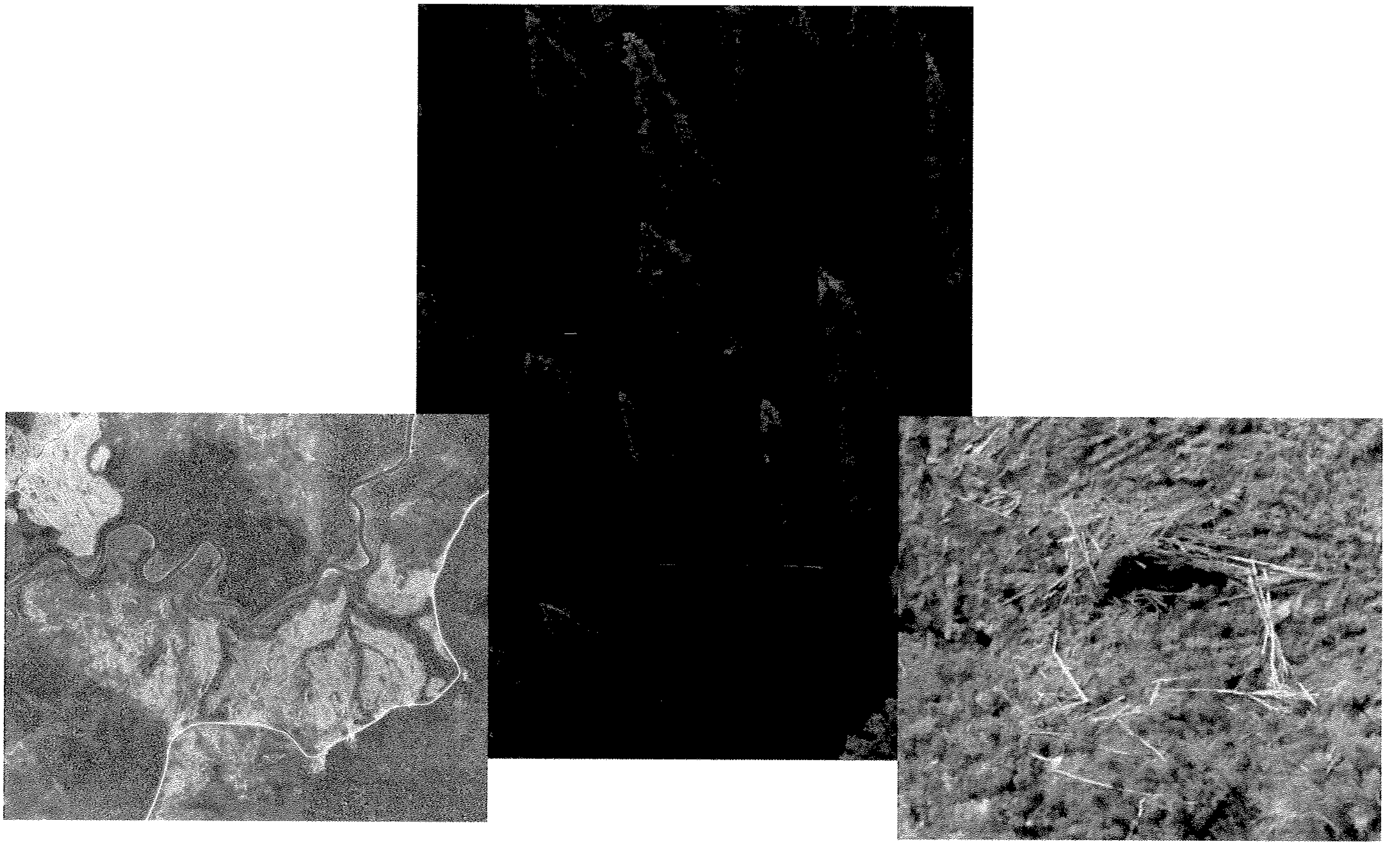
INVENTORYING CUTOVER LOGGING RESIDUES:

A Remote Sensing Approach

By

ALEXANDER M. BILYK



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LAKEHEAD UNIVERSITY
THUNDER BAY, ONTARIO

JANUARY 2012

INVENTORYING CUTOVER LOGGING RESIDUES:
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by

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A Master's Thesis Submitted
in Partial Fulfillment of the Requirements
for the Degree of Master of Science in Forestry

Faculty of Natural Resources Management

Lakehead University

January 2012

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ABSTRACT

Bilyk, Alexander. 2011. Inventorying Cutover Logging Residues: A Remote Sensing Approach. Lakehead University: Thunder Bay.

Keywords: Atikokan, Bioenergy, Biomass, Coarse Woody Debris, Forest Industry, Green Economy, High Resolution Imagery, Remote Sensing, Slash, Volume Estimates.

The purpose of this study was to quantify the volume of logging residues within forest harvest blocks, using an airborne, remote sensing based method. The objective was to measure the volume using a field technique, and using remote sensing and then compare the two to see if remote sensing techniques are a viable alternative for logging residue volume estimation. An essential piece of knowledge for infrastructure investment is the amount and quality of fuel available. Many past efforts have attempted to quantify the amount of logging slash on the ground, but few have utilized airborne imagery and none of those developed an inventory method that could be applied readily to industry needs. This study used 8 cm spatial resolution, digital imagery, combined with a proven field method, to quantify logging slash. The field estimated volume was then compared to the remote sensing derived volume, with no significant difference between estimates being found. This result justifies the further exploration of large-scale digital image analysis for determining harvest block logging residue volume. The analysis technique fits into the current industry work-flow, with the only change being the resolution of the imagery flown for certain harvest blocks and some additional time to conduct the survey. On an average it took the author under a half-an-hour to conduct these measurements but the additional time required for measurement was not a factor of consideration in this study, as this study was a proof of concept for the image analysis.

ACKNOWLEDGEMENTS

I would first like to extend my thanks to my supervisor, Dr. Ulf Runesson, for his direction and support throughout this project; both academically and otherwise. I would also like to thank my committee members, Dr. Reino Pulkki and Dr. Chander Shahi, for their insights and feedback. I have to also thank Dr. Doug Pitt of the Canadian Forest Service for offering his comments, edits and suggestions as the external examiner.

I would also like to thank Resolute Forest Products for providing financial support, data and project direction. Without the support of Resolute FP, it would not have been possible to conduct this study or use such advanced imagery.

I would finally like to give my special thanks to my family, and to my girlfriend Jen, for their support during the entire project. They helped keep me grounded in reality and provided emotional support. I am eternally grateful.

INTRODUCTION

BACKGROUND

Any journey begins with a single step. This saying applies to a variety of research problems that face us in the future, with the largest looming questions being climate change, world financial health, and human health. These are complex challenges, requiring a multitude of approaches to seek out sustainable solutions. Without an understanding of the basic building blocks of a problem, we cannot begin to search for a global solution. One facet of the problem involves our dependence on fossil fuels for energy production. Alternative solutions are being explored, with one proposed partial alternative being the adoption of bio-based fuels. A fundamental building block of the bio-economy is the availability of raw materials especially waste wood products from the forest industry. It has been proposed that the waste from the forest products industry can be collected and used to drive the development of a bio-based economy in Ontario and Canada. The question that arises from this alternative is the long-term sustainable availability of this wood supply without harvesting trees specifically for energy production; a waste of their economic potential. The focus of this study was to develop a method of measuring logging residue (also known as slash or biofibre) availability using large-scale airborne digital images. This method, if proven equivalent to a field volume, could then be used to develop regional, reliable biofibre inventories. With this inventory available, it would be possible to determine the long-term sustainability of bio-based projects for a given area and make sure that specific geographic areas do not become saturated with too many projects that draw upon the resource. The inventory would help drive these efforts by identifying which regions can support projects of a given scale, keeping sustainability the primary goal.

This study is not intended to promote the use of woody biomass energy production over other energy solutions, including: energy conversion, wind, geothermal and solar. It is also not an endorsement of the use of woody biomass, rather an examination of an inventory system that would allow for informed decisions to be made about the use of this technology and the building of supporting infrastructure.

STUDY OBJECTIVES

The purpose of this study was to quantify the amount of logging residue left on site after a harvest for the purposes of bioenergy production using an airborne, digital image analysis method. The objectives of this study were to (1) measure the volume of harvest residues using a remote sensing technique, (2) measure the volume of harvest residues using established field methods and (3) to statistically compare these two volume estimates to determine if remote sensing can be a viable substitute for extensive field measurement. Field measurements are still required for ground verification of estimated volume. The short-term goal of the study is to determine if digital image analysis can be used for inventorying forest biofibre and then use it to determine biofibre availability within the study blocks. With a robust biofibre inventory system, it will be possible for forest planning managers to create regional biofibre maps. Maps of this kind will show if there is enough biofibre in Northwestern Ontario to support the creation of a bio-based industry and provide some insight into a sustainable volume that can be harvested annually. This study does not create this inventory but presents a measurement tool, which can potentially be used to create such an inventory. The infrastructure for biofibre utilization may include cogeneration plants, pellet production industry or conversion of coal generated power to biofibre power. In the long term, it may be possible to combine the remote sensing based inventory with an economic model to determine which harvest blocks are worth collecting biofibre from and which are located too far away or have limited volume. If the inventory is not possible or proves to be impractical with the remote sensing methods tested, then digital image analysis can be used to stratify blocks into groups with similar logging residue distributions and eliminate the variability for a ground-based method. This would reduce the time it takes to conduct a ground-based effort and potentially increase accuracy. Although the term biofibre refers to logging residue, standing timber that is not currently utilized and even some merchantable timber under the Ontario Biofibre Policy, this inventory focuses solely on the logging residue portion (OMNR 2008). This study did not conduct an analysis of the time taken to conduct either the field or remote sensing effort, so any comments on efficiency of time are the author's personal experience.

LITERATURE REVIEW

Remote sensing projects are usually a combination of using established methods to complete a set task or adapting methods used for other purposes with a new question or challenge. A clear outline of the problem is first necessary and looking into ground methods that are currently used for measuring the metric of interest help to outline avenues for solving the problem from the air. If a ground based method can successfully measure a feature but the problem is scale or cost, than remote sensing may simply adapt the ground method for use from the air. This study examines the use of remote sensing as it applies to establishing a reliable biofibre inventory. It is important however to understand the depth of history behind the biofibre question and the driving forces behind the current interest. This includes the government policies driving the creation of a bio-based industry and some potential lessons from jurisdictions that currently have biofibre technology.

HISTORICAL CONTEXT

The first national effort towards bioenergy and energy independence was driven by the 1973 oil crisis (Akins 1973, Rybczynski 1976). During the second half of 1973, the political situation in the Middle East degraded and the oil industry was dragged into politics as it had never been before (Parra 2004). The Israeli occupation of lands that the Arab nations considered theirs caused considerable turmoil and the Arab nations blamed the U.S. for its support of Israel; with both money and arms (Parra 2004). "A tightening market and growing U.S. imports seemed to reveal a chink in U.S. armor, and the Arabs came to view oil as perhaps a powerful political weapon" (Parra 2004). In an attempt to take the lands back, a multi-nation offensive was undertaken, with Saudi Arabia playing "the oil weapon" (Parra 2004). In 1973, the Saudi ambassador told the US that they would not be expanding production if the US did not modify its policy towards Israel (Parra 2004). The US chose not to modify their Israeli policy and the oil embargo was the result (Parra 2004). The Canadian supply was subsequently impacted, as was the economy. When the price of oil rose dramatically, it became clear that Canada was extremely dependent on foreign oil supply (Rybczynski 1976). Even though Canada had oil reserves, the effect of this increase impacted both the global market as well as the Canadian economy.

