECORDED (-0:00)
884	7/6/2006	2.3	• Operator 27 skidding on rocky/steep/hilly terrain, 8.8 PMH, utilization 88% – 31704 tract • Hitches estimated
1190	10/28/2006	2.1	• Operator 27 skidding on hilly terrain, 7.3 PMH, utilization 85% – 30305 tract
1512	**2/5/2007**	**7.6**	• **Operator 27 skidding on flat terrain, 4.8 PMH, utilization 43% – 22300 tract** • **500hr oil change (-2:00)** • **Put chain on LDL6 (-4:00)**
1517	**2/9/2007**	**8.0**	• **Operator 27 skidding downhill, 3.8 PMH, utilization 68% – 25800 tract** • **Move from Medway-McLaughlin to Lee-Burkey (-1:30)**
1633	**3/12/2007**	**8.6**	• **Operator 27 skidding on flat terrain, 4.8 PMH, utilization 43% – 79366 tract** • **Oil change (-1:30)** • **Move from Springfield to Forkstown (-4:30)**
1659	**3/23/2007**	**7.9**	• **Operator 27 skidding on flat terrain, 7.8 PMH, utilization 86% – 79366 tract** • **Tighten chains (-0:30)**

BIOGRAPHY OF THE AUTHOR

Charles Coup was born in Lewisburg, Pennsylvania on March 1, 1984. He grew up in the town of Milton, Pennsylvania and graduated from Milton High School in 2002.

Charles attended The Pennsylvania State University in University Park, Pennsylvania, and received a Bachelor of Science degree in Forest Science (with an emphasis in Forest Management) in August, 2006. During the summers of his undergraduate education, Charles worked as an intern for the Pennsylvania Department of Conservation and Natural Resources, Bureau of Forestry in the Bald Eagle State Forest. Following graduation he worked for the U.S. Fish and Wildlife Service in the Pennsylvania Field Office directing SILVAH examinations and assisting with stream and wetland restoration, and later for the School of Forest Resources at Penn State organizing and assisting with greenhouse and plantation research.

In 2007 he was enrolled for graduate study at the University of Maine. He is a candidate for the Master of Science degree in Forest Resources from The University of Maine in December, 2009.