THE USE OF LIGHT DETECTION AND RANGING DATA TO IDENTIFY SOURCE AREAS AND MODEL THE RATE OF TREES FALLING IN STREAMS

by

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Large wood is an important component in the physical and biological character of many stream ecosystems in the Pacific Northwest. This study used a remote sensing technology called Light Detection and Ranging (LIDAR) to assess the condition of forests adjacent to 55 kilometers of streams. LIDAR is a new remote sensing technology that uses an array of laser pulses emitted from an airborne sensor to determine the height of surfaces such as the ground and terrestrial vegetation. These LIDAR signals correlate to canopy height and basal area. This forest structure information was used to model the rate of wood delivery to streams, the source area for large wood, and the location of key wood pieces.

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CHAPTER I

INTRODUCTION

The purpose of this study was to determine whether a remote sensing technology called Light Detection and Ranging (LIDAR) could accurately characterize certain aspects of streamside vegetation important to the function of stream ecosystems. This research attempted to answer three questions. First, could LIDAR be used to predict the rate at which wood is delivered to streams? Second, could the LIDAR accurately identify source areas that deliver wood to streams? Third, could LIDAR be used to identify source areas for large or "key" pieces of wood?

LIDAR is a new remote sensing technology that uses an array of laser pulses emitted from an airborne sensor to determine the height of surfaces such as the ground and terrestrial vegetation. This information has been used to derive a variety of vegetation structure metrics. In this study, a LIDAR scanning unit on board an airplane at an altitude of approximately 2,000 meters collected information about ground, forest canopy, and understory elevation for a research forest in western Oregon. Since, the travel rate of the emitted laser pulse is constant (i.e., the speed of light) the time it takes for a single pulse to reflect back to the sensor is a function of the distance it has to travel. The LIDAR scanning unit used in this study is capable of emitting 15,000 pulses per second, and the airborne sensor is capable of processing five return signals for each pulse. The return signals collected by the sensor each have a unique set of three-dimensional coordinates that can be converted to surfaces such as ground elevation and forest canopy elevation. These surfaces can then be used to study various characteristics of the landscape, such as forest structure.

Throughout the Pacific Northwestern United States, human activities (e.g., timber harvesting) have changed the structure of streamside forests and altered the natural delivery of wood to streams, thereby degrading the streams and their ecological functions. A number of streamside forest characteristics have the potential to affect the condition of streams. For example, streamside vegetation is particularly important to small streams, as it is the source of most organic inputs such as large wood. Large wood increases a stream's ability to retain nutrients, dissolved organic matter, fine particulate matter, and gravels. In addition, large wood can cause the formation of large pools, and it also provides refugia and cover for a wide variety of stream organisms.

Because the function of Pacific Northwestern streams is closely tied to the condition of the streamside vegetation, the ability to assess the condition of the streamside forests over large areas would be a valuable tool to assess overall watershed health. This study was designed to determine if LIDAR could serve this purpose.

This study used LIDAR-derived forest structure metrics to model the rate at which wood is delivered to streams, and I identified the probable terrestrial origin, or source area, of this wood. One unique aspect of this study was that it quantified the wood contribution of streamside forests along 55 kilometers of streams. Ground based studies of wood delivery from streamside forests rarely, if ever, cover more than a few hundred meters because of extensive data collection requirements (e.g., the height and location of every tree adjacent to the stream). In this study, I also developed a method to identify the potential of the streamside forests to deliver wood of large length and diameter classes to streams because these "key" pieces have greater influence on bed morphology and hydraulic retention than do smaller pieces.

The wood delivery model, when compared to data from western Cascade streams, appeared to overestimate the rate of wood delivery. Another finding was that older forested stands have greater source areas per meter of stream length than do younger stands. I also found that of nearly 600 hectares of streamside forest only 45 hectares, or seven percent of the total area, had the potential to deliver wood greater than 40 meters in height.

CHAPTER II

REVIEW OF LITERATURE

The Source and Rate of Wood Delivery to Streams

Because of the importance of wood in stream ecosystems, a number of studies have attempted to quantify the rate at which wood is delivered to streams from the streamside vegetation, as well as the spatial extent of the source area of that delivery. Most wood entering streams originates in the adjacent vegetation. In a study of 29 streams in Oregon and Washington, over 90% of the in-stream wood came from within 30 meters of the channel (McDade 1988). In a study in southeast Alaska, nearly 99% of the wood came from within 30 meters of the channel (Murphy and Koski 1989). The primary mechanism for delivery of wood to streams appears to vary depending on the site. Windthrow was identified as the primary delivery mechanism for five streams in the western Cascades (Lienkaemper and Swanson 1986). In southeast Alaska, however, bank erosion was the primary mechanism in three of six channel types. Across all channel types, bank erosion and windthrow combined accounted for 73% of wood delivered to the stream, while landslides accounted for only 4% of the wood loading (Murphy and Koski 1989). Interestingly, McDade et al. (1990) found that the slope of the adjacent stream banks did not significantly increase the source area for wood recruitment in streams in Washington and Oregon.

These results inspired the development a number of probabilistic models that defined the source area as a function of tree height and distance from the stream (McDade et al. 1990, Robison and Beschta 1990, and Van Sickle and Gregory 1990). Attempts to quantify the rate at which source areas deliver wood to streams have been limited. Over a seven- to nine-year period, Lienkaemper and Swanson (1987) recorded all the trees that fell into five streams surrounded by old growth forests in the western Cascades, Oregon. They found that between 0.44 and 0.25 trees fell into the stream per 100 meters of channel per year. Van Sickle and Gregory (1990) expanded on earlier tree fall models by incorporating rate of fall data collected by Lienkaemper and Swanson (1987). The Van Sickle and Gregory (1990) model also attempted to predict the rate at which trees fall. By combining the probability that a tree will fall with the probability that it will fall into a stream, and taking into consideration the density of trees in the stand, tree delivery could be predicted along stream reaches for which sufficient data existed. The required components of this predictive model were probability of tree fall, the height of every tree, the perpendicular distance to the stream, and the number of trees per length of stream. Van Sickle and Gregory (1990) successfully predicted the angle orientation of wood pieces in Mack Creek, in the western Cascades, indicating that the direction of tree fall was randomly distributed. In their study, the length and volume of individual wood pieces were overestimated because the model could not account for breakage and fragmentation of the tree boles caused by a variety of physical processes. A variation of the Van Sickle and Gregory (1990) model is used in this study.