In response to this, much new research was focused on developing a fuel source that Canada could produce domestically (Rybczynski 1976). An entire division of the federal forest service was created called ENFOR (energy from the forest). For about 10 years, this research moved along and continued to prosper but when the price of oil dropped back down, the need to create a new technology was removed and the drive to do so with it. The funding sources started to dry up and soon the idea of bioenergy was gone from most people's research focus. We are now seeing a resurging of this trend, beginning with the war in Afghanistan and Iraq, a global financial crisis and a call from the public for environmentally friendly policies. If we learn anything from the past, it should be that even if the price of oil drops, the drive for new technology should not drop with it.

Another place to take inspiration from is the Nordic countries, specifically Finland and Sweden. Biofibre has been an important fuel in the energy systems of

Finland and Sweden for a long time. After World War II, biofibre use decreased, reaching its lowest level in the 1970s (Statistics Finland 2001). This was mostly due to the demand for convenient energy delivery and the relative price difference that made coal and oil cheaper (Ericsson *et al.* 2004). Since then, the use of bioenergy has increased again, driven by increased oil prices in the 1970s (1973 oil crisis), and government policies aimed at increasing the share of bioenergy in total energy supply (Ericsson *et al.* 2004). In Finland, the drive for renewable energy had increased in the 1990s by efforts to mitigate climate change (UNEP 2009). It has been a political objective as early as 1990, when Finland pioneered carbon taxes on fossil fuels (UNEP 2009). They currently have long-term objectives set out with the goal being 25% renewable energy by 2015 and 40% by 2025 (UNEP 2009).

Canada shares three basic energy policy goals with Finland and Sweden; secure energy supplies, low health/environmental impacts, and economic competitiveness through efficient use and cost-effective supply (Ericsson *et al.* 2004). Biofibre allows them to satisfy these goals, which are partially conflicting, but only through government willingness and proper energy/biofibre policy (Ericsson *et al.* 2004). The supply issues in Finland and Sweden are different from North America, since they have plantation/production forestry with less environmental emulation. However, the lessons of biofibre collection efficiency still apply, as should the policies developed to support and grow the biofibre industry.

The use of logging residues for bioenergy has been a relatively new phenomenon in Canada. Prior to its use as a fuel, the harvesting residue from full tree logging was piled up and burned at roadside to eliminate it from the visual landscape. The debris from chipping operations were not piled and burned in this way and can be considered another potential source of biofibre. As bioenergy is being explored as a possible energy offset, this practice of burning is being suspended and the harvest blocks are being tracked for future biofibre harvest. These harvest blocks now present a challenge for usage due to a lack of road maintenance and inventory for future collection efforts.

CURRENT EFFORTS

This study builds on a previous undergraduate thesis effort (Bilyk 2009), which utilized a ground-based method to inventory logging residues at roadside and in the harvest block. It was a part of a larger study looking at the possibility of replacing the coal in Ontario electric generating stations with biofibre (FBi 2006). The Ontario government has been talking about phasing out coal-fired power for many years now. As early as 1978, it was stated as a government goal to phase out fossil fuel generation by 1995. This goal was not met on time, but has since been restated as government legislation and must be completed by the end of 2014 (OPG 2011). The intent is to convert Ontario energy production into one which does not utilize coal. It is expected that current energy production capacity will decrease due to the reduced energy output of forest biofibre in comparison to fossil fuels (FBi 2006). This means that a medium sized power plant (200MW) will reduce energy output by approximately 30% (FBi 2006).

POLICY IMPLICATIONS

To keep this form of energy "green", effective government policy must be instituted to keep harvest levels sustainable and to help keep options open for new opportunities. In North America, this policy is just beginning to be written but lessons can be learned from across the Atlantic, where this form of energy has been in place for far longer. As discussed previously, Sweden and Finland have both had biofibre as part of their energy portfolios for a long time. Their political system does not differ much from North America in terms of how policies regarding energy are brought into power. The essence of the policy is debated and compromises are made to appease those from across the political spectrum. While some environmentalist minded parties argue for tougher regulation on coal fired forms of energy, economists argue that they should be fully funded to help drive the economy. An example in Finland recently was "to grant permission for the construction of a new nuclear power plant, which was complemented with a decision to improve conditions for renewable energy" (Ericsson *et al.* 2004). The policies in both countries surrounding bioenergy have been controversial and hotly debated at times, but overall the process tries to keep energy markets stable (Ericsson *et al.* 2004). Carbon taxation (including CO_2 emissions) is considered by economists as an efficient market-based environmental policy instrument (Vehmas *et al.* 1999).

As in Canada, national and local governments dominate ownership of energy infrastructure and this has kept the formal regulations to a minimum. In 1970, oil accounted for 57% and 77% of the primary energy supply in Finland and

Sweden, respectively (Ericsson *et al.* 2004). When the oil crisis hit in 1973, reducing oil dependence became a top priority for energy policy in both countries (Ericsson *et al.* 2004). As a result, the use of electricity, coal, peat and biofibre increased due to higher oil prices and various support schemes (Ericsson *et al.* 2004). In a bold statement made in 2005, Sweden committed to being oil free by 2020. This does not mean that bioenergy will take up the decrease in production; the bulk of the energy production will switch to nuclear and hydroelectric generation (COI 2006). "Today, 45 % of Sweden's energy supply – electricity, district heating and fuel – comes from renewable energy, which is more than in most EU countries (Sweden 2011). Sweden has set a target of 50 % renewable energy by 2020 (Sweden 2011). Sweden is unique in that it has an extensive district heating system, powered by biofuels or municipal garbage, which provides heat and power (Sweden 2011). Figures 1 and 2 below compare the current energy breakdown for Sweden and Ontario.

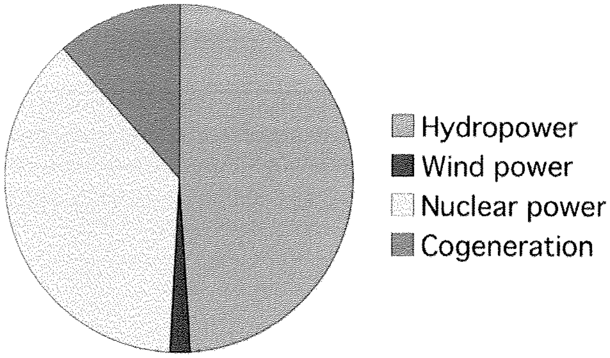


Figure 1. Energy breakdown in Sweden (Sweden 2011)

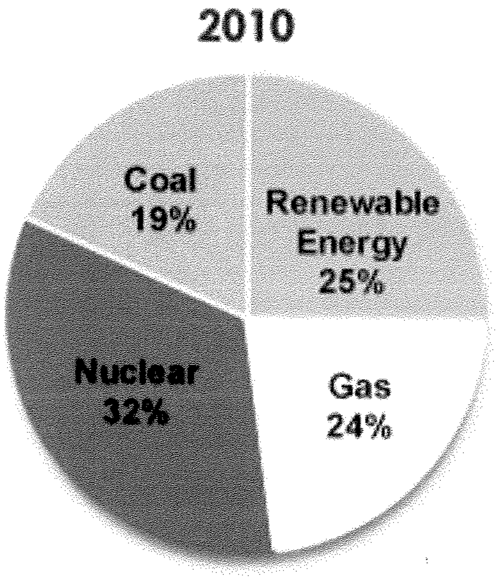


Figure 2. Energy breakdown in Ontario (EverEnergy 2010)

The governments of Finland and Sweden have both supported bioenergy policy for a long time (Ericsson *et al.* 2004). Some policies that directly influence its success include research and development support, investment grants, and energy and environmental taxes (Ericsson *et al.* 2004). Bioenergy research and development (R&D) has been a major component of the government energy R&D since the 1980s; about 10-20% of the total R&D budget for energy in both countries (Elforsk 2010). This funding is in addition to energy company and forest industry R&D contributions (Elforsk 2010). This R&D effort has targeted the whole supply chain, "from biofibre extraction or harvest to ash handling and recycling" (Ericsson *et al.* 2004).

Another method that was used to help reduce oil dependence was taxation, beginning in the 1970s (Ericsson *et al.* 2004). While taxes on fossil fuels have continued to rise, biofibre has been exempt from taxes except for a value added tax (VAT) (Vehmas *et al.* 1999, Ericsson *et al.* 2004). As a result of strict carbon and energy taxes, biofibre became cheaper than oil in 1991 in Sweden and in 1997 in Finland (Ericsson *et al.* 2004). Combined with incentives aimed at every part of the biofibre supply chain, these policies have allowed biofibre to thrive. One example of complimentary incentives is in Finland where in 1991, they introduced a subsidy for woodlot owners who commercially thinned their stands (Ericsson *et al.* 2004). In 1999, they added an incentive to chip these thinned trees, and the resulting chips are then used for biofibre (Ericsson *et al.* 2004).

There is another lesson to be learned from the Nordic countries, and that is that without knowing the long-term supply, it is possible that we may run out of biofibre in a short number of years. It is the job of policy makers to set guidelines for the scale of biofibre projects allowed in a given region to ensure long-term viability. Ontario does not want to be in the same situation as Nordic countries are currently for biofibre; "Forecasts show that Europe will have to import biofibre if it is to meet the EU's 2020 goals" (Vattenfall 2011). Even with the most optimistic forecasts, total biofibre deficit is projected to be 30 to 150 million tonnes of pellets per year (Vattenfall 2011). This corresponds to the output from 50 to 300 large-scale pellet plants (Vattenfall 2011). Figure 3 below is taken from a Nordic power company information pamphlet and outlines where they source biofibre currently as part of the global trade of biofibre.

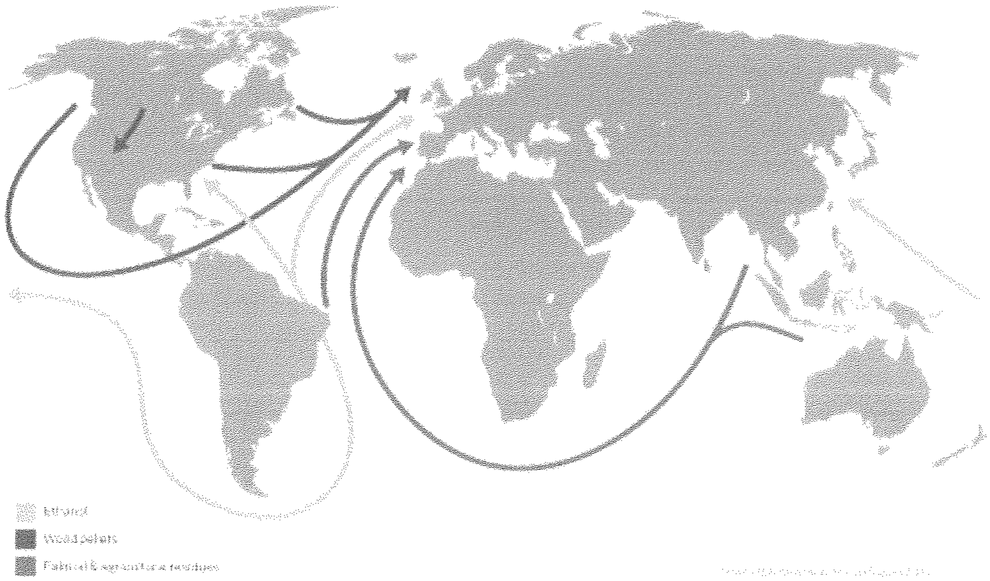


Figure 3 - Global trade of biofibre (Vattenfall 2011)

It is interesting to note that pellets are being shipped from British Columbia, down through the Panama Canal and across the Atlantic Ocean by ship. The recent mountain pine beetle outbreak caused a massive surplus of wood with little use (BC Energy 2011). If the wood is harvested within a year or two of being hit by the beetle, it can be salvaged for commercial purposes (Stennes and McBeath 2006). Due to the nature of how the beetle kills the tree, the wood dries out too quickly and becomes useless for standard commercial uses. Combined with the sheer volume of trees impacted, many are dying on the stump and becoming useless. This has led to large-scale harvesting for the purposes of pellet production (Stennes and McBeath 2006, BC Energy 2011). The market demand in Canada does not match the massive supply of pellets, but the European market creates a favourable environment and they are shipped to Scandinavia. The recent massive beetle kill in British Columbia is affecting future wood supply for the British Columbia forest industry. However, this is offset to some degree by a massive production of pellets from destroyed forest and taking advantage of a demand in the European market. To encourage the adoption of renewable energy, governments can alter the market conditions so that either the cost of environmental degredation or the benefits of reduced emissions are considered in market outcomes (Stennes and McBeath 2006). Some of these mechanisms exist in Europe so the pellets are worth the cost.

