Using Logging Residues as Biofuel Feedstocks in the Pacific Northwest: Estimating Slash Pile Volumes with Low-cost, Lightweight Terrestrial LiDAR

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James M. Casey

Major Professor: Randy Brooks, Ph.D.
Committee Members: Jan Eitel, Ph.D.; Robert Keefe, Ph.D.
Department Administrator: Randy Brooks, Ph.D.

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AUTHORIZATION TO SUBMIT THESIS

This thesis of James Casey, submitted for the degree of Master of Science in Natural Resources and titled “Using Logging Residues as Biofuel Feedstocks in the Pacific Northwest: Estimating Slash Pile Volumes with Low-cost, Lightweight Terrestrial LiDAR,” has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

Major Professor: ____Date: ____________
Randall Brooks, Ph.D.

Committee Members: ____Date: ____________
Jan Eitel, Ph.D.

____Date: ____________
Robert Keefe, Ph.D.

Department
Administrator: ____Date: ___________
Randall Brooks, Ph.D.

ABSTRACT

With logging residues gaining momentum as potential biofuel feedstocks in the Pacific Northwest (PNW), refined methods of measuring piled slash are needed to inform the appropriate supply chain infrastructure that can ultimately make the slash-to-biofuels process economically feasible. This study presents the design of a rudimentary, low-cost (~$450), lightweight (5.6kg) terrestrial laser scanner (TLS). Its viability as an option for estimating the volumes of slash piles is then explored by comparing it to two traditional slash pile estimators on a random sample of thirty slash piles. The inexpensive, field-mobile, and user friendly TLS (in comparison with traditional terrestrial laser scanners) was found to be more accurate than traditional ground measurements for estimating the volumes of small and irregularly shaped slash piles. Point clouds generated from TLS data are used to create 3D models of objects, which can be useful in a wide scope of terrestrial remote sensing applications.

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DEDICATION

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1.1 Context of Study

1.1.1 Global climate change and the prospect of renewable energy

Long-term increases in oceanic and atmospheric temperatures have resulted in the general acceptance of climate change as fact among the scientific community. These rising temperatures have been attributed to increased concentrations of heat-trapping greenhouse gases in the atmosphere. Multiple scientific models agree that climate change has been augmented by the anthropogenic emission of greenhouse gasses that have been released in vast quantities over the past century due to the burning of fossil fuels (Intergovernmental Panel on Climate Change, 2014; U.S. Global Change Research Program, 2009). Policy makers worldwide now bear the onus of mitigating and adapting to the potentially detrimental effects of a changing global climate.

One auspicious method of reducing our dependence on fossil fuels is a shift to alternative fuel and energy sources. The Energy Independence and Security Act of 2007 was designed by the federal government to meet Environmental Protection Agency (EPA) renewable fuel standards, and to promote energy independence and security ("H.R. 6 (110th): Energy Independence and Security Act of 2007," 2007; US Department of Agriculture, 2010). In terms of alternative fuel sources, the *USDA Biofuels Strategic Production Report* (2010) lists woody biomass from forest residues as a potential source of biofuel worthy of exploration.

1.1.2 Slash piles in the Pacific Northwest (PNW)

Driving around the PNW, the ubiquity of slash piles is striking. These piles are the result of logging and forest thinning treatments mandated by federal land-management policies such as the National Fire Plan and Healthy Forests Restoration Act of 2003. These policies aim primarily to mitigate the fire hazard that has become dangerously high in the past century due to environmental changes (e.g., increased likelihood of droughts) and the growth of increasingly dense western forests. Land managers in Idaho are required by law to remove post-harvest slash (Idaho Forest Practices Act, 1974), which is traditionally piled and left to dry for at least six months before it is set ablaze.

When burning slash, the process of incomplete combustion creates various pollutants regardless of the condition of the constituent woody debris. These pollutants (i.e., primarily carbon dioxide, carbon monoxide, methane, and particulate matter) are concerning in regards to air quality (Hardy, 1996). Sandberg et al. (1989) found that in the PNW, prescribed fires of piled and scattered slash emit an estimated 100,000 metric tons of particulate matter annually, and that performing pre-burn operations such as residue removal could significantly reduce the quantity of pollutants produced. Therefore, not only does burning slash offer little economic benefit, but it can also be environmentally deleterious. While the common practice of piling and burning slash meets the management objectives of reducing woody fuel loads and thereby decreasing fire hazard, gathering and transporting slash off-site could likewise meet those management objectives.

1.1.3 The opportunity of using slash as a fuel source

Using logging residue as feedstock for alternative fuel/energy is a promising alternative to the folly of burning slash and is not as fanciful as once believed. The Idaho Governor's Office of Energy Resources (2014) estimates that energy generated from the various forms of biomass (i.e., primarily logging and agriculture residuals, animal and municipal solid waste, and agriculture processing residues) has composed roughly 9 percent of the total energy feedstock consumed per year in recent years. Similarly, Washington has been using biomass as a feedstock for producing fuels, electricity, and steam. An estimated 16.9 million tons per year of biomass is still yet to be utilized in Washington, the majority of which is woody waste (Fuchs & Frear, 2011).

In 2011, the US Department of Agriculture (USDA) awarded a 40 million dollar grant to Washington State University that established The Northwest Advanced Renewables Alliance (NARA). A collaboration of various private industries and educational institutions across Washington, Idaho, Oregon, and Montana, NARA works to implement a biomass-derived replacement for a number of petroleum-based chemicals, particularly focusing on aviation fuel. NARA is working on converting woody residuals (i.e., from logging, thinning, and mill residues, and construction and demolition waste) into isobutanol, a biofuel that can be conveniently used as a substitute for gasoline in the current fossil fuel infrastructure

(Peralta-Yahya, et al., 2012). In bringing the slash-to-biofuels idea to fruition, their mission links environmental stewardship with economic and technological feasibility.

Future demand for isobutanol is promising. The US Air Force is currently the largest consumer of federal fuel and has recently expressed interest in alternative fuel sources in aiming to reduce carbon emissions and heighten fuels security and independence (The Assistant Secretary of the Air Force for Installations Environmental and Logistic, 2010). In addition, Alaska Airlines has identified the commercialization of alternative fuels as a priority and has been participating in projects that aim to research, develop, and test up-and-coming biofuels-related technologies (Alaska Air Group, 2009).

A major impediment to a prosperous wood-based biofuels industry is the relatively low commercial value of woody residues (Patton-Mallory, 2008). Economic models have indicated that bringing the slash-to-biofuels idea to fruition ultimately depends on economic factors associated with the production of such fuels (Bright et al., 2010; Obersteiner et al., 2006). Renewable and lower emission fuels are projected to become more competitive with other fuels as the price of carbon emissions rises (Obersteiner et al., 2006).

Exploring the viability of slash as a biofuel source calls for an understanding of its current and future availability on the local scale, as well as the broader scale demand for timber harvest that ultimately influences that availability. Amount of residual biomass left from logging is a function of many factors, including harvest amount, logging method, silvicultural treatment, and type and location of timberlands (Kersetter & Lyons, 2001).

According to the most recent (2014) USDA Forest Inventory and Analysis data, Idaho encompasses nearly 17 million acres of timberland (i.e., non-reserved forestland that is available for timber production) (Table 1).