Impacts of Human Disturbance in the Source Area

The effects of timber harvesting in the vegetation adjacent to streams are numerous and widely documented. These effects include increased stream temperature, decreased large wood inputs, and decreased stream stability. Additionally, large wood in streams helps to trap particles and form pools, and it provides a major source of organic input as well as refugia for many aquatic organisms. Each of these effects is discussed in greater detail below.

Stream Temperature

Riparian vegetation is the dominant control on stream temperature for small streams. Streamside vegetation helps to moderate stream temperature changes by intercepting sunlight that would otherwise warm the stream (Beschta 1997). Streams with little or no streamside vegetation exhibit greater temperature changes than streams in unlogged stands (Davies and Nelson 1994).

Wood Size and Stability

Timber harvesting in riparian areas changes the number and size of wood pieces delivered to streams. First, the volume of very large wood pieces found in streams is drastically reduced because the primary source of these pieces is eliminated (Evans et al. 1993, Headman et al. 1996, McHenry et al. 1998). It has been shown that the number of pieces of wood in streams surrounded by old growth forests exceeds that of streams in harvested forests (Bilby and Ward 1991). Although, in some cases, the number of pieces of pieces of wood found in streams increases with intensive streamside harvesting (Evans et al. 1993, Poole et al. 1994), the size of these pieces is much smaller than in streams surrounded by old growth (Poole et al. 1994).

It is recognized that wood pieces of different sizes perform different roles in stream ecosystems. Large woody debris is often defined as wood greater than ten centimeters in diameter and 1.5 meters in length (Lienkaemper and Swanson 1986, Hairston-Strang and Adams 1998). Recognition is growing that very large wood pieces may have a greater influence on the physical and biological nature of streams than small pieces. For instance, McHenry et al. (1998) found that wood pieces greater than 80 centimeters in diameter were less likely to move in flood events than their smaller counterparts. Lienkaemper and Swanson (1987) observed that in small streams in the Cascade Mountains wood pieces longer than bankfull width (15 meters) did not move in a storm event with a 10-year return interval, while unanchored pieces shorter than bankfull width were in some cases moved over 100 meters. Benke and Wallace (1990) found that in streams in the southeastern United States 42% of wood pieces that were five to ten centimeters in diameter moved over a 20-month period. None of the wood pieces greater than 40 centimeters in diameter moved in that same period.

Very large wood pieces may play a critical role in determining how streams respond geomorphically to disturbance events such as floods. Reviews of previous studies provide no objective, justifiable guidance or criteria on how "big" wood must be to constitute a "key" piece. This is probably related to the variation in key piece size from stream to stream. Conceptually, small constrained channels are less likely to move wood pieces than are open unconstrained channels. Wood of a given length and diameter may be highly mobile in one system, yet very stable in another.

Impact on Physical Character of Streams

Particle Retention

In general, streams with wood retain more particles and other materials than streams without wood. This appears to be true across a range of particle sizes for both organic and inorganic substances. Wood is a roughness element in streams that reduces the energy of flow, thereby trapping moving objects. Lienkaemper and Swanson (1987) found that large logs, often in place for many decades, accumulate other wood pieces mobilized by flood events. In larger streams, these accumulations can result in the formation of floodplain islands (Fetherston et al. 1995). Large wood in streams can cause localized dissipation in stream energy, or shear stress, resulting in the formation of gravel bars (Lisle 1986). Evans et al. (1993) found that for streams flowing through ancient forests a larger portion of the substrate in pools was comprised of small particles (1-1.9 mm) than for streams in younger forests with a history of harvesting. This study also reported that none of the pools in the streams in ancient forests contained bedrock substrates. In streams in harvested stands, however, 14 to 28% of the pool substrate was bedrock. These results indicate that streams in harvested stands lack the wood to dampen the energy of flows that would otherwise mobilize the bed. Streams with wood can trap fine sediments, whereas streams without wood lose small particles in high flow events. In harvested stands, the magnitude of bed mobilization often results in exposure of the bedrock substrate.

The presence or absence of wood also influences the retention of dissolved and particulate organic matter. In a study at the Hubbard Brook Experimental Forest, debris dams were removed from 175 meters of a stream (Bilby and Likens 1980, Bilby 1981). Surveys revealed that the absence of woody debris dams increased the export of dissolved organic carbon and coarse particulate organic matter. It was also found that fine particulate organic carbon export increased 632%, and the total annual dry mass export tripled in the experimental stream, whereas dry mass export in the control stream experienced only a 1% increase. In a similar experiment in the Sangre de Cristo Mountains, New Mexico, wood was added to reaches in two wood impoverished streams and removed from a reach in one wood rich stream (Trotter 1990). Experimental controls were established for all three treatments. Fluorescent dye was added to each of the stream reaches, and dilution over time and distance was monitored. Dye concentrations peaked later in streams with wood than those without wood. Dye concentrations fell to trace levels earlier in the reaches without wood indicating that the dye had been exported faster than in the reaches with wood. Additionally, marked leaves and wood chips were released into the stream reaches and tracked for distance traveled. In the stream reaches with wood 72% of the wood chips stayed within 50 meters of the release point. Only 49% of the wood chips remained within the same distance in the reaches without wood. Additionally, one of the streams that received wood as a treatment retained twice as many leaves as streams without wood. In a separate study, Angermeier and Karr (1984) found decreased organic litter retention on the stream bottom in reaches where wood was removed. The ability of a stream to retain energy resources is critical to aquatic organisms. This is especially true in headwater streams where the majority of nutritional energy resources are allocthonous, or terrestrially derived (Vannote et al. 1980).