Ontario has addressed some of the concerns around biofibre in the "Forest Biofibre – Allocation and Use" directive (OMNR 2008). This piece of legislation outlines the policy context that the Ontario Ministry of Natural Resources operates within, and how forest biofibre fits into the current framework. The policy allows the harvesting of logging residues that were previously burned at roadside for the purposes of energy production or some other use that is identified in the forest management plan (OMNR 2008). This policy also governs the charges that can be levied on any user who collects forest biofibre. Currently this rate is set to $0 but as the demand for the material goes up, this charge will probably increase to help keep the sector competitive (OMNR 2008). This policy does not address the use of coppice growth, as it is an extension of the Crown Forest Sustainability Act, which governs the management and use of trees (OMNR 2008). This policy does provide a framework in which policy makers can influence the forest biofibre sector as it develops and allows the ministry to implement restrictions where it deems them necessary. This policy does allow companies to harvest stands of timber, that were approved under a forest management plan, for the purposes of energy production if there is no other suitable use in other forest products due to their quality or species (OMNR 2008).

SOURCES OF BIOFIBRE

While this study is focused on harvesting residue as a source of biofibre, there are several other sources being explored where remote sensing may play a role. Two other main sources are low quality stands with little commercial value and stands of coppice growth. Low quality stands may be assessed in similar ways to commercial stands, however the social implications of harvesting for energy are unknown and the subject of another study. Coppice is a term for plants, which sprout or reproduce from the root system of the plant that was previously killed or harvested. Coppice growth is the focus of much research globally and looks at using plants, which grow rapidly and have significant energy output vs. growth time (Allen 2008). The inventory of this energy crop may not be necessary as each plant will have similar energy output and energy potential can be predicted on a simple area calculation. A third other source of biofibre may be areas affected by forest disturbances, including fire, insect and windthrow and disease.

SAMPLING METHOD BACKGROUND

Coarse woody debris (CWD), including branches, logs and treetops, is an important component of the forest ecosystem. CWD influences soil nutrients, provides habitat for wildlife and plays a vital role in forest fire behavior. Biofibre is another form of CWD and is simply CWD distributed across a harvest block after harvest. Standard methods exist for inventorying this material to quantify the volume, with one of the most popular being the line intercept (transect) method; pioneered by Warren and Olsen in 1964. Their research was in the context of fuel loading for forest fire prediction, but this can readily be applied to the bioenergy inventory problem (Warren and Olsen 1964). Many studies have followed this initial work to quantify the amount of logging slash left on site after harvest (Van Wagner 1982, Schueller 1982, Ride 1998, Sorenson 2007).

A problem shared by all of these studies is that each site presents a new slash distribution and slash volumes can be highly variable due to the harvesting system and operators involved (Pulkki 1978, Fang 1993). The previous undergraduate study that this project is based on employed the line intercept method in a triangle configuration. Research in British Columbia comparing several methods of line intercept method found that a triangle was the most efficient design for time and accuracy (Nemec and Davis 2002).

The Minnesota logged area residue analysis conducted by Sorenson (2007) of the Minnesota Department of Natural Resources, looked at the question of logging residue availability from the ground on a large scale. They used the triangle transect design to estimate biofibre volume within harvest blocks. One hundred and twenty four sites were selected covering an area of 4,037 acres or approximately 1,634 hectares (Sorsenson 2007). The field effort for a study of this size would have been intensive as each site was visited and transects were conducted. The study goal was to develop biofibre availability information for each county to help support economic development and inform policy. The problem with the study was that biofibre volume is related to pre-harvest cover type, but every cover type was not equally represented in the data collection effort. Some cover types are under-represented and the biofibre volume should be examined critically, as outlined by the author (Sorenson 2007). This study did not report on the cost of field collection effort, in either time or dollar amount.

The findings of Bilyk (2009) reinforced those of Pulkki (1978) and Fang (1993), which found that the distribution of logging residue is spatially variable across a harvest block and that a ground-based method was unable to fully capture this variation. Some trends were found that may be useful in operational planning: (1) hardwood blocks generally had more biofibre due to larger tops; and (2) efficient slash pile design can facilitate measurements and ultimately collection. This leads to two possible avenues for continued research. One would be to stratify the blocks using remote sensing and then conduct a ground-based inventory. This method could potentially deal with the variable nature of slash by directing the sampling effort to measure where the harvest residue is. The second would be to try and conduct the entire inventory using large-scale digital image analysis, with the use of ground-truthing plots for training. This method would account for the unique nature of every block and could be applied to entire forest management units. The key economic factor in this stream is the imagery used, because it is the major expense.

This idea is not a new one, as demonstrated by Runesson (1982). He conducted an aerial-based inventory of logging residues using large-scale photos, but the technology at the time was limited, making the effort difficult. The effort was also labour intensive, which would drive up the end-user cost. The basis of this technique was sound, but it was ahead of its time and the technology. The digital imagery, including gyroscopes and inertial navigation systems and Global Positioning Systems (GPS), available now help to eliminate issues such as tilt error, scale variation and effects of terrain. With new software packages, the labour requirements should also be reduced.

Some other studies have tested image analysis methods that might be adapted to biofibre volume estimation. One study looked at assessing the damage to forests caused by hurricanes and identified unique combinations of electromagnetic spectrum wavelengths (also known as signatures) that correspond to downed woody debris (Wang *et al.* 2009). These signatures may be transferrable to logging residue or areas affected by windthrow, another potential source of biofibre. Another study conducted in Yellowstone National Park, attempted to quantify the volume and quality of coarse woody debris using remote sensing (Huang *et al.* 2009). The term "coarse" generally means it is over 8 cm in diameter, while fine woody debris is under 8 cm in diameter.

The Yellowstone study was successful in finding certain signatures that correspond to more or less coarse woody debris, but it stated that the results were limited. The problems stemmed from the type of data used, which was Synthetic Aperture Radar (SAR). SAR is a form of radar in which successive pulses are processed to form a high-resolution image (CCRS 2005). Radar is a system which emits microwave wavelengths, and these wavelengths reflect off an object. Depending on the nature of the objects and its location, some of the emitted energy will return to the receiver. The strength and dispersion of the signal return can be interpreted by a human or a computer to give meaningful results. The problem with radar is that the signal does not always return because the object absorbs the signal, or reflects it away from the receiver. Certain conditions, such as terrain or object surface water (e.g. rain) may distort the return, making the interpretation difficult. Synthetic aperature radar also has trouble dealing with certain types of vegetation, which is why it was combined with optical imagery for the Yellowstone study (Huang *et al.* 2009). While the results are not directly applicable to this research, certain lessons were learnt from it that can be applied to the efforts of this project, and certain signatures to focus on.

Other efforts have been conducted in the field of remote sensing inventory of biofibre but these have all focused on inventorying standing timber for above-ground biofibre or have involved the use of Light Detection and ranging (LiDAR) (Hilker *et al.* 2008). LiDAR uses shorter wavelengths than radar (UV, visible and short infrared) and a laser system to concentrate the signal, as opposed to radar, which uses much long wavelengths (e.g. microwave). This difference in wavelength and the use of laser systems to concentrate the output, allows LiDAR to create very high resolution elevation surfaces. This means that LiDAR can return very high resolution data, making it an attractive imagery source for this type of research.

A study conducted in Norway recently focused on using LiDAR to inventory biofibre volume pre-harvest. The data that is returned from LiDAR is a scatter plot of points, with each one representing elevation values. This type of data is called a point cloud and many different mathematical methods can be used to generate meaningful information from the point cloud (Hauglin et al. 2011). The study looked at trying to quantify the upper portion of the tree that is not used commercially and termed this material as "potential logging residue" (Hauglin et al. 2011). This technology is still relatively new but the study showed some promise in predicting the volume.

The current cost of LiDAR data may be prohibitive for full scale applications of this nature in Canada, however, in future it may be possible to take advantage of this data (Northwest Geomatics 2011). Norway has more private land ownership, so there is economic return on investing in this type of technology and the scale is much smaller than in Canada where most land is publically owned and is many times larger. The goal of the current study was to create a method that can be implemented industrially, and for this reason LiDAR is not being considered for this project.

REMOTE SENSING BACKGROUND

Jensen (2005) presents a combined definition for photogrammetry and remote sensing as:

> "the art, science, and technology of obtaining reliable information about physical objects and the environment, through the process of recording, measuring and interpreting imagery and digital representations of energy patterns derived from non-contact sensor systems."

This definition captures the fact that there are no absolutes in remote sensing; it takes input and interpretation from the user to yield meaningful results. Sensors can be used to obtain specific information about an object, with electromagnetic radiation being a surrogate for the actual property under investigation (Jensen 2005). "The electromagnetic energy measurements must be calibrated and turned into information using visual and/or digital image processing techniques" (Jensen 2005).

Remote sensing presents many advantages to traditional field methods. The primary advantage is the cost savings for large scale projects, such as biofibre inventory. The variable nature of biofibre, both in volume and spatial location, demands a technique that is capable of dealing with this variability, as demonstrated in Bilyk (2009). However, remote sensing does have its limitations. "Perhaps the greatest limitation is that it is often oversold" (Jensen 2005). It does not provide all the answers, but it does provide "some spatial, spectral and temporal information of value that we hope is efficient and economical" (Jensen 2005).

The world of image analysis was initially a stereoscopic effort but with the introduction of digital image analysis techniques in the 70s, it became a flat 2D approach. It was possible to extract some meaningful information from flat images by enhancing the images to highlight a feature of interest (e.g. insect infestation). However, the current technology is now allowing stereoscopic (3D) techniques to be used again in conjunction with computer based image analysis techniques. Recent advances in technology have made 3D computer work stations more affordable. These workstations can be used to extract accurate digital elevation models (DEMs) and differentially corrected orthophotography (term used for photographs that have been corrected to remove terrain and thus line up with existing base maps) from the aerial imagery, as well as to view the images in three dimensions with the ability to zoom in and out (Jensen 2005). This allows effective image analysis techniques for pattern recognition to be augmented by experienced human knowledge (e.g. stereoscopic photo-interpreters). The digital imagery available now can be flown at a higher resolution, as camera sensors have improved. The entire image database can exist digitally and be manipulated for photointerpretation as well as advanced image analysis techniques. Ontario has flown its new enhanced forest resources inventory (eFRI) in a completely digital format, 20 cm black and white and 40 cm colour pixel resolution (OMNR 2011). This is a huge change from the old imperial 1:15,840 and metric 1:20,000 black and white imagery of previous inventories, which were not digital and did not allow the user to zoom in or manipulate the images, and may be useful for future biofibre extrapolation.

POTENTIAL DIGITAL IMAGE ANALYSIS METHODS

Several techniques have been used in digital image analysis that may be useful in estimating the biofibre volume from logging residue, both at roadside and within the cutover. They include direct measurement and shadow fraction estimation (Leboueuf *et al.* 2005, Mitchell 2005). Direct measurement is the actual measurement of each piece of wood visible on large scale aerial photography and deriving a volume from that (Runesson 1982). The Runesson study was ahead of the technology available to automate some of the process. Although the method did work, it was time consuming and would ultimately be inefficient with the technology at the time.