Table 1.1. Acreage and percentage of non-reserved timberland in Idaho

Ownership Category	Acreage	Percentage
National Forest	12,353,423	73.1
Undifferentiated Private	2,821,823	16.7
State	1,086,864	6.4
Bureau of Land Management	598,981	3.5
Department of Defense or Energy	27,866	0.2
Totals:	**16,888,957**	**100**

That timberland, which lies mostly in the northern panhandle and comprises roughly 31.5% of the total land area of Idaho, has played a historically crucial role in the state's economy by providing the raw material needed for timber harvest (Figure 1.1).

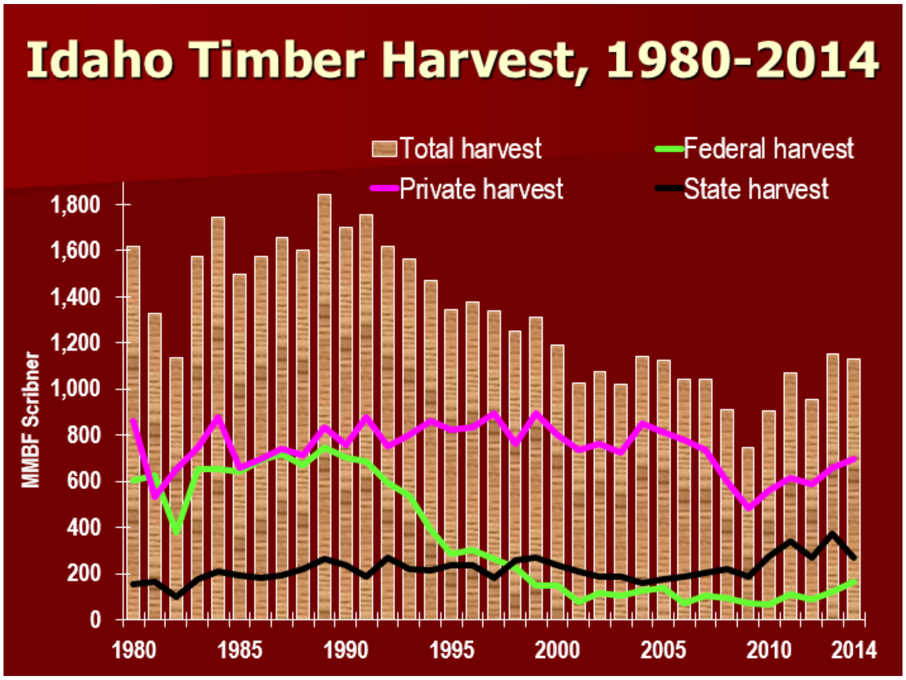

Figure 1.1. Idaho timber harvest by ownership category (Morgan et al., 2015)

Logging residue quantities are affected by timber harvest rates, which are a function of the demand for timber and wood products. In the past decade the timber industry has faltered—harvests on federal land began to decline around 1990 in response to various policies (Morgan et al., 2013), and also on private lands as a result of a rapid decline in demand for housing and associated wood products during the mid 2000's (U.S. Census Bureau, 2014) (Figure 1.2). While the industry has wilted in recent years, the Idaho Forest Products Industry Forecast (2013) predicts that demand for wood and paper products, number of housing starts, and home values will continue to modestly increase.

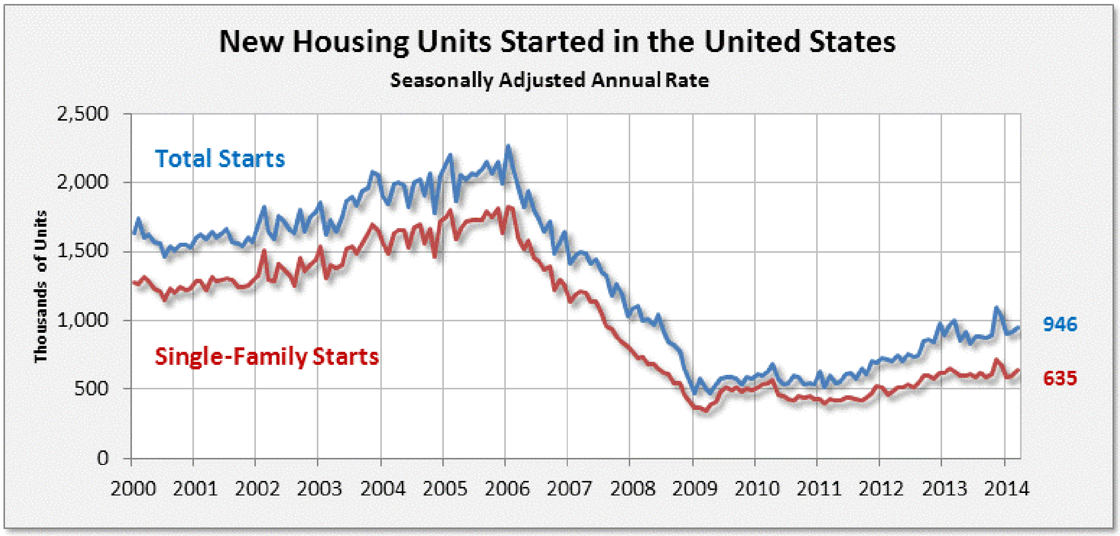

Figure 1.2. New housing starts in the U.S. (U.S. Census Bureau, 2014)

A recent study by Simmons et al. (2014) found that the average diameter of trees sent to the mills in Idaho has been steadily decreasing over time, while the volume of mill-delivered wood has remained relatively stable. Because thinner trees with smaller bole diameters have been shown to produce more logging residue per unit volume of merchantable wood (i.e., they tend to have a higher ratio of branch and unmerchantable top volume per bole volume) in comparison to larger diameter trees, mills are currently receiving a higher number of small trees in order to produce the same mill-delivered volume. This dynamic suggests that if the trend continues, the total amount of logging residue produced via logging will continue to increase (Simmons et al., 2014).

1.1.4 Summary

Logging residue is currently a largely untapped resource in Idaho. Instead of sending the energy contained in residual biomass up in smoke, converting that biomass to a usable fuel and/or energy source can be less environmentally adverse and more economical, bolstering local economies and reducing the import of other energy resources (Idaho

Governor's Office of Energy Resources, 2014). In light of the benefits of using slash as a fuel source, foresters, economists, and biofuel scientists alike seek to know how much slash is currently on the ground and how it can be best utilized.

Total Idaho timber harvest in 2014 was estimated at around 1.1 billion board feet (Idaho's Forest Products Industry Current Conditions and Forecast, 2013). Morgan et al. (2012) provide an estimate of 1.6 green tons of logging residues produced in Idaho per MBF Scribner of mill-sent wood. Using that estimate, in 2012 roughly 1,760,000 green tons of slash were produced, the vast majority of which has been or will be burnt on-site. According to the North American Wood Fiber Review (2014), processed chips from logging residues are being are priced at $50 per bone dry ton (bdt) ±$30 depending on cleanliness and species, and often also on other factors such as buyer-seller relationships (e.g., length of time having been in business together). Taking into account the current price of $50 per bone dry ton, and 880,000bdt of logging residue produced per year (i.e., total slash quantity of 1,760,000 green tons at 50% moisture content) gives a very rough estimate of **$44,000,000** set ablaze in Idaho in 2012, discounting the transportation, processing, and labor costs that would be inherent in the biofuels supply chain.

1.2 Study Rationale

1.2.1 The importance of quantifying logging residues in the PNW

The dynamic nature of the logging industry in Idaho presents a challenge when it comes to estimating slash availability as a fuel feedstock; changes in logging machinery, silvicultural regimes, forest structure, and ecological considerations (e.g., importance of leaving some nutrients on-site) have dated the many past studies of potential logging residues in Idaho. Therefore, diligent, up-to-date studies are needed to provide reliable estimates of current slash availabilities.