Pool Size and Number

Wood is a major factor in the formation of pools in streams (Lisle 1986). Decreases in the number or volume of wood pieces in streams often results in reduced pool surface area and depth (Ralph et al. 1994). The mean pool area in streams surrounded by intensively logged forests was half that of the area found in streams in unlogged forests (Ralph et al. 1994). Evans et al. (1993) studied pools formed exclusively by large wood in streams in 1) ancient native forests, 2) 120-year-old native forests, and 3) 10-year-old plantations. Pools in the streams in ancient native forests were longer and wider than pools in streams in the 120-year-old forest. The area and volume of pools in streams in the ancient forests was twice that of pools in the streams in the 120-year-old forests. None of the streams in the 10-year-old plantations had pools formed by woody debris. The number of pools formed by mechanisms other than wood was roughly equal across all study sites. These results imply that wood is a critical part of the pool formation process.

Impact on the Biological Character of Streams

The physical conditions of streams are the template upon which biotic interactions take place. In some stream ecosystems, the absence of wood results in conditions that are not favorable to indigenous biotic assemblages. Angermeier and Karr (1984) removed all wood on one side of a centerline running down the middle of a stream and then studied the response of the fish assemblages. They found greater numbers of species and individuals on the side of the stream reaches with wood than side without wood. The researchers suggested that the wood pieces provided shelter from current, increased food availability, or camouflage from predators or prey. However, they could not distinguish which, if any, of these factors were most important to the observed distribution of fish populations in their study.

The role that wood in streams plays in providing protection from current was documented in a study of juvenile cutthroat trout in the western Cascade Mountains of Oregon (Moore and Gregory 1988a). Large wood and boulders along the edge of streams create low velocity "lateral" habitat that is important to cutthroat trout. Moore and Gregory studied this by increasing the amount of lateral habitat in a number of reaches by adding logs and boulders and decreasing lateral habitat in other reaches by removing debris. The juvenile cutthroat biomass and growth rates were greater in reaches with increased lateral habitat than reaches with unchanged or reduced lateral habitat.

In a related study, Moore and Gregory (1988b) found that in the early stages of development, juvenile cutthroat trout relied almost exclusively on stream margins and backwater habitats. As the fish aged over the course of the study, their habitat preferences diversified and reliance on lateral habitats decreased. Less than half the fish found in the stream reaches that flowed through open and deciduous forests were found in lateral habitat. Preference for these lateral habitat areas was slightly greater for the same age class in the coniferous forests with just over 50% of the fish found in lateral habitat.

The impacts of logging were observed in multiple compartments of the food web in a set of Australian streams (Davies et al. 1994). Density of macroinvertebrates and vertebrates (*Salmo trutta*) was lower in streams with extensively logged streamside vegetation. Algal abundance, however, increased in streams without riparian vegetation indicating a release from canopy-induced light limitation.

In addition to retaining Fine Particulate Organic Matter (FPOM), large wood is a significant source of FPOM. Ward and Aumen (1986) found that the FPOM loading from log decay in streams rivals that of leaf and needle litter, which is widely considered the primary energy source in headwater streams (Vannote et al. 1980). Log decay in streams is the result of fragmentation by physical forces, biological transformation, and leaching (Harmon et al. 1986). Although refractory in nature, this FPOM is a great source of nutrition for the microbial and invertebrate food web.

The function of stream ecosystems in the Pacific Northwestern United States is closely tied to the condition of streamside forests. Hundred of miles of streamside forests have been altered by anthropogenic disturbances. The resultant decline in the condition of stream ecosystems is cause for great concern, and efforts are underway to identify stream reaches for preservation and restoration activities. Ground-based characterization of streamside forests over large distances is time consuming and cost prohibitive. Developments in remote sensing technology may help to bridge this information gap.

Characterization of Forests with LIDAR

Numerous forms and varieties of LIDAR technology are being used to characterize forest structure. Some instruments emit straight-line pulses toward the ground in a technique known as profiling (Nelson et al. 1997). Other LIDAR instruments emit laser beams in a sigmoid scanning pattern (Naesset 1997b). The footprint, or size of the emitted pulse at ground level, is adjustable and varies among laser manufacturers. Many studies use small footprint (0.2 to 2 meters) LIDAR (Ritchie 1993, Naesset 1994a, Nilson 1995, Magnussen and Boudewyn 1998), while others use large footprints (~10 meters) (Lefsky et al. 1999, Means et al. 1999). The airborne platform and transport system for LIDAR may be a helicopter (Nilson 1995), an airplane (Ritchie 1993), or a satellite (Dubayah et al. 1997). Some LIDAR systems are set up to analyze the continuous reflected returning energy, or waveform, from the top of the forest to the ground (Lefsky et al. 1999, Means et al. 1999). In these laser systems, canopy height is determined by subtracting the elevation value at the termination of the return waveform from the elevation value at the beginning of the return waveform. Other LIDAR systems, like the one used in this study, capture discrete portions, or return signals, of the reflected emission. LIDAR technology as a whole is being used to assess a diverse array of landform (earth surface elevation) and forest structure characteristics (e.g., canopy height, basal area, or the cross sectional area of a tree trunk at breast height, and leaf area index).

Canopy Height Characterization

Small footprint LIDAR systems (~1.0 meter in diameter) have successfully been used to measure forest structure characteristics in a variety of environments. In a study of eight forested plots in Mississippi, no significant difference was found between the height of the ten tallest trees and the elevation of the highest 5% of the laser measurements at those locations (Ritchie 1993). The horizontal spacing between the laser pulses in this study was very tight (0.0125 to 0.025 meters). The extensive data processing requirements of this particular spacing interval, which produces an extremely large data set, is likely to preclude application of this method of data acquisition to larger spatial extents. To limit the size of the data set, studies with larger spatial extents have necessarily used more diffuse point densities. This reduces the resolution of laser measurements and the accuracy of forest measurements at very large scales is consequently reduced because less area is sampled. Naesset (1997) compared the weighted arithmetic-mean height of forest stands, ranging from 0.5 to 4.6 hectares, to a series of laser derived metrics. This study found a positive correlation between ground measured weighted mean canopy height and the maximum laser height within a 15 meter by 15 meter grid. The laser values, on average, were 0.4 meters lower than the ground based measurements but were not significantly different (>0.05). The arithmetic mean laser height in this study underestimated canopy height by just over 4 meters and was significantly different from the ground based measurements (<0.001). Magnussen and Boudewyn (1998) used a similar approach with nearly identical results. Large footprint scanning systems (~10 meters in diameter) have also accurately characterized forest structure. The mean height of the dominant and co-dominant trees in a 2,500 square meter ground plot were positively correlated with the weighted mean of the waveform canopy height profile (Means 1999).