With today's technology and software, however, it is possible that this method may work. Programs that combine spectral image data with contextual information (e.g. similar colours, textures, slope position, proximity to like objects and shapes) can be used to derive a base volume, with a technician checking to make sure that the program is not making mistakes. These programs attempt to look at images in the same way the human brain does. When a human looks at a picture, he/she groups colours together and puts them into context based on shape and position. For example, a round blue area may be a lake, but if the area is thin and skinny it may be a river. This is known as supervised classification, and has been a standard remote sensing technique for many years (Mitchell 2005). In simple terms, supervised classification means that a human is defining specific labels for different elements (e.g. trees, roads, lakes or streams) of an image and tells the computer the characteristics that define these labels. For example, trees are green while water is blue, and lakes are round and large while streams are narrow and winding.

The second method, shadow fraction estimation, involves measurements where the wood volume is not immediately visible. This method may not apply to every scenario, but rather for unique situations like slash piles. The idea is simple, in that it uses the shadow of objects to derive their size, based on the time of day and geographic location (Leboeuf *et al.* 2005). Like many remote sensing techniques, it takes some ingenuity to apply it to a new situation, but it seems that the method may work for objects like slash piles, which would be difficult to quantify any other way from the air. If these techniques fail, then there is the possibility of using remote sensing to identify the components of a tree at roadside and use known growth and yield equations to predict volume.

At this time, there are no studies that look at the specific problem of harvest residue inventory using remote sensing that do not use LiDAR. A few studies have attempted to use remote sensing for coarse woody debris estimation but these were not industrially feasible and had limited success. There are also no remote sensing studies that outline a specific procedure that can be directly applied to this question without some testing and customization. The study goal of having a technique that is industrially viable requires some creative problem solving and must avoid high cost imagery such as LiDAR. With a reliable inventory, informed government policies can be drafted. Without this type of inventory, policies may allow too much industrial development or they may restrict industrial development, depending on the inventory results.

METHODS

STUDY LOCATION

The study area was located within the Crossroute Forest Sustainable Forest License, which is under license by Resolute Forest Products (formally AbitibiBowater Inc). The study blocks were selected as part of a previous study (Bilyk 2009) and represent a typical Boreal forest-harvesting scenario. A map showing the locations of all study blocks is located in APPENDIX III. Three annual work schedule years were selected, going backward from 2008-2009 to 2006-2007. These schedules run from April 1st to March 31st of the following year and describe how the companies structure all of their reporting to the Ontario Ministry of Natural Resources. One block from each AWS year was selected at random from the previous study blocks (Bilyk 2008). A larger sample size would have been ideal but the cost of image acquisition forced a decrease to three study blocks. The previous study blocks were selected from within a 200 km radius of Atikokan, to reflect a potential wood basket to feed the Atikokan Generating Station. After the imagery was flown, it became clear that the oldest block from 2006-2007 AWS year would not work as a study block because of the growth of vegetation that obscured all residual biofibre. This block was subsequently dropped but did yield some insights discussed below.

LOGGING RESIDUE INVENTORY METHODS

Post-Harvest

Line Transect through Harvest Blocks

The method used to measure volume in the field was the line-intersect method. The previous study (Bilyk 2009) gave some insights that were adapted for this study. The first was that pieces of wood less than 8 cm in diameter have a negligible effect on volume and so were ignored for this study. The second was that the sample sizes had to be large enough to account for the large variability of slash volume distribution within a block.

The transect method employed by Runesson (1982) was adapted for this study. The transect was designed and laid out according to Figure 4. The parameters for the transect were that it would be 1 km long, intersect a road within the harvest block and allow for side transects of 50 m. With these parameters, a computer program was used to generate random start points and random azimuths for each transect. At each end of the 1 km line, three 50 m transects in the form of an equilateral triangle were located. This was to account for any orientation bias of wood pieces within the block. At each corner of the triangle, a 0.61 m x 0.61 m square of white hardboard with a letter painted on it was nailed to a stump or log (Ranging from A – F). Figure 5 shows one of these scale checks while Figure 6 shows the proper layout of one triangle. These served as scale checks for the remote sensing effort conducted later on. An additional marker labeled numerically was placed at each 200 m mark down the 1 km transect. These markers were placed in the field prior to the imagery being flown. At every scale marker placed, a corresponding GPS waypoint was created to allow for referencing later on. At each 100 m mark down the transect, a 50 m spur transect was conducted north or south of the line on an alternating basis. The direction of the first line was chosen at random.

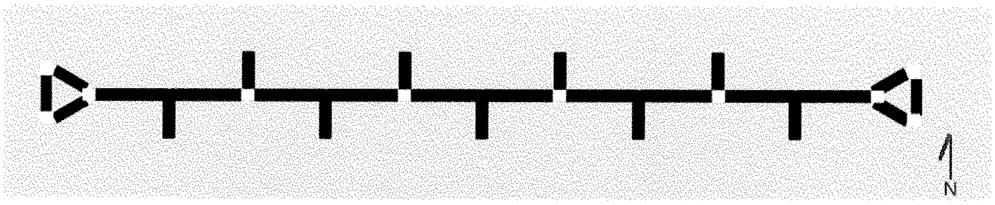


Figure 4 - Transect layout

Figure 5 - Scale check

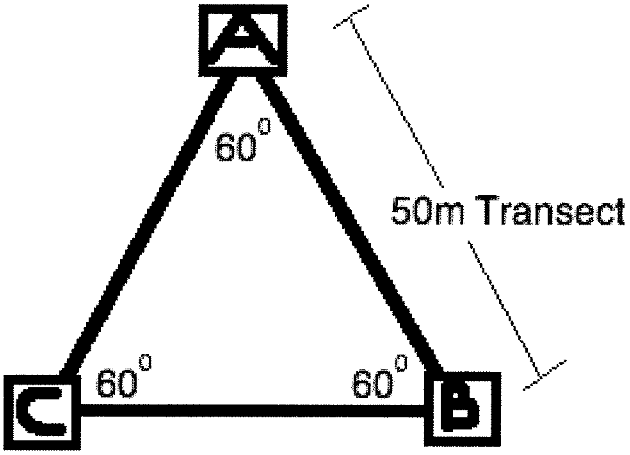


Figure 6 - Triangle transect arrangement

Along each transect, every piece of wood over 8 cm in diameter outside bark (DOB) that intersected the line was tallied. The DOB was recorded to 2 cm diameter classes using parallel calipers and the species was also noted. Species was recorded for use in potential future studies and was not a parameter sought after in the remote sensing effort. Other notes were made regarding tree cover if it was dense and any special circumstances. For example, one transect intersected a lost bundle of wood so notes were made because this could skew the overall block volume prediction.

Image Acquisition

The imagery used for this study was acquired using fixed wing aircraft with a high resolution digital-frame camera. This camera array was equipped with an inertial navigation system, which tracked when the camera fired and recorded the GPS position as well as flight parameters, which are used to process the imagery. The resolution of interest was 8 cm pixel ground resolution and represented the extreme limit of the camera and plane system commercially available at the time of study. 8 cm did not necessarily represent the preferred resolution – the ultimate resolution would be the coarsest resolution necessary to gain acceptable results. Aerial imagery was selected because it is readily available and cost effective, and should provide the scale needed to derive the information of interest. Forest product companies already invest funds in inventorying harvest blocks using supplemental aerial photography (SAP). Hence, it was the goal of this study to make the method effective at this resolution, but the testing will not be limited to it.

The imagery used for this project has a pixel size of 8 cm. This means that any object larger than 8 cm should be visible. The flight information is displayed below:

- Flight height was 3500 ft = 1066.8 m
- Lens on the camera was 105mm.

The frame inside the camera is 4500 pixels x 3000 pixels (Figure 7) because they are technically using the optics of a traditional 35 mm SLR camera with a ratio of 24 mm to 36 mm in the frame with a resulting 1:5 ratio. The film has been replaced by a chip representing this ratio.

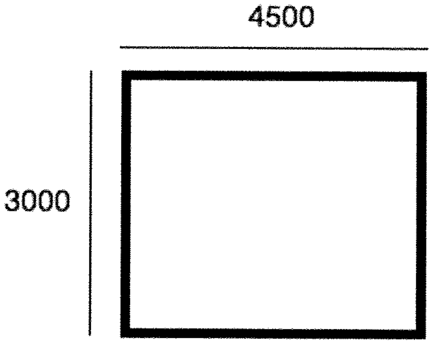


Figure 7 - Image dimensions in pixels

The calculations necessary for determining the image resolution are shown below.

- Shutter speed = 1/1000 of a second
- f stop of 5.6
- $scale = \frac{0.105m\ (mm\ of\ lens)}{1066.8m\ (flight\ height\ in\ m)} = \frac{1}{10160.000}$
- 1mm = 10160mm or 10.16m
- 36mm = 365.76m

- $$\begin{aligned} resolution &= \frac{365.76m}{4500\,pixels} = 0.08128m \times \frac{100cm}{1m} \\ &= 8.13cm \end{aligned}$$

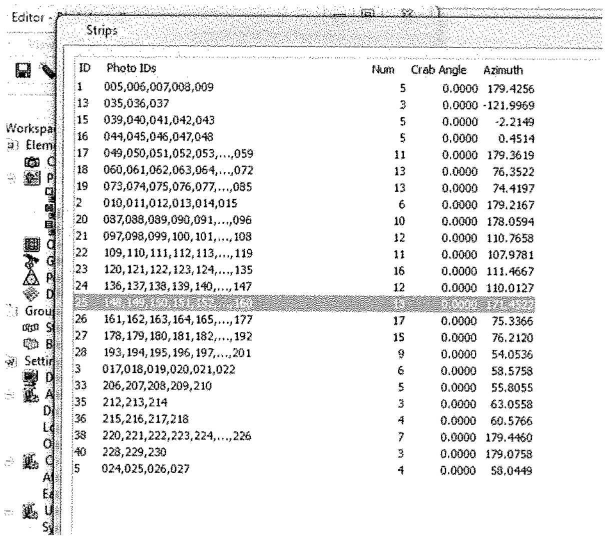
There is one more parameter that needs to be considered when having imagery flown and this is known as image motion. Image motion is a result of the forward movement of the plane as the photos are taken. Standard practice is to ensure that image motion is less than half of the pixel resolution. If image motion is too high, it can introduce a source of error into the images, causing blur. The image motion calculation is shown below:

- Flight speed of the plane was 140km/h
- Shutter speed of the camera was 1/1000 of a second
- $$\begin{aligned} &= \frac{140km}{h} \times \frac{1000m}{km} \times \frac{1h}{3600\sec} \times \frac{1}{1000\sec}(shutter\ speed) \\ &= 0.039m \times \frac{100cm}{m} \\ &= 3.89cm \approx 4cm \end{aligned}$$

Since the image motion is half of the resolution, it is safe to assume that there was no error caused by image motion.

At the time of image collection, 8 cm resolution had not been attempted at any large scale. As a result, some errors occurred during collection. During the processing of the imagery, errors were found in the accuracy of spatial alignment. This means that the software was not confident that the location being suggested for individual photos was accurate due to differences between subsequent flight lines. An error of this sort is rare and can be attributed to GPS drift on the day that the control points were collected. If the GPS used had the ability to be differentially corrected, this problem may have been negated. Because of this problem, some other steps were necessary.

The individual images were converted from the raw Kodak camera format of .DCR to the standard .TIFF using Kodak's Professional DSC Photo Desk. The images were opened all at once as a contact sheet and batch saved to .tiff; renumbering from 001 to 230 at the same time. This was done so that the images could be sorted by flight line; in the same way that inPho would sort the photos. inPho is a software package that is capable of reading IMU data and applying the spatial information to each image. Figure 8 is a screenshot from within inPho and shows which images correspond with each flight line.