Because the collection, processing, and transport of slash can be costly compared to the potential profit margin, establishing an efficient supply chain ultimately dictates the economic feasibility of the slash-to-biofuel process. Before slash can be collected, processed, transported, and utilized it must first be located and quantified on a regional scale. This first step is necessary in determining the appropriate biomass infrastructure that will make the whole process feasible.

Logging utilization studies provide estimates of the amount of logging residue left at logging sites in proportion to the amount of mill-delivered wood. The results from such studies (e.g., Simmons et al., 2014 in Idaho, and O’Neil and Lippke, 2009 in Washington) can help answer the overarching question of how much slash currently exists in the Pacific Northwest that is available for conversion to biofuel. Conducting such studies though is very time and economically energy intensive. Because the amount of slash left by logging is a function of so many variables (e.g., harvest amount, logging technique, species composition, forest density, location of timberland, etc.), the needed sample size of recent harvests and the high detail of data collected on each site usually call for large teams of researchers, large sample sizes of logging sites, and meticulous study designs. As opposed to naively attempting to collect valid data on a large inventory of recent harvest sites, comparing the many slash estimators currently used to conduct such logging utilization studies was much more feasible, and no less relevant in shedding light on the big picture of slash availability. Since the method used to estimate slash volume is often as important in shaping our understanding of slash availability as the true amount of slash on the ground, the presentation of a novel method of estimating slash along with a comparison of traditional slash estimators will contribute nicely to the body of knowledge needed to put the slash-to-biofuels initiative into motion.

1.2.2 Methods of estimating slash volumes

The many methods that have been used in the past to measure slash volumes include: (1) ground measurements coupled with geometric equations (Hardy, 1996), where the dimensions of a pile are measured and plugged into the respective geometric volume formula; (2) pre-harvest inventories and allometric equations (Brown, 1978) whereby tree species and diameter at breast height (DBH) are tallied before a harvest and slash volumes are later estimated based on the number of each species felled from each DBH class; (3) the use of laser rangefinders (Yanling et al., 2010; Long & Boston, 2014), which are handheld devices typical in measuring solid stockpiles (e.g., of gravel, sand, coal, etc.) that measure volumes in different ways depending on brand and model; (4) line intersect sampling protocol for scattered slash (Brown, 1974, 1982; De Vries, 1974; Pickford & Hazard, 1978; Van Wagner, 1982), in which transects are laid out over areas covered in scattered slash, and volume inferences are made based on systematically observed slash depths; and (5) post-harvest samples of tree bole and residue volumes per felled tree (Simmons et al., 2008, 2010, 2014), which are used as case-sensitive allometric equations that are later used to estimate total slash volume per harvest based on the number of trees felled from each species/DBH class.

While the actual amount of slash produced in Idaho is a function of many factors, *estimates* of that actual amount vary due to the method used to estimate it.

For example, in terms of piled slash, O'Neil and Lippke (2009) found that pre-harvest inventories were flawed in overlooking the various configurations of cut and leave volumes present within typical logging sites. They also found that traditional ground-geometric measurements in their sample generated a very low estimate of slash quantity (almost half the size of the actual total that they measured by picking apart and weighing piles). Similarly, Long and Boston (2014) found the ground-geometric method to underestimate true slash values, evidently due to exclusion of limbs protruding from piles. Wright et al. (2010) found this method to generally underestimate pile volume for small piles, and overestimate the volume of large piles, which also broadly agreed with findings by Hardy (1996). Long and Boston (2014) found that laser rangefinder data generated more accurate estimates due to the ability to account for the irregularities found in more complex pile shapes.

1.2.3 Aerial and terrestrial LiDAR

Since its conception in the 1970's, LiDAR (light detection and ranging) has been used for a variety of applications relating to climatology, meteorology, hydrology, engineering, natural resources, and others. In terms of forestry it has been used to estimate crown bulk density and foliar biomass at the plot level (Riaño et al., 2003), individual crown parameters (Falkowski et al., 2005), fuel bed characteristics (Seielstad & Queen, 2003), carbon pools and fluxes (Spangler & Vierling, 2011), vertical forest structure (Zimble et al., 2003; Nilsson, 1996; Hudak et al., 2002, Lefsky et al., 2002), and other landscape and finer-scale forest attributes. A continuously advancing technology, scientists have taken an interest to exploring its many applications.

Aerial LiDAR technology is flown over an object or landscape of interest by a small airplane, helicopter, or unmanned aerial vehicle (UAV), and consists of: a laser emitter attached to the aircraft that scans an area of interest with laser pulses via an oscillating prism or mirror, and a receiver that detects laser pulses reflected back to the aircraft; an inertial measurement unit (IMU), which measures roll, pitch, and yaw (sometimes called “heading”) of the aircraft; a finely tuned global positioning system (GPS) on the aircraft calibrated to verify aircraft position relative to the ground; and a computer to store data (Figure 1.3) (Andersen et al., 2006).

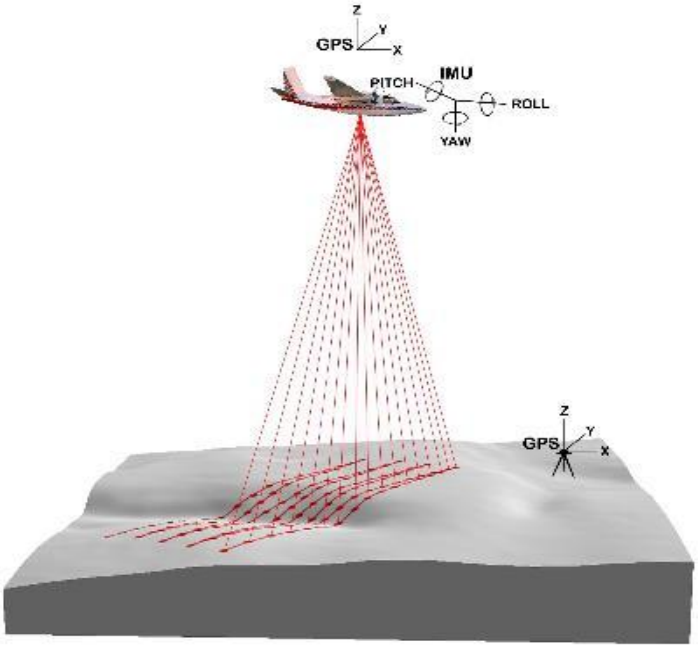

Figure 1.3. Basic aerial LiDAR concept (Andersen et al., 2006)

In conjunction with precise measurements of the position, trajectory, and orientation of the aircraft and laser scanner, each laser return can be attributed x, y, and z coordinates, a distance value that is calculated with the equation: (laser time of flight * speed of light)/2, and a degree of intensity, which depends on surface reflectivity. Data yielded by LiDAR acquisitions are affected by a number of laser system characteristics such as pulsed vs. continuous laser operating system, wavelength of laser used, pulse duration, pulse repetition frequency (PRF), scan pattern and angle, and spot size of laser pulse (i.e., “beam divergence” and “laser footprint”) (Nayegandhi, 2007).

When a LiDAR acquisition is completed, laser return data are amassed to produce point clouds (Figure 1.4), which can then be post-processed to generate various 3D models based on the goals of a particular LiDAR acquisition. These include bare-earth models, canopy top (first return) models, vegetation metrics (e.g., multiple return models that show forest structures), intensity returns, and others (Nayegandhi, 2007).