Basal Area Characterization

I found only one study in which small footprint LIDAR was used to characterize the forest characteristic of basal area (Nelson et al. 1997). This study used a profiling instrument at three different study sites in Costa Rica. The correlation between basal area and the laser-derived metric was weak. Large footprint systems have reported greater success. Means et al. (1999) used a laser metric based on the amount of the return waveform energy reflected by the canopy. Lefsky (1999) used a set of laser height metrics (mean height, quadratic mean height, median canopy height) in regressions against field measured basal area. The strongest relationship was between quadratic mean canopy height and basal area ($R^2 = 0.70$).

Large Area Assessment of Streamside Forest Structure

Highly accurate characterization of streamside forests over large areas via ground surveys is both time-and cost-prohibitive. Thus, assessments of streamside forests over large areas are often conducted with aerial imagery. This method is also time-intensive though potentially less costly. The studies above suggest that LIDAR technology may be capable of providing detailed quantitative information over very large areas.

CHAPTER III

METHODOLOGY

Overview

The purpose of this study is to determine whether a remote sensing technology called Light Detection and Ranging (LIDAR) can accurately characterize aspects of streamside vegetation important to the function of stream ecosystems. This research attempts to answer three questions: 1) Can LIDAR be used to predict the rate at which wood is delivered to streams? 2) Can LIDAR be used to identify source areas for the delivery of wood to streams? 3) Can LIDAR be used to identify source areas for "key" pieces of wood? To answer these questions, I first converted LIDAR return data into surfaces approximating ground elevation, canopy elevation, and canopy height. The canopy height surface was compared to forest structure information obtained in ground-based surveys in order to assess the accuracy of the derived surface. I then used the LIDAR-derived forest structure information (i.e., height and density) to study the rate of wood delivery to streams, the source area for potential wood delivery, and the source area for the potential delivery of "key" pieces.

Study Area

This study was conducted in the McDonald-Dunn State Research Forest (McDonald-Dunn Forest) near Corvallis, Oregon (fig. 1). The McDonald-Dunn Forest is located in the Valley Foothills subecoregion of the Willamette Valley ecoregion. The Valley Foothills range in elevation from 10 to 1,500 feet and receive 40 to 60 inches of rain per year (Pater et al. 1997). The McDonald-Dunn Forest comprises approximately 48 square kilometers and within its boundaries are 30 different tree species (Appendix A). The majority of stands in the McDonald-Dunn Forest are either coniferous or a coniferous/hardwood mix (Table 1). The study area, coincident with a LIDAR flight line captured in October of 1998, covered approximately 28 square kilometers of which 14 square kilometers are privately owned. Ground based data describing vegetation on the private lands are not currently available. There are 194 stands within the study area, most of which are in second growth forests. Only thirteen of these 194 stands are over 200 years old, and half of the stands are less than 60 years old (Table 2). Approximately 55 kilometers of stream are found within the study area, most of which are first and second order. The largest, Soap Creek, is a fourth order stream and lies on the eastern boundary of the study area. Only 95 of the 194 stands have streams flowing through them.

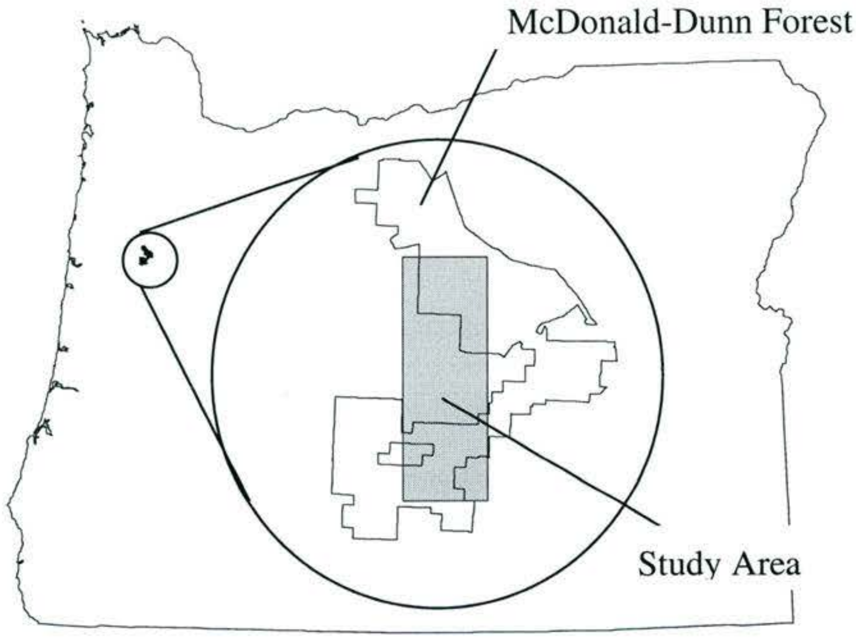

Figure 1. Study area location.

Table 1. Composition of McDonald-Dunn Forest

Stand Type	Average age (yrs)	Area (ha)	Percent of total
Pure conifer (> 85%)	71	46758	52.4
Conifer/hardwood (51-85%)	89	36206	40.6
Pasture/meadow	Na	2876	3.2
Hardwood/conifer (15-50%)	86	2238	2.5
Hardwood other	60	1142	1.3
Total	58	89220	

Information derived from StandPoly GIS data layer.

Table 2. Age and Height Characteristics of the McDonald-Dunn Forest

Combined summary of all stands	Stand age	Mean height 40 largest trees	Mean height dominant co-dominant trees
Average	75	79	46
Median	60	98	39
Maximum	314	240	174
Minimum	0	0	0
> than 200 yrs	13		
< than 200 yrs	179		

Information derived from StandPoly GIS data layer.