ID	Photo IDs	Num	Crab Angle	Azimuth
1	005,006,007,008,009	5	0.0000	179.4256
13	035,036,037	3	0.0000	-121.9969
15	039,040,041,042,043	5	0.0000	-2.2149
16	044,045,046,047,048	5	0.0000	0.4514
17	049,050,051,052,053,...,059	11	0.0000	179.3619
18	060,061,062,063,064,...,072	13	0.0000	76.3522
19	073,074,075,076,077,...,085	13	0.0000	74.4197
2	010,011,012,013,014,015	6	0.0000	179.2167
20	087,088,089,090,091,...,096	10	0.0000	178.0594
21	097,098,099,100,101,...,108	12	0.0000	110.7658
22	109,110,111,112,113,...,119	11	0.0000	107.9781
23	120,121,122,123,124,...,135	16	0.0000	111.4667
24	136,137,138,139,140,...,147	12	0.0000	110.0127
25	148,149,150,151,152,...,160	13	0.0000	[illegible]
26	161,162,163,164,165,...,177	17	0.0000	75.3366
27	178,179,180,181,182,...,192	15	0.0000	76.2120
28	193,194,195,196,197,...,201	9	0.0000	54.0536
3	017,018,019,020,021,022	6	0.0000	58.5758
33	206,207,208,209,210	5	0.0000	55.8055
35	212,213,214	3	0.0000	63.0558
36	215,216,217,218	4	0.0000	60.5766
38	220,221,222,223,224,...,226	7	0.0000	179.4460
40	228,229,230	3	0.0000	179.0758
5	024,025,026,027	4	0.0000	58.0449

Figure 8 - Flight lines

Each flight line was then built in Adobe Photoshop and common flight lines were mosaicked to form the final mosaics for each block. The critical step throughout this process was to make sure that no compression was applied to the images. They were kept as uncompressed tiffs to ensure this did not happen. Compression would have degraded the quality of the images, reducing their usefulness and spatial resolution. At this point, the images lacked any spatial information, so this information had to be generated. The individual mosaics were brought into ArcGIS 10 and georeferenced to the Ontario eFRI imagery using more than 50 tie points per mosaic. Georeferencing is a process where obvious points on the image are tied to the same point on another source of data, gaining that spatial information. This is a common practice for data that is lacking spatial information, and as long as tie points are distributed across the full extent of the image, high quality results are possible. Although this process is not ideal, it was done with as much accuracy as possible and was the only course of action available to make the data work.

As a check for the scalar accuracy, the white panels of known size were located and measured on the imagery. The differences between computer size and real size were less than a pixel, so this can be considered a negligible source of error (see Tables 6 and 7 in Appendix I).

Image Analysis Procedures

The measurement of biofibre volume took place within ArcGIS 10. The mosaics were imported and the control points on the ground were located. The transect lines were generated using the control points as reference, and the editing tool to allow for a visual reference. Figure 9 demonstrates a section of this transect within block 7276. The blue dots represent the location of each ground control point, while the orange lines were generated by the software and demonstrate the location of the transect.

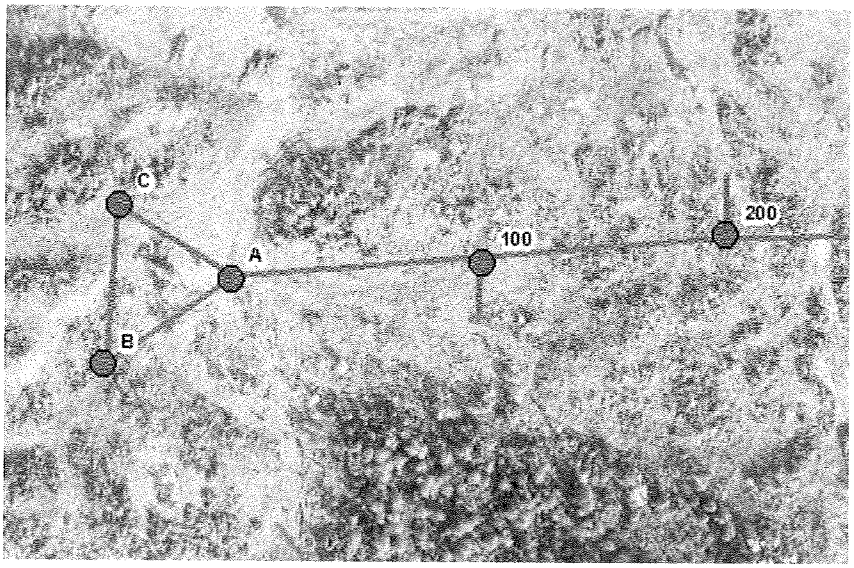


Figure 9 – Transect section

Once the lines were generated, the next step was to zoom down and start measuring all the wood that the lines intercepted. The order followed was the same as the field and a scale of 1:125 seemed to work well for measurements. Every piece of wood that the line crossed was measured at that point for diameter using the measurement tool. The key to the success of this tool is making sure that the projection of the imagery is correct since it is the projection that drives the measurement. This area fell in UTM zone 15N so this datum was used. Figure 10 below shows one part of a transect. Wood is clearly visible at this scale and the placement of the measurement tool is also accurate at this scale. The figure also highlights one issue that can happen with the imagery and that is tree cover. This problem will be discussed later.

Every effort was made to align the virtual transect with the one conducted in the field but the image analysis measurements are independent measurements from those taken in the field, since it is impossible to know that the exact same pieces of wood are being measured in both cases.

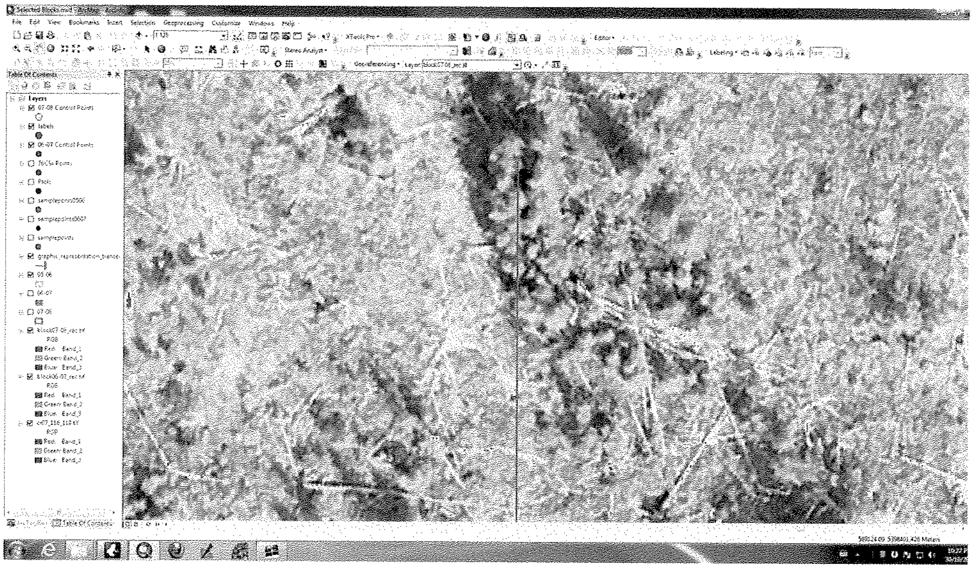


Figure 10 - 200m Transect

Statistical Procedures

The equation used for the volume (m^3/ha) calculation post harvest is described in a paper written by members of the BC forest service on different coarse woody debris assessment methods (Nemec and Davis 2002). The original equation (1) used in their paper is:

$$\frac{\pi}{2L}\sum_{j=1}^{m_i}\frac{a_{ij}}{\cos\lambda_{ij}} \qquad [1]$$

Where:

L = Length of sampling unit
i = sample point
j = piece number
m = number of pieces that intersect the line
a_{ij} = the cross-sectional area (measured in cm^2) of piece j where it intersects the line transect
λ = the acute angle between the piece and the horizontal (= 0 if the piece is lying flat on the ground)

All pieces were measured perpendicular to the log at the point where the line intersected it (Figure 11); so λ can be disregarded.

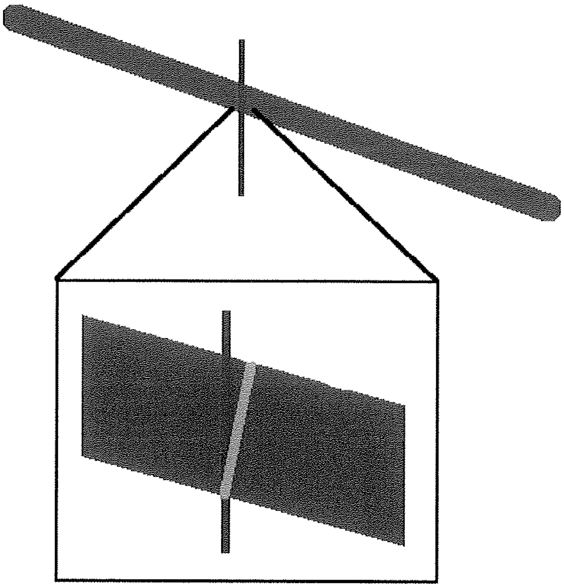


Figure 11 - Measurement method: the red line shows the transect line while the orange shows where the diameter measurement takes place

The new volume equation (2) with λ removed is shown below.

$$\frac{\pi}{2L}\sum_{j=1}^{m_i} a_{ij} \quad [2]$$

Where:

L = Length of sample unit
i = sample point
j = piece number
m = number of pieces that intersect the line
a_{ij} = the cross-sectional area (measured in cm^2) of piece j where it intersects the line transect

For this study, the length of sample unit (L) was 50 m and included all three sides of each triangle as well as the side transects. The equation (3) for the confidence interval at 95% is as follows and reflects the stratified (by AWS year) random sample design used.

$$\bar{y} \pm t_{0.025,n-1} * s_{\bar{x}} \quad [3]$$

Where:

$\bar{y}$ = the mean volume (m^3/ha)

$t_{0.025,n-1}$ = the number corresponding to 2.5% probability in the upper tail of a t distribution with n-1 degrees of freedom

$s_{\bar{x}}$ = standard error (4)

$$s_{\bar{x}} = \frac{s}{\sqrt{n}} \quad [4]$$

s = standard deviation (5)

$$s = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \bar{y})^2}{n-1}} \quad [5]$$

n = number of transects

The goal of this project was to achieve a standard error of less than 10%. The 10% goal was one that Van Wagner outlined in his report "Practical Aspects of the Line Intersect Method," and he states that this goal should suffice for any end use of the volume estimate, with a percentage as high as 20% being acceptable for many applications (Van Wagner 1982).

The test statistic for analysis in this project was a Student's t-test and is used when two samples are normally distributed and are assumed to have equal variances. The samples were unpaired and independent of one another so the equation (6) for calculating the t statistic for each harvest block is as follows:

$$t = \frac{\bar{x}_1 - \bar{x}_2}{Sx_1x_2 \cdot \sqrt{\frac{2}{n}}} \quad [6]$$

where

$$Sx_1x_2 = \sqrt{\frac{1}{2}(S_{x_1}^2 + S_{x_2}^2)}$$

Sx_1x_2 is the pooled standard deviation, 1 = field measurements, 2 = image-based measurements. The denominator of *t* is the standard error of the difference between two means. For significance testing, the degrees of freedom for this test is (2n-2) where *n* is the number of transects in each group.

Once the t value has been found, a range of P-values can be found using a Student t-test distribution table. However, to calculate an exact P-value, computer software can be used. Graphpad Prism 5.0 was used for this calculation and the results are in Table 4.

RESULTS

Transect volume means for field and image-based estimates were similar for both harvest blocks (Tables 1 and 2).

Table 1. Block 7276 Summary.

Transect	Field (m^3/ha)	Image-based (m^3/ha)
A-B	56.00	45.75
B-C	63.40	52.75
C-A	43.48	47.03
E-F	80.85	84.20
F-G	132.32	115.36
G-E	44.17	26.92
100R	34.71	40.52
200L	66.45	42.79
300R	108.65	85.09
400L	118.12	95.93
500R	148.39	99.98
600L	62.41	7.99
700R	61.52	66.16
800L	138.72	90.22
900R	113.98	93.47

Table 2. Block 72842 Summary.