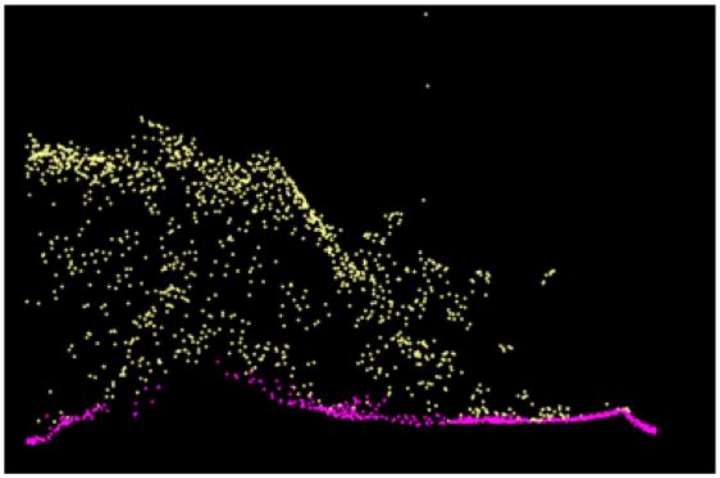

Figure 1.4. 3D point cloud showing trees (yellow points) and ground surface (purple points) (NOAA Coastal Services Center, 2012)

Terrestrial laser scanners (TLS) are grounded LiDAR systems that are useful in collecting finer, local-scale data. They have also been used for a number of forestry applications (e.g., Watt and Donoghue, 2005; Thies and Spiecker, 2004; Parker et al., 2004; Hopkinson et al., 2004) and would be preferable over aerial LiDAR where, for example, a thorough scan of one particular forest parcel, stream bed, etc. is needed. Albeit a very accurate method of measuring slash piles (Long & Boston, 2014), TLS systems are time consuming to use on individual piles and are costly—usually >$40,000 for entry level set-ups—though costs may decrease as the young technology matures. For example, the construction of a <$12,000 autonomously operating TLS was achieved by Eitel et al. (2013). Traditional TLS are large and consist of many components, such as generators, computers, and bulky laser scanners that can be difficult to transport in the field (Figure 1.5).

Figure 1.5. Leica TLS set up in McCall, ID (Jim Casey, 2014)

1.3 Study Goals

To meet its ultimate goal of establishing a sustainable wood-to-aviation biofuels supply chain, NARA works as a collaboration of several research teams: education, sustainability measurement, feedstocks, and outreach. Findings are shared between the five research sectors, each of which plays an equally crucial role in contributing to the ultimate success of the project (NARA, 2015).

The research presented here aims to contribute primarily to the feedstock sector by contributing to the base of knowledge regarding the estimation of feedstock quantities available for conversion to biofuels. This study also hopes to contribute to the outreach sector by developing and outlining a new, user friendly, and affordable method of estimating slash volumes that can potentially be used by the general public.

1.4 Guiding Research Questions

To inform the slash-to-biofuels supply chain the general overarching question to which I hope my research will contribute is: how much slash is there in the PNW that is available for conversion to biofuel? With that broad question setting the stage for the purpose of my study, my specific research objectives are to answer:

1) Is low-cost, terrestrial LiDAR a viable method of estimating slash volumes?
2) How does the low-cost LiDAR compare to traditional ground measurements and laser rangefinders in terms of accurately measuring the volumes of slash piles?

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CHAPTER 2: USING LOGGING RESIDUES AS BIOFUEL FEEDSTOCKS IN THE PACIFIC NORTHWEST: ESTIMATING SLASH PILE VOLUMES WITH LOW-COST, LIGHTWEIGHT TERRESTRIAL LIDAR

James M. Casey, Randall Brooks, Jan Eitel, and Robert Keefe
Authors' Affiliation:
Department of Forest, Rangeland, and Fire Science, University of Idaho College of Natural Resources, Moscow, Idaho 83843, USA
case7735@vandals.uidaho.edu

2.1 Abstract

With logging residues gaining momentum as potential biofuel feedstocks in the Pacific Northwest (PNW) and beyond, refined methods of measuring piled slash are needed to inform the appropriate supply chain infrastructure that can ultimately make the slash-to-biofuels process economically feasible. This study presents the design of a rudimentary, lightweight (5.6kg), low-cost (~$450) terrestrial laser scanner (TLS). Its viability as an option for estimating the volumes of slash piles is then explored by comparing it to two traditional slash pile estimators on a random sample of thirty slash piles. The TLS generated volume estimates were not statistically significantly different ($p=1$) from control volume estimates, and the apparatus was more accurate than traditional ground measurements for estimating the volumes of small and irregularly shaped piles. Though less expensive and more field-mobile than traditional terrestrial LiDAR (light detection and ranging) scanners, the TLS is similarly able to generate point clouds of objects from which 3D models can be constructed and spatial characteristics elucidated. Currently, the price, mobility, and user-friendly design of the TLS make it ideal for close-range scanning of irregularly shaped 3D objects (e.g., slash piles), especially in remote areas. Although relatively time consuming if used to scan objects that merit large datasets of laser returns, modification of the TLS to include an automatic data logger would thwart this shortcoming.

Keywords: terrestrial laser scanning, slash pile measurements, logging residues, low-cost

2.2 Introduction

The dynamic nature of the logging industry in the PNW presents a challenge—changes in logging machinery, silvicultural regimes, forest structure, and ecological considerations have dated the many past studies that attempted to determine the amount of slash that is available for conversion to biofuel. To compensate for the low profit margins associated with the slash-to-biofuel industry (resulting from the low commercial value of logging residues compared with the costs of transportation and conversion), refined methods of measuring slash are needed to inform the appropriate supply chain infrastructure that could ultimately make the whole process economically feasible. While the amount of residual biomass left from logging is a function of many factors, including harvest amount, logging method, silvicultural treatment, and type and location of timberlands [1], *estimates* of total slash volumes are often greatly affected by the methods used to measure slash on the local scale. These methods have included: ground measurements coupled with geometric equations [2], where the dimensions of a pile are measured and plugged into a respective geometric volume formula; pre-harvest inventories and allometric equations [3] whereby tree species and diameter at breast height (DBH) are tallied before a harvest and slash volumes are later estimated based on the number of each species felled from each DBH class; the use of laser rangefinders [4, 5], which are handheld devices typical in measuring solid stockpiles (e.g., of gravel, sand, coal, etc.); line intersect sampling protocol for scattered slash [6-9], in which transects are laid out over areas covered in scattered slash, and volume inferences are made based on systematically observed slash depths; and post-harvest samples of tree bole and residue volumes per felled tree [10, 11], which are case-sensitive allometric equations that are later used to estimate total slash volume per harvest based on the number of trees felled from each species/DBH class. Terrestrial laser scanners are ground based light detection and ranging (LiDAR) systems that are useful in collecting highly spatially resolved (decimeter to mm scale) 3-dimensional (3-D) structural information from objects. This relatively novel technology has recently been employed to derive slash pile volume estimates and is generally considered the most accurate means of measuring slash [5].