Table 3. Streams within the McDonald-Dunn Forest Study Area

NAME	Length (km)
Baker Creek	4.44
Berry Creek	10.03
Frazier Creek	4.65
Jackson Creek	0.95
Maxfield Creek	0.90
Oak Creek	1.42
Soap Creek	23.53
South Fork Berry Creek	0.17
Unnamed	8.66
Total	54.75

Information derived from StandPoly and Streams GIS data layers.

Description of Data Used in this Study

Two general categories of data were used in this study, airborne and ground. The airborne, or laser data, were collected to explore the use of remote sensing technology, specifically LIDAR, to describe forest structure characteristics. The ground data used in this study were collected as part of a long-term forest inventory of the McDonald-Dunn Forest. The ground data was used to verify the accuracy of the airborne laser data and to test the conceptual models describing the delivery of wood to streams. In this section, I describe the two categories of data, discuss how the data were transformed for use in these analyses, and evaluate the accuracy of the LIDAR-derived canopy height surface.

Airborne Data

Data Collection

The LIDAR scanning system used in this study directed laser emissions at the study area in a sinusoidal pattern at the rate of approximately 15,000 pulses per second (fig. 2) from an airplane flown at an altitude of approximately 2,000 meters. The footprint was approximately 0.5 meters in diameter. The horizontal spacing between pulses was approximately six meters, and the width of each scan was approximately 4,500 meters. The horizontal spacing between points, in a two-dimensional horizontal plane, was often less than six meters. The number of return signals was highly variable, although a single first return was most common. The number of return signals decreased with increasing return order (fig. 3).

This decrease in the number of return signals is partly related to technology and partly to forest structure. There is a limit to the speed at which return signals can be assimilated. The scanning equipment is capable of recording only one return signal every 0.2 nanoseconds. Once a signal is recorded, additional signal captures cannot be recorded for 0.2 nanoseconds, which equals approximately 5 meters of travel distance. If returns can be generated every 0.2 nanoseconds, then a minimum forest height of 25 meters is required for 5 return signals. Not every forest taller than 25 meters will reflect 5 signals, however because the vertical configuration of potential reflective surfaces is commonly patchy across the path of a laser pulse (Lefsky et al. 1999). Nonetheless,

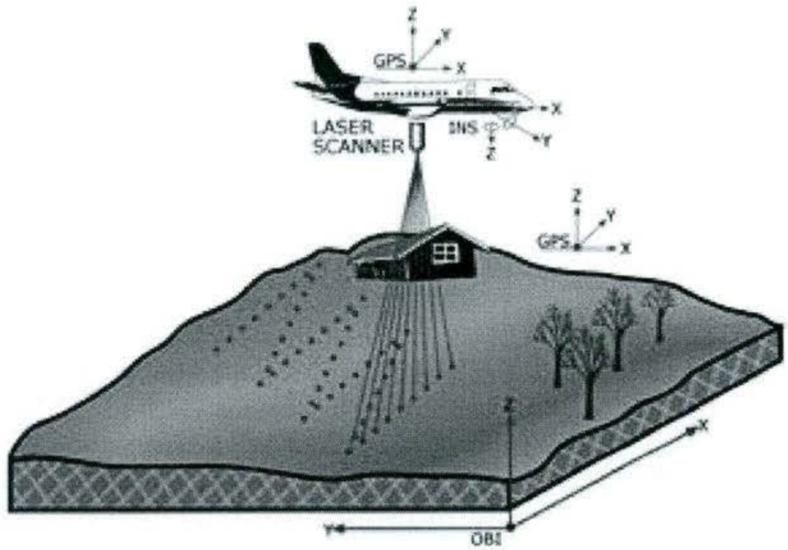

Figure 2. LIDAR scanning system.

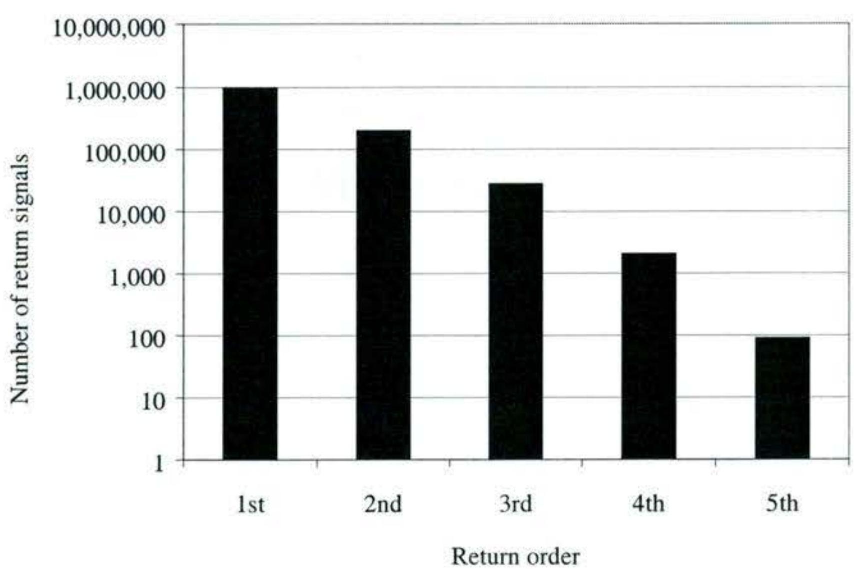

Figure 3. The number of return signals by return order.

nearly every surface, whether forest or bare ground, can potentially generate at least one return signal.

Data Transformation

The objective of this portion of the study was to convert the raw LIDAR data points into a format conducive to the spatial analysis used in this study (fig. 4). Therefore, the data format used in the models in this study consisted of continuous, two-dimensional surfaces of a regular array of pixels. Few published studies exist describing the transformation of raw LIDAR elevation points into elevation surfaces. Therefore, it was necessary to study different approaches for generating these surfaces in order to determine which method resulted in the best conversion of data from points to surfaces.