Transect	Field (m^3/ha)	Image-based (m^3/ha)
A-B	26.13	42.40
B-C	97.41	106.88
C-A	27.71	33.72
E-F	8.78	13.41
F-G	13.11	16.76
G-E	18.54	24.35
100R	50.68	55.51
200L	39.34	65.96
300R	126.50	28.89
400L	60.54	40.72
500R	71.78	24.65
600L	71.48	30.86
700R	57.58	42.00
800L	48.21	16.66
900R	81.24	51.76

Summary information for these two datasets, along with some other descriptors are displayed below (Table 3). The results provide some insight into the volume of biofibre available within a given harvest block. The Image-based volumes are lower than those recorded in the field but the coefficient of variation demonstrates that the two methods are sampling within the same larger population.

Table 3. Summary Statistics

	7276		72842	
	Field	Image-based	Field	Image-based
Average (m^3/ha)	84.88	66.28	53.27	39.64
Std. Deviation (m^3/ha)	38.07	31.11	33.01	23.98
Std. Error (m^3/ha)	9.83	8.03	8.523	6.192
Upper 95% CI (m^3/ha)	106.00	83.50	71.55	52.92
Lower 95% CI (m^3/ha)	63.80	49.05	34.99	26.35
CV	44.85%	46.94%	61.97%	60.51%

The t values generated in Graphpad Prism 5.0 are reported along with the P value and some other summary statistics (Table 4). The table summarizes the results of both Block 7276 and 72842. Table 5 provides some further analysis results from Graphpad 5.0, these describing the variance within each sample population.

Table 4. Unpaired *t-test* of Field and Image-Based Volume

	Block 7276	Block 72842
P value	0.154	0.206
t value	1.465	1.294
Degrees of Freedom	28	28
Mean ± SEM of Field Volume (m^3/ha)	84.88 ± 9.829	53.27 ± 8.523
Mean ± SEM of Image-based Volume (m^3/ha)	66.28 ± 8.032	39.64 ± 6.192
Difference between means (m^3/ha)	18.60 ± 12.69	13.63 ± 10.53
95% confidence interval	-7.396 to 44.60	-7.942 to 35.21

Source: Graphpad Prism 5.0

Table 5. F test to compare variances

	Block 7276	Block 72842
F value	1.498	1.894
Degrees of Freedom (numerator)	14	14
Degrees of Freedom (denominator)	14	14
P value	0.4595	0.2443

Source: Graphpad Prism 5.0

The t-test results show no significant difference between field volume and volume measured from the imagery for both harvest blocks. The f-test for both harvest blocks also shows no significant difference between the sample variances of each measurement method. With the design of the experiment, no further statistical tests were required. Figure 12 is a graphical representation of the volume estimates, from the field effort, for block 7276 with standard error being included. The volumes for the same block, derived from the imagery, are displayed in Figure 13, again with standard error. Figure 14 is a graphical representation of the volume estimates, from the field effort, for block 72842 with standard error being shown. The volumes for the same block, derived from the imagery, are displayed in Figure 15. Figure 16 is a summary of the average volume for both blocks and both methods. The error bars demonstrate that the means are not significantly different.

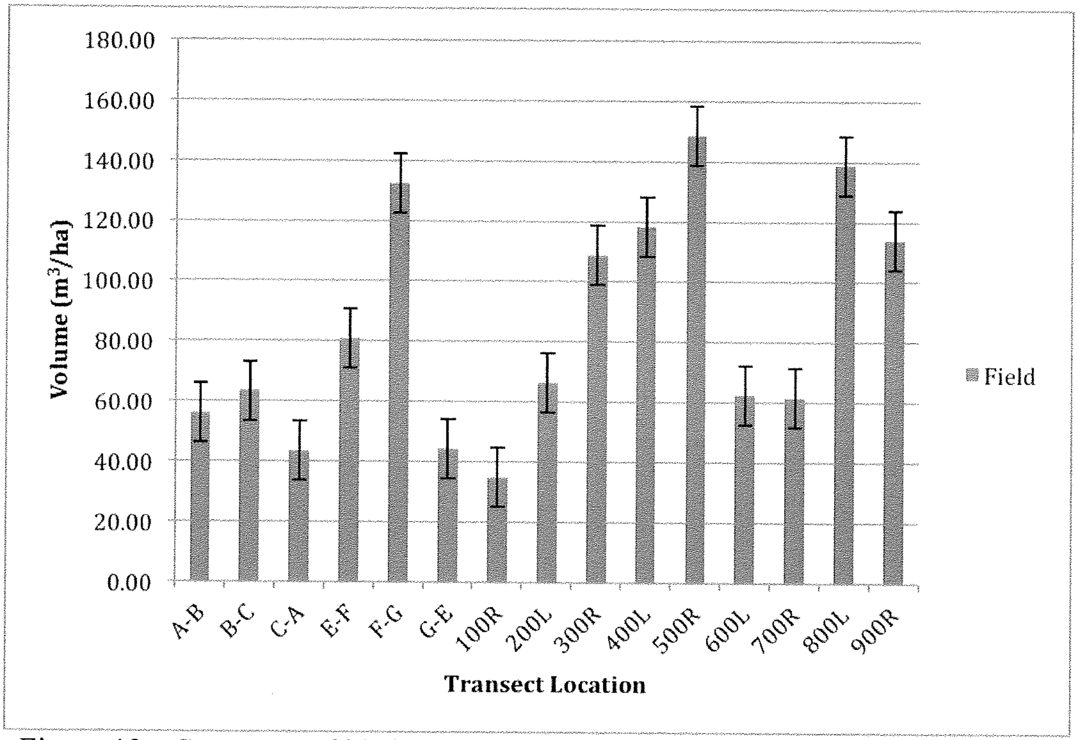


Figure 12 – Summary of biofibre volume derived in the field from harvest block 7276 (bars depict standard error of the mean)

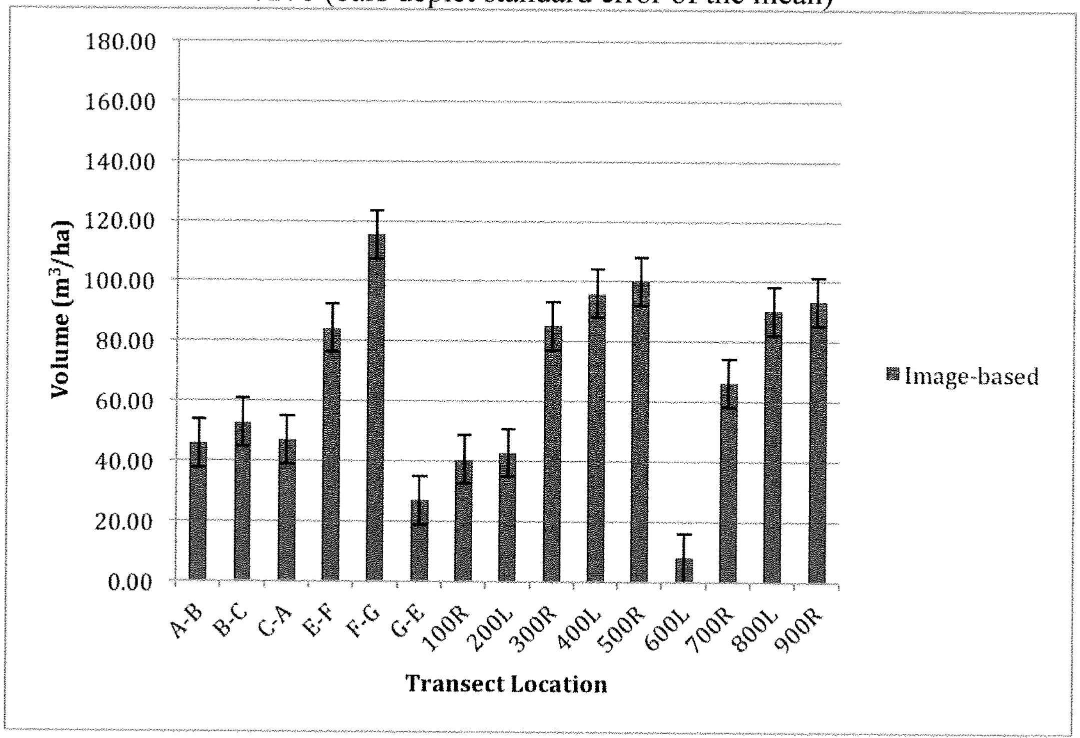


Figure 13 - Summary of biofibre volume derived from the image analysis effort from harvest block 7276 (bars depict standard error of the mean)

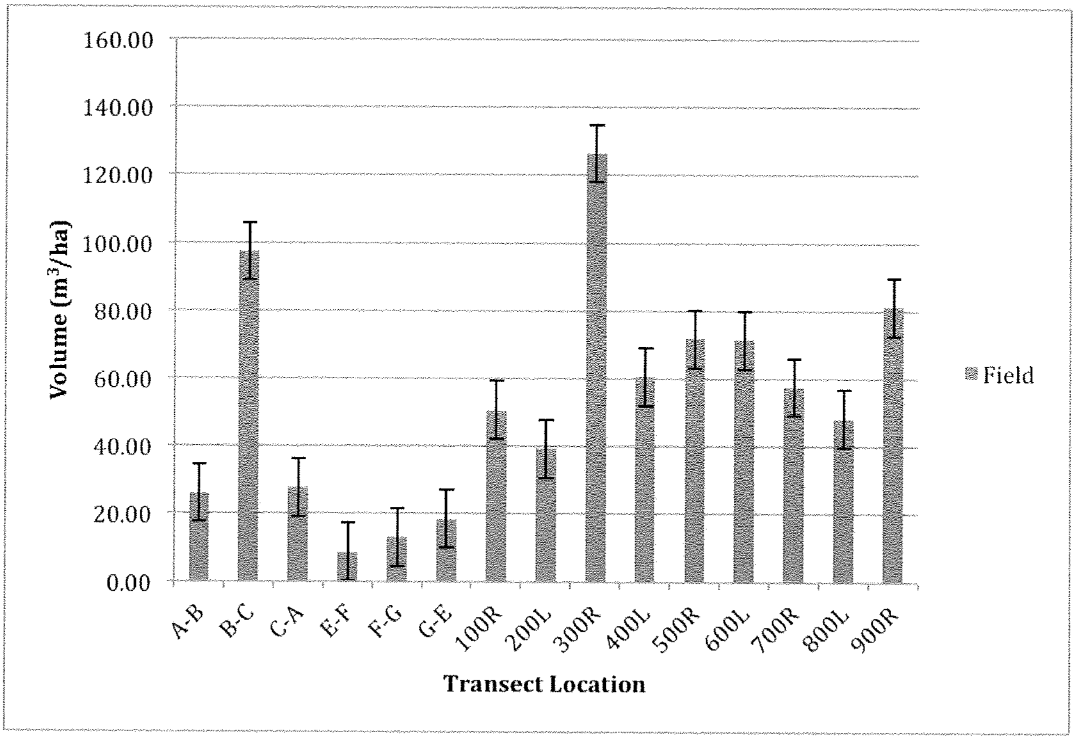


Figure 14 – Summary of biofibre volume derived in the field from harvest block 72842 (bars depict standard error of the mean)