Traditional measurement approaches have been shown to overlook various configurations of cut and leave volumes present within typical logging sites [12]. Further, traditional ground-geometric measurements have shown to generally underestimate pile volume for small piles, and overestimate the volume of large piles [13, 2, 5]. In contrast, estimates of slash volumes provided by laser rangefinders have shown to provide very accurate estimates due to their ability to account for irregularities found in more complex pile shapes [5]. TLS systems, though very accurate in estimating slash pile volumes, require time-consuming and expensive training, are time consuming to use on individual piles, and are costly—usually >$40,000 for entry level set-ups—though costs may decrease as the young technology matures (e.g., [14]). Moreover, TLS systems consist of many components (e.g., generators, computers, and bulky laser scanners) that are difficult to transport in the field.

This study aims to present a novel apparatus for measuring slash pile volumes: a low-cost (~$450), lightweight terrestrial laser scanner (TLS). To test its viability as a method of estimating slash, this study then compares it to two traditional methods of measuring slash volumes: the ground-geometric method, and the use of a laser rangefinder.

2.3 Experimental Section

A simple random sample of 30 slash piles was established in the Coburg Hills, thirty miles northeast of Eugene, Oregon. The sample was comprised of small hand piles from a Bureau of Land Management thinning operation and medium to large machine piles from a commercial logging operation. To compare the volume estimates generated by the novel method presented in this report to traditional methods, each pile was measured with:

i) a rudimentary, low-cost, lightweight terrestrial laser scanner (TLS)
ii) ground measurements and geometric equations [2] and
iii) a laser rangefinder equipped with Mapsmart + Volume Solution software [5].

The volume estimates generated by the laser rangefinder were then used as the standard against which the volume estimates yielded by the ground-geometric and TLS methods were later compared.

2.3.1 Low-cost, lightweight terrestrial laser scanner

Design

A low-cost, lightweight TLS was constructed with a laser rangefinder, two digital angle sensors, aluminum housing fixture, tribrach, and surveying tripod (Figure 2.1). Total cost in

US dollars for TLS components as of October, 2015 (including tripod) is $457.30. Total weight of the apparatus including the tripod is 5.6 kg.

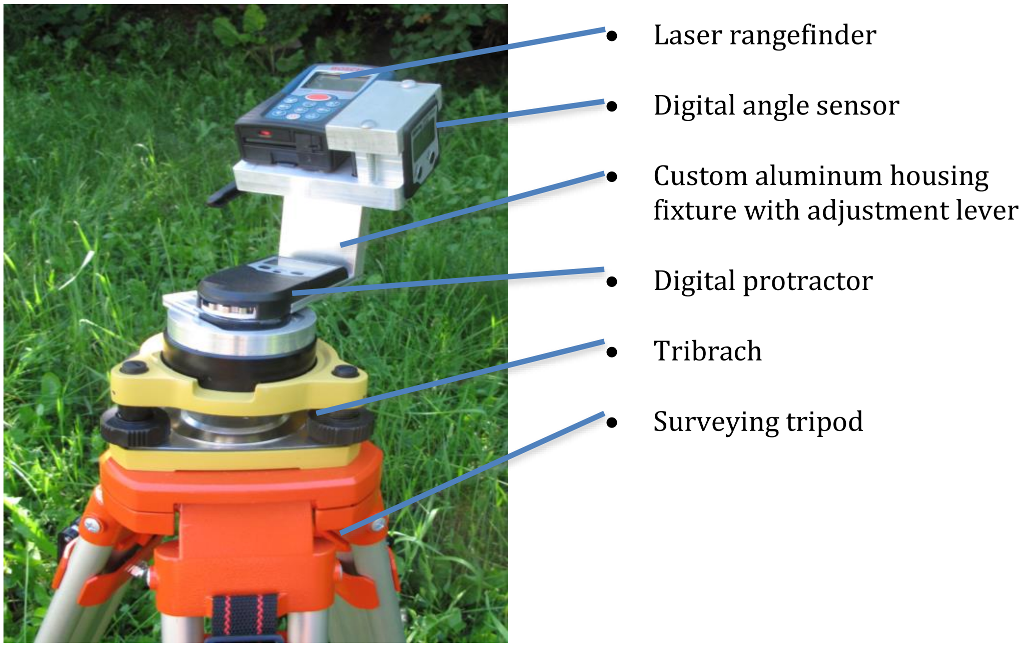


Figure 2.1. Low-cost, lightweight terrestrial laser scanner (TLS)

Table 2.1. Costs of TLS components as of October, 2015

Item	Provider	Price
Bosch DLR165 digital laser rangefinder	Robert Bosch LLC, Broadview, IL 60155, USA	$79.99
Wixey digital angle sensor	Barry Wixey Development Sanibel, FL 33957, USA	$29.99
Wixey digital protractor	Barry Wixey Development Sanibel, FL 33957, USA	$59.99
Custom aluminum housing fixture with adjustment lever	University of Idaho Machine Shop, Moscow, ID 83843, USA	$50.00
CST/Berger surveying tripod	Tiger Supplies, Inc., Irvington, NJ 07111, USA	$59.99
CST/Berger tribrach	Tiger Supplies, Inc., Irvington, NJ 07111, USA	$149.99

Total = $429.95

The rangefinder included in the design utilizes an eye-safe (class two) laser that is accurate to +/- 1.5mm up to 50m, though the apparatus can include any basic distance-measuring rangefinder, preferably one that is inexpensive and weather resistant. The rangefinder is mounted adjacent to a digital angle sensor (to record zenith angle) on an aluminum fixture. Together, they are moved vertically and secured by loosening and tightening the lever. Below them on the aluminum fixture is another angle sensor that swivels horizontally to record azimuth angle.

Before scanning an object from a particular scan location, the tripod legs must be steadied, the tribrach leveled (via adjusting the foot screws until the circular bubble is level), and the two angle sensors zeroed. It is important to ensure that the object being scanned does not intersect the azimuth (i.e., side-to-side) angle zero, as the angle sensor used in this design does not account for negative values. When acquiring a single laser return by pointing the visible red dot at a point of interest and clicking the rangefinder to record distance, distance, azimuth angle, and zenith angle must all be recorded manually. To sufficiently scan the surface of an object, a collection of data points is gathered that appropriately covers its surface contours and irregularities.

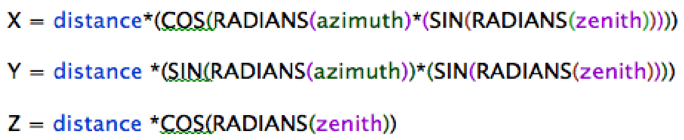
More than one scan location is often needed to sufficiently scan the surface of a 3-D object (e.g., a slash pile). When this is the case, no less than three immobile reference targets are scanned along with the object of interest (Figure 2.2). These are crucial in later aligning point clouds (i.e., using the laser returns collected from each scan location to assemble an accurate 3-D representation of the object of interest). These targets must be visible from each scan location.

(a) **(b)**

Figure 2.2. Two options for arrangement of reference targets: (**a**) the tips of three cones set up around a slash pile, and (**b**) three points on a single boomerang-shaped target

Registering point clouds

For each surveyed point the distance between the TLS and each surveyed point, the azimuth angle, and the zenith angle (polar) are converted to X, Y, and Z (Cartesian) coordinates as follows:



```
X = distance*(COS(RADIANS(azimuth)*(SIN(RADIANS(zenith)))))

Y = distance *(SIN(RADIANS(azimuth))*(SIN(RADIANS(zenith))))

Z = distance *COS(RADIANS(zenith))
```

The x,y,z coordinates were then imported into the open source software package CloudCompare [15]. Target points were then manually aligned by using the “aligns two clouds by point picking equivalent point pairs” tool.