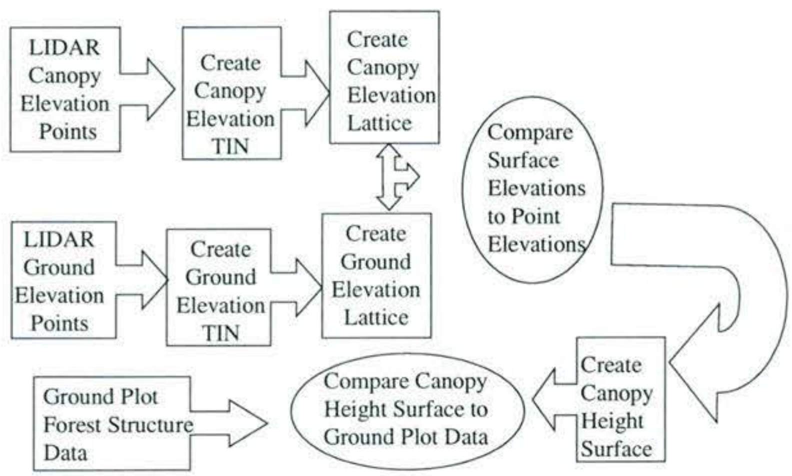

Figure 4. Process for Generating and Assessing the Accuracy of the Canopy Height Surface.

In their raw form, LIDAR data consist of large text files in which horizontal and vertical coordinates represent individual return signals. Such text files were created for first, second, third, fourth, fifth, and last return signals. Some processing of the raw data is required to separate ground elevation return signals from other return signals. This was accomplished via a proprietary processing algorithm (Mike Renslow, personal communication). The text file coordinates and the elevation values from the ground elevation and first return point files were used to compute Triangulated Irregular Network surfaces (TINs). A TIN is a set of adjacent triangles that form a smooth continuous surface (fig. 5). The TINs were then used to generate regularly spaced square cell surfaces called lattices. Lattices are similar to TINs in that the nodes of cell intersection,

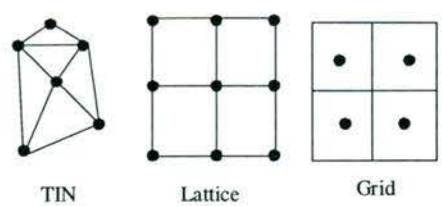

Figure 5. Data Model Structure

or mesh points, contain the elevation information. The spacing and resolution of these two data models, however, is very different. The mesh points of a TIN (where triangles intersect) contain only information from the original point files, and the distance from mesh point to mesh point in a TIN is a function of the geographic location of the original data and can be highly variable. In lattices, the distance from mesh point to mesh point is uniform across the spatial extent of the data set. The new mesh points are interpolated from the original data points. Lattices, created from TINs, closely reflect the elevation information derived from the TIN (fig. 6). The principle advantage of a lattice over a TIN is that a number of cartographic modeling functions, including mathematical operations such as addition and subtraction, can be performed on lattices, although this is not possible for TINs. After the lattices were generated, the ground elevation surface was subtracted from the first return elevation surface to create a new lattice of canopy height.

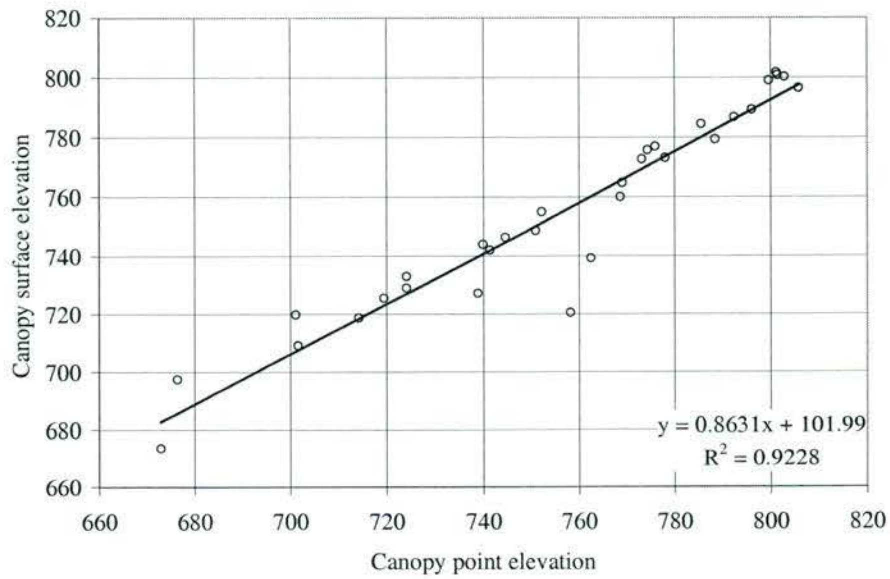

Figure 6. Comparison of laser canopy point elevations to lattice cell values after interpolation from TIN.

Several variations of an interpolation method called "kriging" were used to generate ground elevation and canopy elevation surfaces from the point data. Kriging predicts values for areas between sample points based on the variance between the sample points (McBratney and Webster 1986). Five variations of the kriging method were tried, and the results were compared to the ground plot data. The variations used were spherical, circular, linear, exponential, and Gaussian. The surface created by converting TINs to lattices was compared to surfaces generated by kriging lattices from points. The elevations of the surfaces created in the TIN-to-lattice process were approximately equal to that of the original point elevation data (fig. 6). The relationship observed in Figure 6 is nearly one-to-one indicating that every point in the original elevation data set has a closely corresponding elevation value in the created surface. The surfaces created by the kriging process did not exhibit the expected one-to-one relationship (fig. 7) indicating that the original elevation data was not well approximated in the interpolated elevation surface.