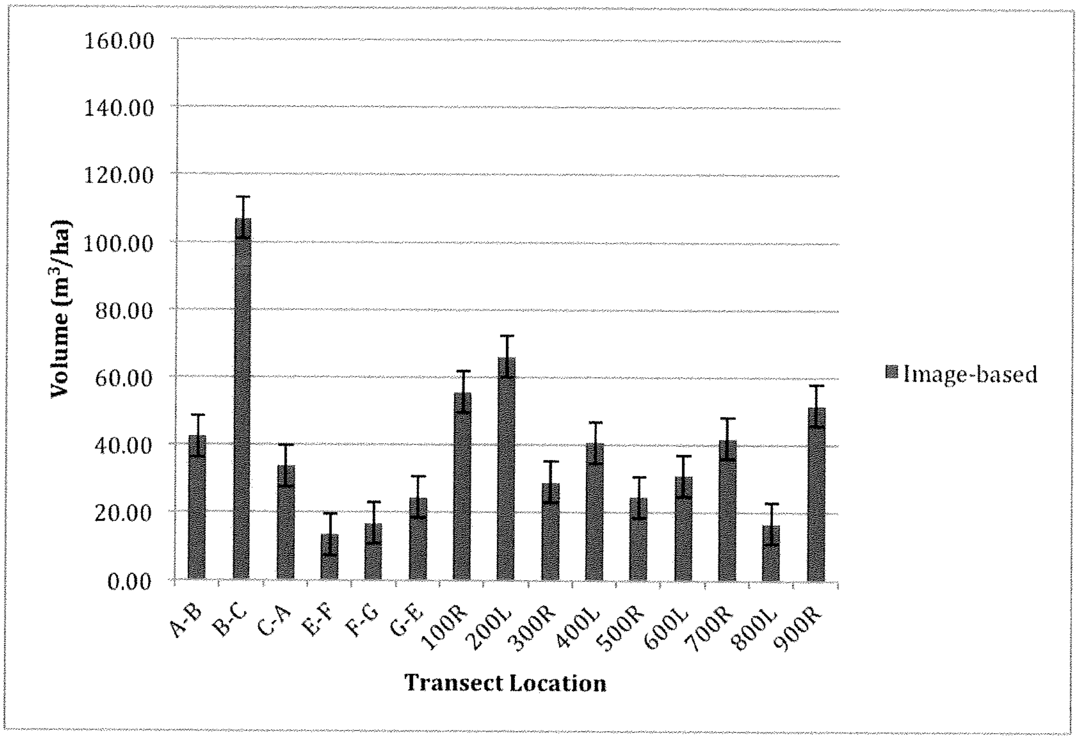


Figure 15 – Summary of biofibre volume derived from the image analysis effort from harvest block 72842 (bars depict standard error of the mean)

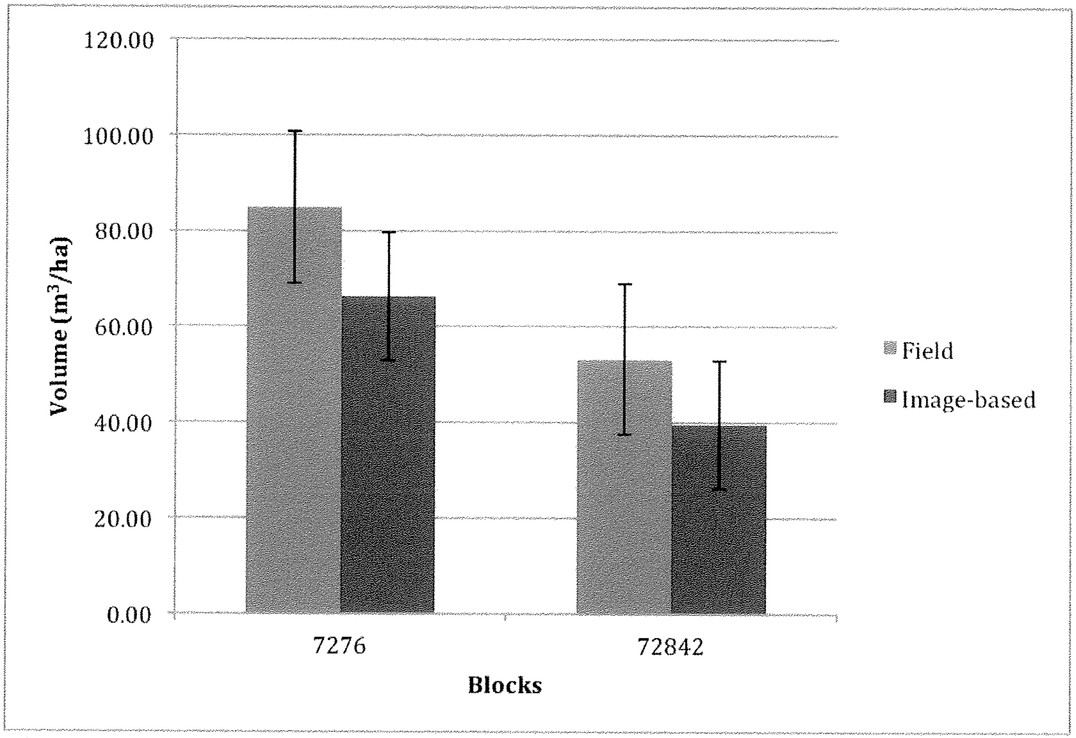


Figure 16 - Summary of both blocks showing average volume estimates from field and digital image analysis effort (bars depict standard error of the mean)

There is no metric to compare between blocks because that was not the focus of this study. The variability between blocks is what drives the need to explore image analysis as an alternative to traditional field sampling.

DISCUSSION

The goal of this project was to determine whether image analysis techniques, combined with high resolution imagery, could be used for assessing biofibre volume as accurately as field methods. The field method is a sound one and previous studies have proven its validity at estimating biofibre volume within harvest blocks (Nemec and Davis 2002, Bilyk 2009). The large variability of slash volume seen between the study blocks prevents the extrapolation of this study results to any regional scale.

With some effort put into developing regional biofibre availability databases, it will be possible to help direct appropriate development to regions that have the biofibre to sustain those projects. One possible use is by regional economic development corporations. Currently, if an entrepreneur wants to get a loan to start a pellet company, the bank loan officer requires the entrepreneur to show the long-term wood supply. Since he/she cannot do that, the loan application is denied, and a potential business leaves the community. If the economic development corporations helped develop the supply databases, then sustainable economic development can occur. The business startups can get the loans they need from the banks and the development corporation can help prove the long-term sustainability of all business startups in their respective areas. There is currently no mechanism like this available, and inventory estimates are little more than educated guesses. Educated guesses are not enough to justify or direct millions of dollars in funding and infrastructure; it should be based on sound science and economics. This lesson can be seen in Sweden, where biofibre fired power plants were built and ran out of wood to fire them. These plants are now buying pellets from British Columbia, shipping them around the world and firing their plants (Vattenfall 2011). The cost of power produced by the plants is not cheap as a result and one could argue the environmental impact of shipping pellets that far. While wood may be sustainable, the fuel cost and impact of shipping across the world may defeat the potential benefits. Had an inventory been available, the plants there could have been built smaller to run only on the supply available, and the requirement to ship pellets would have be removed.

With the digital-image analysis method proven effective, it will now be possible to assess biofibre questions on a regional scale. The next logical step will be to develop regional inventories of biomass to help drive infrastructure investment and provide a solid foundation for policy decisions. For decisions like converting Atikokan Generating Station to one fired by biomass (OPG 2011), it would be possible to develop a wood basket map for the station and determine how much biomass can be taken on a yearly basis. This map could then be applied to any other business ventures within the same wood basket so that the supply of biofibre does not become an issue.

Theoretically, this procedure should be applicable globally for measuring harvest biofibre. It would need to be locally calibrated for the tree species of interest but the concept is universal. The major limitation would be the cost of software, which is why it is more likely that a consulting company would take on the task of generating the volumes for regions, rather then each region attempt to generate the information itself. If each region tries to conduct an inventory on their own, the chances of success are limited due to the complex nature of the software and the cost of computer equipment. This is the equipment and software that consultants already have and use, so it makes sense that it could expand as another part of what they offer.

The problem with any popular/hot topic such as bioenergy is that initially there is a great amount of government and private company interest and funding that gets thrown at the problem; but when the price of oil drops, the interest fades with it. The only way that we can avoid this from happening is to address the fundamental questions of implementation and then get projects going. Only by investing can we insure the long-term interest in the technology. The danger however is to build too much, too quickly, without doing the fundamental research.

The question of inventory is often overlooked but it is the single defining factor that determines how large the production of energy can be. It does not matter if a larger plant can be built if there is not enough economically available wood to keep it running. This is the case in both Grassy Narrows First Nation and Geraldton. Both of these communities installed district-heating plants, and initially they were running seamlessly. The problems started when the wood supply diminished. They had to pay much higher prices for wood to chip and burn and this caused the system to become economically infeasible.

Had some inventory been explored, it would have shown that there was an insufficient wood supply economically available and they could have either adjusted the size of heating plant installed or scrapped the idea entirely. In the case of Grassy Narrows, the sawmill shutdown so all the free sawdust and shavings were no longer available. Had some more thought been put into the wood supply, issues like that could have been identified and contingency supplies prepared in the event of a shutdown. It is this kind of unsustainable development that needs to be avoided.

The current issues that are cropping up are that competition will start to occur in certain regions because all the biofibre efforts are being concentrated in one forest area. This will drive the demand up, increasing raw material cost. However, if the location of biofibre projects were dictated by the supply of the region, then these issues could be mitigated and a more successful business community would arise. It is better to allocate companies to regions that can supply the material than to put them all in one area and drive the price of the raw material up.

The implications of this study are widespread and suggest that the creation of regional biofibre maps is possible with the use of digital image analysis, ground-truthing plots and GIS. There are some other conditions that must be explored first though. The first is the increased cost of high-resolution imagery acquisition. Current SAP imagery provided for comparison was collected at a resolution of 30-40 cm, while the imagery used in this study is around 8cm. To move from 30 cm resolution to 8 cm resolution would require approximately three times the imagery. This would also increase the processing time and cost for the imagery by about three times (Mizon 2011). This does not mean that every harvest block needs to be flown at high resolution; only the blocks where it makes sense to do so. This means that operations personnel need to keep track of a few standard metrics in the depletion shapefiles.

The first factor that needs to be tracked is the season in which the block was harvested. If the block was harvested in winter, this means that the road is usually not drivable during summer months and to harvest biofibre during the winter may not be efficient. In harvest blocks harvested in winter, a centralized landing may be something to consider or have the biomass collection efforts conducted in conjunction with harvest to maximize biofibre yield. The season of harvest is not tracked in all forests but was for some time in the Crossroute SFL. Tracking this factor will also aid in regeneration efforts, as planting contractors can be made aware of access issues prior to the start of the season and plan to access it later.

The second factor that needs to be considered is haul distance from the block to the mill. After talking to several hauling contractors in the field, the generally accepted economic haul distance for biofibre is about 100 km. Past this point, the cost of transportation and harvesting outweighs the cost benefits of biofibre. Even assuming a distance of double that to 200 km, the number of potential blocks drops dramatically.

The third factor that needs to be tracked more closely is the harvest method for a given harvest block. This information could not be found for the study blocks, so the harvesting system has to be estimated based on the site condition and the logging residue. Both study blocks were not chipper operations, as full trees were found roadside and there was no evidence of chipper debris piles. The debris piles found at roadside seemed to indicate full tree harvesting because the limbs were in regular piles as would be expected to be left by a delimber. At the time of this study, no cut to length operations or single grip harvesters were operating in the Crossroute SFL so neither of these systems could be a possibility. By tracking biofibre volume in relation to harvesting system, some other trends may be discovered that give further insight into biofibre recovery.

The final factor that emerged from this study was that blocks older than three AWS years have vegetation growth too high to allow for measurement from digital image analysis. Even ground measurements in this block were almost impossible, as the ground was not visible and most logs were found by tripping over them. The recovery in a block of this age would not justify the effort and would cause more disruption to the site.

If these factors were accurately tracked, it would be possible to build an economic model for the biomass harvesting system and use image analysis to identify harvest blocks which may be economically viable for harvest. A model of this type would have to consider things such as the price of fuel for transportation, distance to mill, and the price of biofibre (both in terms of harvest costs and energy value). Such a system must have a solid inventory to build on, and digital image analysis provides that inventory method.