Once point clouds from each scan location were aligned, they were merged with the “merge cloud” tool (i.e., saved as one point cloud instead of multiple clouds from each scan location). Target points were then removed from the point cloud via the “segment” tool, resulting in the comprehensive point cloud of a pile (e.g., Figure 2.3).

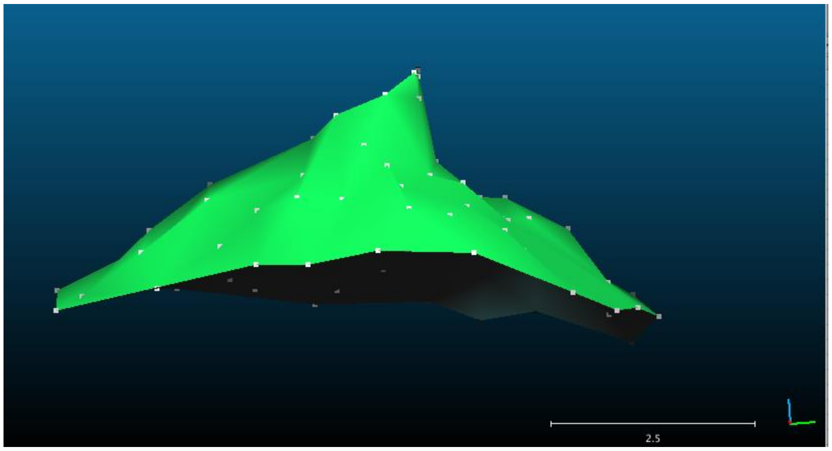
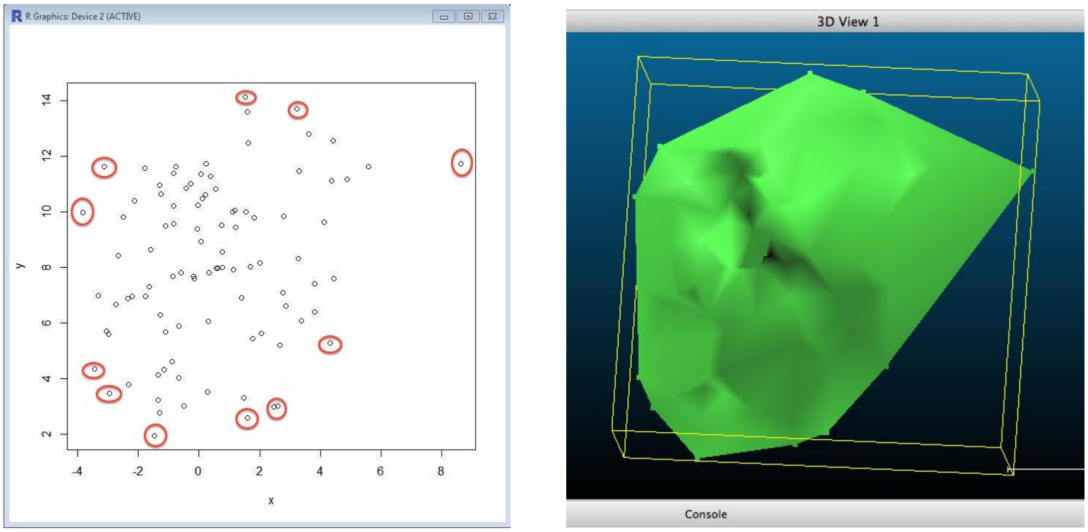


Figure 2.3. Three dimensional (3-D) model of a slash pile with overlapping mesh in CloudCompare v2.5.4. [15]

Calculating pile volumes in R

A script was written in R [16] that calculates the volume of a slash pile from its point cloud. With the “slash pile volume estimator” found in Appendix I open in R, and required packages downloaded, the merged point cloud .txt file was entered into the input section of the script. Once the script was run, point cloud data were shown on a two dimensional (2-D) x, y plane (as seen in Figure 2.4). Base shots (i.e., laser returns where the slash pile meets the ground) were then manually selected. Simultaneously looking at the 3-D point cloud of the same pile in CloudCompare was helpful in distinguishing base shots from surface shots. Number of base shots factored into the script were manipulated in the input section of the R script based on the size and shape of a given pile.



(a) **(b)**

Figure 2.4. (a) 2-D representation of a slash pile in R, in which base shots (circled in red) were manually chosen after running the script, and **(b)** the 3-D representation of the same pile in CloudCompare that was useful to look at while selecting said shots.

After distinguishing and selecting base shots, the script attributed a bottom to the pile. Maximum Z values (i.e., heights; distances from the pile's bottom) were generated for each pixel of the x, y grid. To calculate total pile volume, mean pixel height was multiplied by the total basal area of the pile.

2.3.2 Laser rangefinder

For determining slash pile volumes with a laser rangefinder, a TruPulse 360B laser rangefinder ($1,795) (Laser Technology Inc., Centennial, CO, USA) and Archer 2 handheld ($1,590) (Juniper Systems Inc., Logan, UT, USA) with Mapsmart + Volume Solution software ($700) (Laser Technology Inc., Centennial, CO, USA) were used. Before shooting, 2-4 reference targets were set up around a pile. The pile was then shot from each target area—with this method, target areas double as scan locations—while base shots and surface shots were distinguished on the handheld computer. The steps outlined in the Mapsmart + Volume Solution software were followed to calculate pile volumes on site (via using a series of laser return points to create a convex hull from which total shell volume is extracted).

2.3.3 Ground-geometric method

The general shape of each pile was determined (Figure 2.5), and the dimensions required for corresponding volume equations (Figure 2.6) were measured. Measurements were entered into an online calculator [20] to determine the volume.

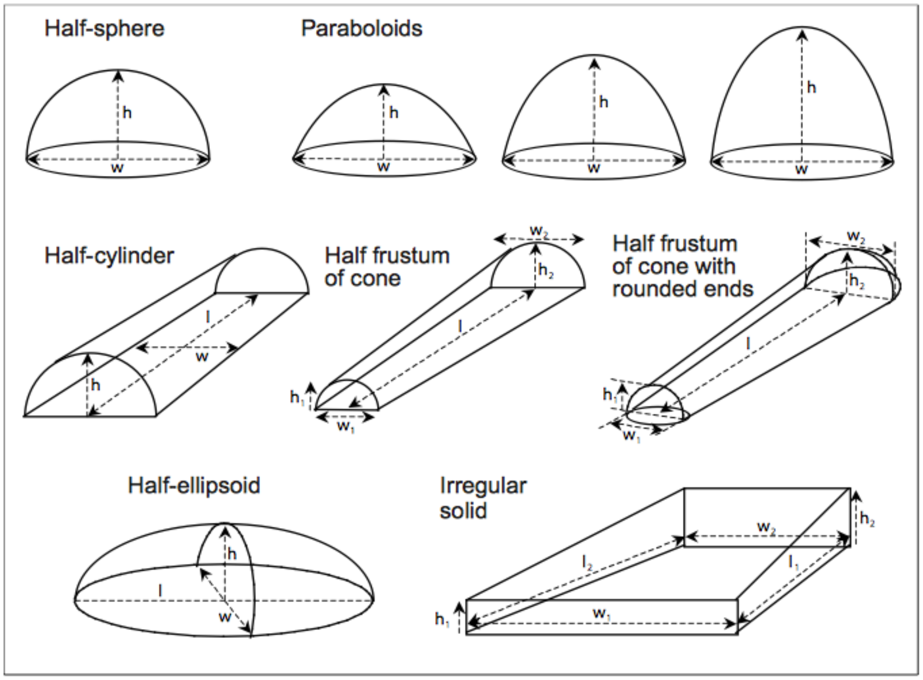
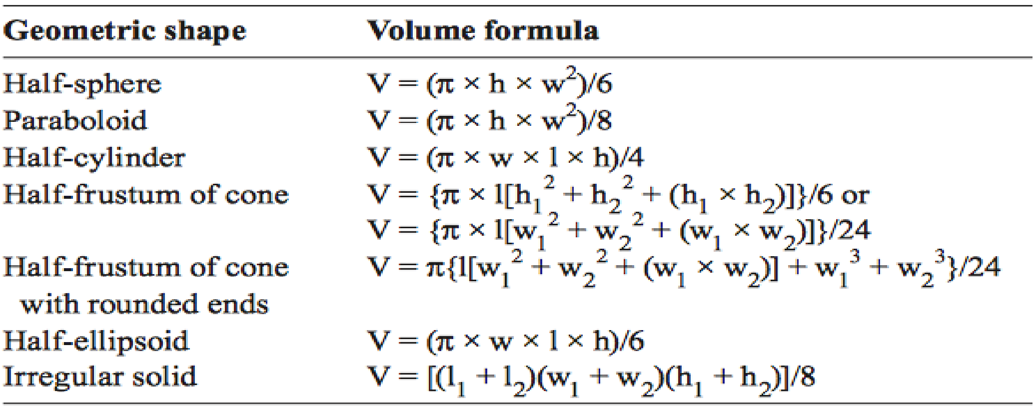