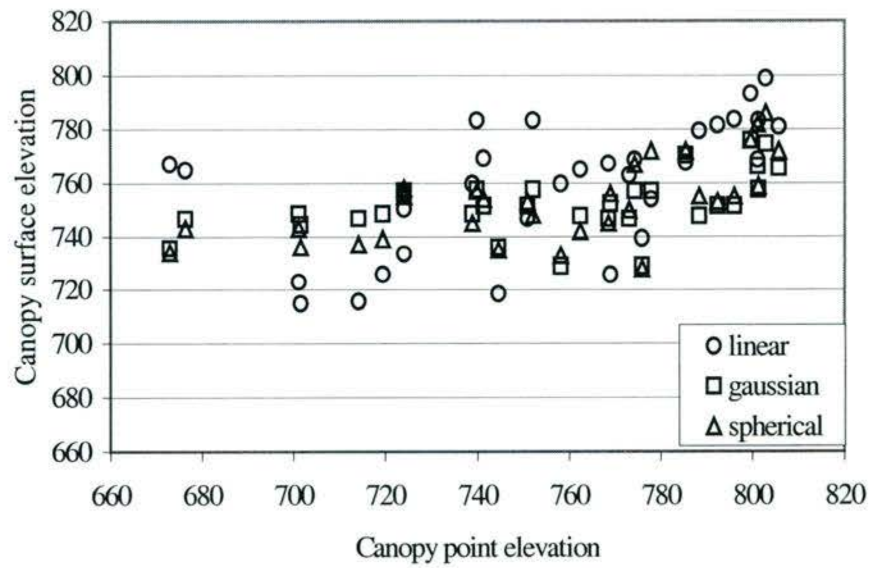

Figure 7. Comparison of canopy point values to canopy surface values after interpolation by kriging.

Ground Data

Several ground-based data sets were used in this study. Ground plot data were used to validate the LIDAR-derived canopy height surfaces. Stand ground data (aggregated from individual plot data) were compared to the model outputs to validate the rate of tree delivery to streams, the source areas, and the key piece source areas.

Ground Plot data

The ground data used in this study were collected as part of an ongoing forest inventory at the McDonald-Dunn Forest. The data used in this study were collected between July 1997 and February 1998. A variable radius sample plot method was used in the collection of forest structure information (see Bell 1993 for more information). All trees equal to or greater than 20 centimeters in diameter at breast height (DBH) and within 6.1 meters of the plot center were included in the sample. The inclusion of trees greater than 6.1 meters from the plot center was based on their size and distance from the plot center. Either prisms or relaskops were used to identify large trees beyond the 6.1 meter threshold for inclusion in the sample (Oregon State University 1999). DBH and tree height measurements were recorded for all trees, living or dead, within the plot. A geographic information system (GIS) data set containing the surveyed location of each ground plot and the associated attribute information, was obtained from McDonald-Dunn Forest personnel.

Stand Data

Several other GIS data sets were also obtained from McDonald-Dunn Forest personnel for use in this study. The most frequently used GIS data was the stands polygon data set (StandPoly). The StandPoly data were derived from the ground plot data and digital orthophotographs. Individual stands, in this data set, were clusters of ground plots with similar structural characteristics (e.g., height, age). Boundaries were drawn around the ground plot clusters based upon features observed in the aerial photographs. The attributes of the StandPoly polygons included the information collected at the plot level then summarized to the stand level. Three stand attributes used in this study were mean height of the forty tallest trees, mean height of the dominant and co-dominant trees, and stand age. Since ground plots were not sampled every year, a growth and yield model called ORGANON was used to simulate the growth of individual trees from the last period of record to the present date.

This study also used a digital GIS data representation of the stream network in the McDonald-Dunn Forest. The stream network GIS data set used in this study (Streams) was digitized off orthophotographs from various time periods.

Ground Height to Laser Height Evaluation

A 929-hectare section of the southwestern portion of the study area was selected for comparison of the ground based and airborne forest structure data. This section of the study area was selected because it contained the full range of forest structure characteristics, from very old to very young. Initially, all ground plots within this section, sampled after July 1997, were selected for inclusion in the analysis. Ground plots adjacent to roads or clear cuts were excluded from the analysis, however, due to concerns about the locational accuracy of the ground plot GIS data set.

Individual tree heights in each ground plot were averaged and the values were compared to the LIDAR-derived canopy height (fig. 8). A GIS was used to identify coincident ground plots and grid cells. A strong positive relationship was observed between the ground plots and the LIDAR-derived canopy surface. As mean ground plot height increased so did the height of the LIDAR-derived surface. Sixty-five percent of the variance is explained between these two variables. The slope of the fitted line in Figure 8 does, however, indicate that the LIDAR-derived surface underestimated mean canopy height. Underestimation of canopy height is documented in numerous studies (Nilson 1996, Naesset 1997, Magnussen and Boudewyn 1998). This likely occurs because the surface area of the highest point on a tree (and hence the size of the potential reflective surface) is small compared to the full surface area of the remainder of the tree.

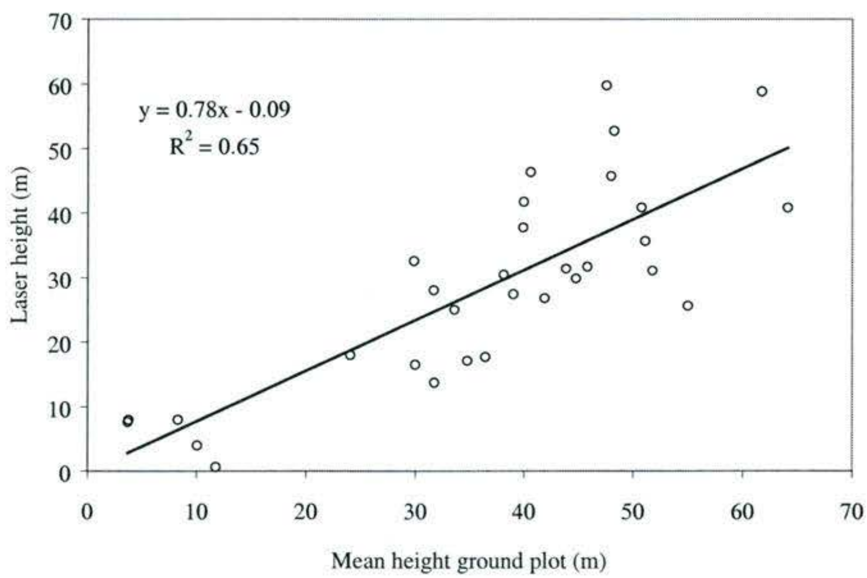

Figure 8. Ground plot height vs. LIDAR canopy surface height.