This study focused on whole block volume so that subsequent recovery studies could be tied back to total volume. While it may make sense operationally to focus on biofibre volume within a buffer of the road networks, this study focused on providing a method to a variety of interests in determining biofibre volume. With this information, it may be possible to start estimating recoverable biofibre volume as a percentage of total biofibre volume or possibly preharvest standing volume. Now that a reliable method for measuring total biofibre exists, these next steps can be taken. Also, because biofibre harvest is not standard practice, being able to measure total block volume as part of a reporting scheme may be helpful in alleviating any environmental concerns.

The key aspect to making sure that this technique works operationally is keeping it simple. Currently, SAP imagery is only used to establish block boundaries, as demonstrated in Figure 17 below. This effort is not automated, but is done by trained personnel who physically draw these boundaries on the computer.

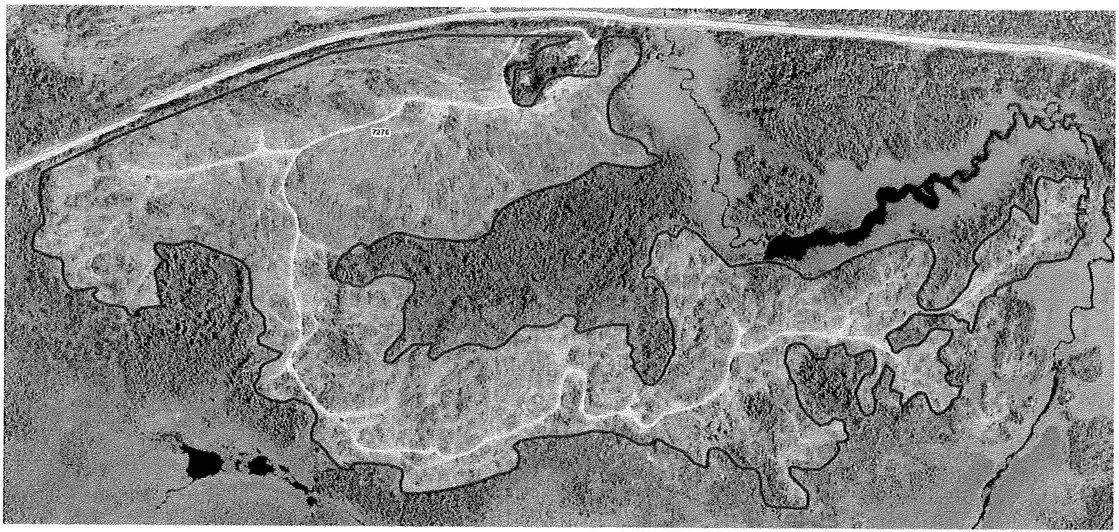


Figure 17 - SAP Boundary Example

If a person is capable of drawing these boundaries, they are capable of conducting this survey. The points are generated by the software and it takes only minutes to draw the transect. Once drawn, the operator zooms down to the scale of 1:125 and begins at point A. Every piece of wood intersected is measured and the diameter is entered into a spreadsheet designed to output volume as it entered. Once the survey is completed, volume measurements can be entered into the shapefile attribute table. With this information stored in the attribute table, it becomes readily accessible and easily tracked for future use. Building an automated routine that generates the transect would be a small effort and would improve the efficiency of the survey even more.

From the author's perspective, it was much faster to quantify the volume for a given harvest block using the digital image analysis effort. The field effort with a field crew of two generally took four to five hours to complete while the digital image analysis took about a half hour to complete. This is a substantial savings in time and does not take into account the time taken to drive to a given harvest block. This does not mean that no field effort is necessary to support a digital image analysis effort; there is always a need to use ground plots for verification and to provide benchmarks for correction factors if they are necessary.

The results showed a strong trend for the image-based analysis to report a lower biofibre volume than the field effort. This may be due to several factors, including tree cover obscuring the ground and smaller pieces not being visible.

The tree cover issue could be dealt with by stating that any transects which would pass beneath tree cover are relocated. The same rule would apply to transects established on the images using GIS software. The trees are left on site in accordance with Ontario forest management guidelines and may not be an issue in other jurisdictions.

Another potential source of error could be the fact that white objects tend to bleed around the edges with bright light. This was evidenced by the control points because the edges of the white board were not straight. This is a potential source of error because hardwoods also have white bark and may be prone to this bleeding. Fortunately, there are techniques which can be used in the software to correct for these issues and their impact can be minimized.

Although the image-based method reported a lower biofibre volume, this discrepancy can be corrected using a standard percentage. This correction factor would be determined by comparing the volumes reported for all ground plots to the image-based volume for those same harvest blocks. The average difference between field and image-based volume would be computed and this average would become the correction factor for all harvest blocks.

Future studies or industrial efforts utilizing digital image analysis should consider some lessons learned from this study. The first is the choice of ground control material. Although the white hardboard functioned as a ground control point, a better choice would be a much larger object such as a large black or orange X constructed from wood or heavy duty plastic. In the center of this X, the control point used in this study could be placed and the surrounding black background would help eliminate the bleeding around the edges. An obvious point like an X would be much easier to identify on the imagery and help make the process efficient. There is a trade off between making a ground control point portable so that field crews can carry them and making them easily visible on the imagery.

The second would be the choice of GPS unit used for ground plot establishment. A common industrial Garmin GPS was used for this study to simulate the hardware available to field crews but this type of GPS cannot accept differential correction, so the precision and accuracy of these GPS points are not ideal. The use of differentially corrected GPS points will help to speed up the raw image processing and provide a better measurement of spatial accuracy.

A final aspect that should be considered is a more detailed assessment of efficiency. This factor was not considered until after the field effort had been completed and so it was not included in this study but were this study to be repeated a detailed analysis of efficiency would be useful. The comments on efficiency are the author's own perspective but sampling a larger sample of GIS personnel and their experience conducting this survey, along with their results, would give some insight into the actual gains in efficiency and a better demonstration of how robust the volume estimate is.

CONCLUSION

In conclusion, the measurement of cut-over logging residues for bioenergy production using an image-based, remote sensing effort is an efficient and effective way to quantify the volume available. The field and image-based volume measurements were not statistically significantly different, indicating that the image-based method is a viable alternative. In the author's experience, it was faster to conduct the image analysis for a given harvest block as compared to the field effort for the same harvest block, saving time and potentially money. This method can deal with the variable nature of biofibre distribution and yields results comparable to a field-based effort. The methodology is simple enough for most users of a GIS environment to implement quickly. The increased cost of the imagery for this study should not prevent the implementation of this method, provided that the higher resolution images are collected only for harvest blocks that have a possibility of biofibre extraction. With the focus of modern forestry being on efficiency, this method will allow for a competitive and cost-effective regional biofibre map to be produced. This will help drive strategic infrastructure investment and help keep Canada at the forefront of the emerging bioeconomy.

This study is a proof of concept for using remote sensing as a substitute for field logging residue volume estimation. However, some field measurements will still be necessary to function as ground-checks. The conclusions are promising but need to be tested across an entire forest before any meaningful inventory can be developed. The same rules mentioned above should be considered for such a study, including using harvest blocks within 200 km of a mill and avoiding winter harvest blocks.

Future research focuses in this area may be directed towards automating part or all of the remote sensing process. An attempt was made during the course of this study to automate the process, but due to time restrictions that avenue was abandoned. It may be possible after several years of using this technique to start to develop general equations for relating biofibre volume as a percentage of standing timber volume pre-harvest. This type of equation development requires much more data than was feasible for this study but, after industrial implementation for a few years, the data sets may exist that allow for such an equation. A final avenue for future research may focus on developing an economic model for the biofibre harvesting system. Combined with a remote sensing inventory, it may be possible to stratify which blocks are economically feasible to collect biofibre from based on haul distance, price of fuel for transportation and the value of biofibre. With a solid inventory, this type of future research can now move forward, making the entire system more efficient.

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APPENDICIES

Table 6. Block 7276 Scale Check Comparison

Location	Imagery (cm)	Ground (cm)	% Difference	# of Pixels
A	63	61	3.28	0.25
B	59	61	-3.28	-0.25
C	69	61	13.11	1.00
D	67	61	9.84	0.75
E	67	61	9.84	0.75
F	62	61	1.64	0.13

Table 7. Block 72842 Scale Check Comparison

Location	Imagery (cm)	Ground (cm)	% Difference	# of Pixels
A	68	61	11.48	0.88
B	62	61	1.64	0.13
C	66	61	8.20	0.63
D	67	61	9.84	0.75
E	N/A*	61	N/A	N/A
F	66	61	8.20	0.63

* The scale check was obscured by tree cover

APPENDIX II

Block 7276

100-R		200-L*		300-R		400-L		500-R	
Field (cm)	Image-based (cm)	Field (cm)	Image-based (cm)	Field (cm)	Image-based (cm)	Field (cm)	Image-based (cm)	Field (cm)	Image-based (cm)
8	24	8	16	12	26	12	32	10	34
12	14	8	18	18	30	8	24	10	20
16	14	8	34	20	24	10	24	10	24
14	26	8		12	20	14	28	8	30
8		8		8	30	16	16	12	32
10		12		22		8	26	12	
10		12		14		10		14	
14		16		12		10		18	
12		12		18		8		14	
12		16		8		10		14	
		20		12		12		10	
		8		8		10		14	
		8		10		8		16	
		14		14		8		8	
		10		14		10		18	
		8		24		16		20	
		12		22		8		14	
		12		14		10		12	
		16		8		16		10	
				10		18		10	
						20		12	
						10		14	
						16		16	
						12		8	
						14		12	
						8		10	
						16		8	
						18		16	
						14		18	
						14		16	
								12	
								22	
								12	

*View of Ground obstructed by Tree Cover

APPENDIX II

Block 7276 continued

600-L*		700-R		800-L		900-R	
Field (cm)	Image-based (cm)	Field (cm)	Image-based (cm)	Field (cm)	Image-based (cm)	Field (cm)	Image-based (cm)
20	18	10	22	10	30	8	20
8		14	36	12	38	8	34
8		28	16	18	16	10	20
8		8	18	14	22	12	22
12		12	18	16	24	10	26
8		30		16		10	24
10		10		12		12	10
12		8		12		16	
14		12		12		12	
14				22		24	
16				12		10	
14				8		8	
10				32		10	
12				16		12	
20				8		14	
				12		18	
				18		12	
				16		16	
				14		14	
				8		18	
				30		14	
						8	
						16	
						12	
						10	
						18	

APPENDIX II

Block 72842

100-R		200-L		300-R		400-R		500-L	
Field (cm)	Image-based (cm)	Field (cm)	Image-based (cm)	Field (cm)	Image-based (cm)	Field (cm)	Image-based (cm)	Field (cm)	Image-based (cm)
14	16	10	24	20	24	14	26	16	18
22	26	10	22	10	14	10	24	18	26
16	12	10	28	10	20	18	20	22	
14	16	10	24	10		14		14	
14	18	18	16	8		12		12	
12	20	14		18		8		22	
14	14	10		20		24		32	
18		24		8		10			
8				10		16			
				8		20			
				32		10			
				38					
				10					
				8					
				28					

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*View of Ground obstructed by Tree Cover

APPENDIX II

Block 72842 continued

600-L*		700-R		800-L*		900-L	
Field (cm)	Image-based (cm)	Field (cm)	Image-based (cm)	Field (cm)	Image-based (cm)	Field (cm)	Image-based (cm)
14	26	10	24	22	26	8	22
18	24	18	26	18		8	16
10		20	16	18		8	28
12		14	14	22		8	24
14		12		12		10	
12		8		14		12	
8		8				10	
10		20				10	
12		16				12	
20		8				14	
10		18				10	
10						10	
8						8	
16						8	
18						10	
12						8	
10						14	
						8	
						8	
						8	
						10	
						26	
						10	
						12	
						10	
						16	

APPENDIX III

Location of Study Blocks within Crossroute SFL