Figure 2.5. Geometric pile shapes (Hardy, 1996)



Geometric shape	Volume formula
Half-sphere	$V = (\pi \times h \times w^2)/6$
Paraboloid	$V = (\pi \times h \times w^2)/8$
Half-cylinder	$V = (\pi \times w \times l \times h)/4$
Half-frustum of cone	$V = \{\pi \times l[h_1^2 + h_2^2 + (h_1 \times h_2)]\}/6$ or $V = \{\pi \times l[w_1^2 + w_2^2 + (w_1 \times w_2)]\}/24$
Half-frustum of cone with rounded ends	$V = \pi\{l[w_1^2 + w_2^2 + (w_1 \times w_2)] + w_1^3 + w_2^3\}/24$
Half-ellipsoid	$V = (\pi \times w \times l \times h)/6$
Irregular solid	$V = [(l_1 + l_2)(w_1 + w_2)(h_1 + h_2)]/8$

Figure 2.6. Volume formulas for geometric pile shapes (Hardy, 1996)

2.3.4 Statistical analysis

Because the pile sizes were not normally distributed, a one-sample sign test was used to determine whether volume estimates generated by the TLS and the ground-geometric methods were significantly different from control volume estimates generated by the laser rangefinder. The one-sample sign test compares the differences between each set of paired data (i.e., the volume estimates generated by each method for each pile) to a hypothesized median of zero. If the null hypothesis is true and there is no significant difference between methods, the probability of observing pile size estimates above the hypothesized median of zero should be equal to the probability of observing estimates below that hypothesized median.

Further, a concordance correlation analysis was conducted. Concordance correlation analysis has been used in many fields to measure agreement between two continuous variables, and to determine whether two measurement techniques result in similar estimates (e.g., [21], [22], [5]). A concordance correlation coefficient (rc) of 1 would indicate that two techniques are entirely substitutable and result in identical measurements of the same phenomenon [23]. Because this analysis can be statistically robust with as little as 10 paired data, it was used to determine whether either of the two measurement techniques is a reasonable substitute for the control method in terms of small and large piles. Although a rc of 1 indicates perfect agreement among methods, and 0 no agreement, there is currently no literature outlining a descriptive scale for degrees of agreement (i.e., the ranges of coefficients that would encompass “near perfect,” “moderate,” and “poor” suitability for a control). All statistical analysis was conducted in the open-source software package R x64 3.1.1 [16].

2.4 Results and Discussion

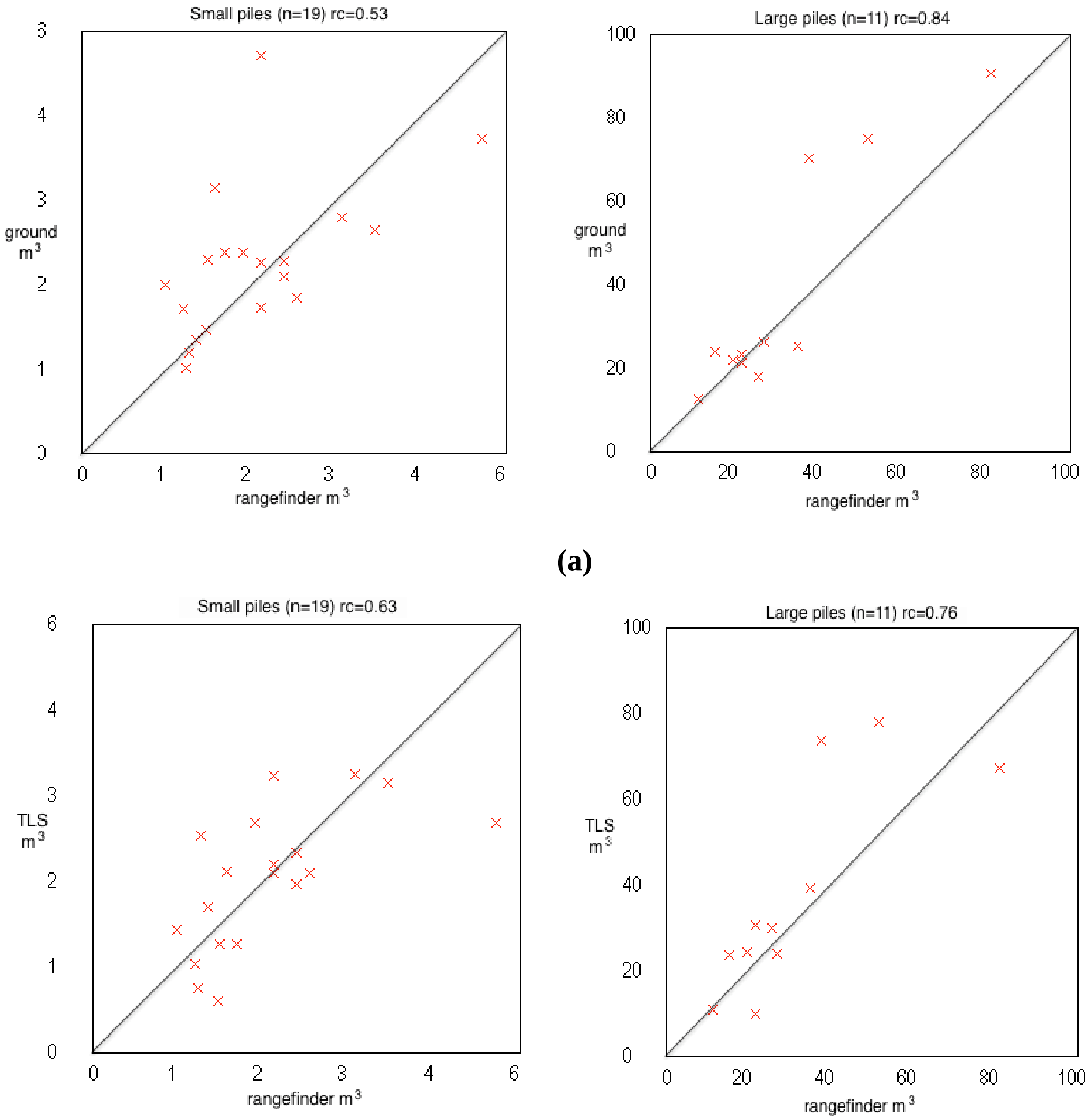
The TLS and laser rangefinder methods each returned a similar number of observations per slash pile, averaging 104 and 117 laser returns per pile, respectively, for the small piles. Number of returns per pile increased with pile size and pile complexity, the largest pile yielding the most returns: 178 with the TLS and 190 with the rangefinder.

The piles ranged from 1.16 to 80.89m^3, the majority of which were very small: 19 between 1 and 5m^3, and 11 ranging from 10 to 80m^3. The one-sample sign test revealed that neither the TLS nor the ground-geometric datasets were significantly different from the rangefinder data (p=1 for each), though such high p values seem to have been a result of the low statistical power of the sign test.

The rc better showed the relative accuracies of each method (Table 2.1). Agreement between pile estimates yielded by the ground-geometric and TLS methods vs. the data yielded by the control method is represented in Figure 2.7.

Table 2.2. Concordance correlation coefficients of ground-geometric and TLS data vs. control data for small and large piles.

	Rangefinder vs. ground-geometric method	Rangefinder vs. TLS method
Small piles (n=19)	.53	.63
Large piles (n=11)	.84	.76
All piles (n=30)	.92	.90



(a)

(b)

Figure 2.7. Agreement between ground-geometric and control volume estimates **(a)** and TLS and control volume estimates **(b)** for small and large piles

Both the TLS and the ground-geometric methods were shown to be substitutable for the control method to a high degree (rc=.90 and rc=.92, respectively). The TLS proved to be a better substitute for the control method for the 19 small piles. For the other 11 piles, the ground-geometric method was shown to be more substitutable for the control. The sample included in the study lacked a number of very large slash piles (>80m^3), for which Long &

Boston [5] and Wright et al. [13] found the ground geometric method to be generally inadequate at measuring.

Although better able to estimate the volumes of irregularly shaped piles (an important quality in measuring slash, as piles rarely fit a perfect geometric shape), the TLS was the most time consuming of the three methods due to the time spent manually recording laser return data. Future research toward developing the TLS will include the addition of an automatic data logger for distance and angle measurements, and its testing on a number of very large slash piles.

2.5 Summary and Conclusion

This work found the TLS to be a viable method of estimating the volumes of slash piles. While the instrument could be helpful in informing the biofuel supply chain, it might also be used for applications relating to air quality, as burning slash piles emits large quantities of hazardous material into the atmosphere. Its rudimentary, inexpensive, and lightweight design in conjunction with the directions for use laid out in this document make the TLS a user-friendly and affordable option of measuring the volumes of slash piles, or whatever the object of interest may be. Similarly to laser rangefinders, the TLS can be used to isolate and scan strategic points on an object, thus generating succinct data sets from which 3D models can be made and spatial characteristics elucidated. Point cloud data generated from the use of this TLS could be used to record and analyze spatial data for a wide scope of applications. For example, spatial qualities of forest understories (e.g., tree density, bole defect, fuel loads, etc.) might be scanned and modeled where the forest canopy is impenetrable by aerial LiDAR. Though LiDAR-equipped unmanned aerial vehicles (UAV's) are an emerging technology, they are currently limited in their abilities to fly through forest understories.

2.6 Author Contributions

James M. Casey is the principal investigator and corresponding author. He conducted the field data collection, analyzed the data, and wrote the paper. Dr. Jan Eitel designed and wrote the "slash pile volume estimator" script. Dr. Randy Brooks dealt with the financial obligations without which the study would not have been possible, and he, Jan, and James designed and structured the study.

2.7 Conflicts of Interest

The authors declare no conflicts of interest.

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Appendix I. Slash pile volume estimator

```
#######################################
#####  Input starts here
#######################################

int_res = 10
ufc = read.table("C:/Temp/1L.txt", sep ="")            ### locate your files on hard-drive
nop = 15                                                              ### number of toe hits

########################################
##### Input ends here
########################################



require(rgl)                                   ### Loads different R packages (aka software)
require(akima)
require(MBA)

### Select points

colnames(ufc) = c("x", "y", "z", "red", "green", "blue", "NA1", "NA2", "NA3")

# plot3d(ufc$x, ufc$y, ufc$z)                                   ### if you want to see the plot in 3d

plot(ufc$x, ufc$y, ylab = "y", xlab = "x")



locations = locator(n = nop)

x_locations = round(locations$x)
```

```
x_locations = data.frame(x_locations)

y_locations = round(locations$y)
y_locations = data.frame(y_locations)

locations = cbind(x_locations, y_locations)


### End select points

### Start interpolation

out_final = c()

for(ii in 1:50){


DTM = c()

for (ii in 1:nop) {


distance = sqrt((locations[i,1]-ufc$x)^2 + (locations[i,2] - ufc$y)^2)

dummy = cbind(ufc, distance)

mini = min(distance)

dummy = data.frame(dummy)

extract = which(dummy$distance == mini)
```

```
out = dummy[extract,]

DTM= rbind(DTM, out)

}

DSM = ufc

                                                  ### fit digital surface model  (aka DSM)
DSM = mba.surf(ufc[,1:3], int_res, int_res, extend = TRUE)$xyz.est

                                                         ### fit bare earth model (aka DTM)
DTM = mba.surf(DTM[,1:3], int_res, int_res, extend = TRUE)$xyz.est


height = DSM

height$z = DSM$z - DTM$z

extract = which(height$z < 0)

height$z[extract] = NA

height = apply(height$z, 2, mean, na.rm = T)

height = data.frame(height)

height = apply(height, 2, mean, na.rm = T)

x <- DSM[[1]]
```

```
y <- DSM[[2]]
z <- ex*DTM[[3]]

pixel_size_x =  sqrt((x[1] - x[2])^2)
pixel_size_y = sqrt((y[1] - y[2])^2)

area = int_res^2 * pixel_size_x * pixel_size_y

volume = area * height

pixel_size = pixel_size_x *pixel_size_y

out_1 = cbind(volume, pixel_size)

out_final = rbind(out_final, out_1)

int_res = int_res + 20

}

out_final = data.frame(out_final)

colnames(out_final) = c("volume", "pixel_size")

plot(out_final$pixel_size, out_final$volume, ylab = "Volume (cubic meters)", xlab = "Pixel size (cm2)")

out_final = round(out_final, 4)

write.table(out_final, row.names = FALSE)
```

```
#### Plot DSM
library(rgl)

ex <- 2
x <- DSM[[1]]
y <- DSM[[2]]
z <- ex*DTM[[3]]
zlim <- range(z, na.rm = TRUE)
zlen <- zlim[2] - zlim[1] + 1
colorlut <- heat.colors(as.integer(zlen))
col <- colorlut[ z-zlim[1]+1 ]

open3d()
surface3d(x, y, z, color=col, back="lines")


#### Plot DTM
```

```
library(rgl)

ex <- 2
x <- DTM[[1]]
y <- DTM[[2]]
z <- ex*DTM[[3]]
zlim <- range(z, na.rm = TRUE)
zlen <- zlim[2] - zlim[1] + 1
colorlut <- heat.colors(as.integer(zlen))
col <- colorlut[ z-zlim[1]+1 ]
open3d()
surface3d(x, y, z, color=col, back="lines")
```