It is, therefore, unlikely that a pulse will bounce off of the uppermost point of a tree (Magnussen and Boudewyn 1998). Another contributing factor in the reduced correspondence between the ground and LIDAR data may be the format of the ground data. These data were not collected for the purpose of testing the LIDAR-derived canopy height values. The variable radius plot size of the ground data used in this study includes large trees from distances beyond 6.1 meters from the plot center, perhaps elevating the mean height of a given ground plot. Ground plots specifically designed to test laser data would likely improve the ground to laser data relationship. Additionally, the locational accuracy of the ground plot GIS data set is unknown and in some cases positional errors were observed. This may have contributed to the lack of correspondence between the GIS data set and the LIDAR data set. The position of the LIDAR points in the horizontal plane is known to within a meter (Mike Renslow personal communication).

Model Description and Application Methodology

This study attempted to model three aspects of how wood is delivered to streams from riparian forests. In this section, I describe each of the models used, including related assumptions. Then I describe the methodology used to apply these conceptual models to specific conditions in the McDonald-Dunn Forest. The three models used in this study were 1) the wood delivery rate model, 2) the source area model, and 3) the key piece source area model.

Wood Delivery Rate Model Description

This part of the study had two objectives. The first was to model the rate at which large wood is delivered to streams. The second was to determine the cumulative frequency of wood delivered to the stream as a function of distance from the stream. Based on the work of McDade et al. 1990, Robison and Beschta 1990, and Van Sickle and Gregory 1990, the model used for delivery of wood to streams in this study was characterized by the equation:

$$W_d = P_s\, D\, R_f \qquad \text{Equation 1.}$$

where W_d is the delivery of wood to a stream in number of trees per unit area per unit time. P_s is the probability that a tree will fall in a stream, D is the density of trees, and R_f is the rate at which trees fall. This model assumes that large wood delivered to streams comes only from trees adjacent to the stream. This model does not incorporate wood delivery from stochastic events, such as debris flows, mass movements, slumps or landslides, that might occur at distances from the stream that are greater than the tallest tree height. LIDAR was used to provide the data for two of the three components of this model (P_s and D). Data for the other component, R_f, were obtained from an individual tree growth model called ORGANON.

Delivery Rate Model Modifications

The wood delivery model used in this study was modified to allow 1) its application over a larger spatial extent and 2) the use of LIDAR data as input. First, density, D, is typically expressed as the number of trees per unit area. I was unable to find a correlation between the number of trees per plot and the LIDAR point density grid or LIDAR-derived canopy height. LIDAR provides information about individual trees small areas (i.e., cells in the grid, which in this study were 1.5-meters by 1.5-meters or 2.25 m^2) rather than individual trees. Second, although (Van Sickle and Gregory 1990) included the probability of tree fall, P_f, in their model, for practical reasons explained later in the text, I used the rate of fall (R_f) is used here instead.

Probability of Falling in a Stream, P_s, Component

The probability of a tree falling in a stream, P_s, is a function of tree height and perpendicular distance from the stream as described by Equation 2:

$$P_s = (arccosine\ (\ d_p / z\ )\ ) / 180 \qquad \text{Equation 2.}$$

where d_p is the perpendicular distance to the stream, and z is the mean height of trees in a given cell (fig. 9). For this study, I assumed that the direction of tree fall was random. P_s

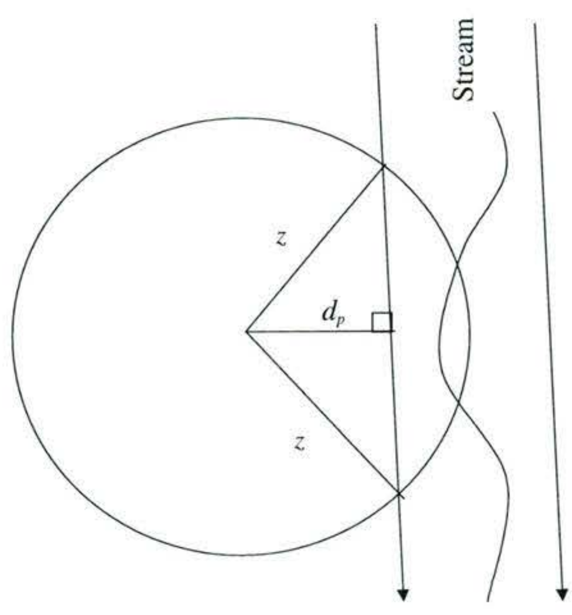

Figure 9. P_s, the probability of falling in a stream where z equals the height of the tree and d_p equals the perpendicular distance to the stream.

was calculated using 1) a set of grid of cells representing the stream network and 2) a grid of canopy height values. I used Arc/Info GIS to determine the shortest perpendicular distance from any cell to the nearest cell that is part of the stream network. For ease of calculation in this model, I assumed that a tree could fall into only one stream and that it would always fall into the nearest stream. Visual inspection verified that only a small percentage of cells were in locations (e.g., confluences) that could potentially allow contributions to more than one stream. Therefore, this simplification of the model was not expected to significantly affect the model results. Using the perpendicular distance and the LIDAR canopy height grid, P_s was computed over the entire study area and rendered as a new grid in which cell values equaled the probability of a tree falling in a stream.

Density, *D*, Component

Standard wood delivery models require a tree density metric, which is typically expressed as trees per unit area, however, this type of information is not directly obtainable from LIDAR. Use of LIDAR data for the density model component precluded me from being able to include the standard metric in the model. I chose to use LIDAR data for the density component of the model because LIDAR data were available for the entire study area whereas ground based information on the number of trees per unit area was confined to small discrete locations. I first attempted, unsuccessfully, to find a relationship between the number of trees per unit area and LIDAR data. I then searched for other measures of forest density. I hypothesized that a relationship between the number of LIDAR return signals per unit area and forest density might exist. Recall that once the airborne sensor has captured a returned laser signal, it is unable to record the next return for 0.2 nanoseconds, which equals 5 meters of travel distance. Therefore, taller stands have the potential to return more signals than shorter stands. Also, the number of reflective surfaces in the *z* dimension (height) is likely to vary depending on stand characteristics, such as age and density. Conceptually, dense, even-age stands with a single uniform canopy layer will have fewer reflective surfaces over the travel distance of a laser pulse and, consequently, may return fewer signals than undisturbed older stands with gaps and multiple canopy layers. Sites with vegetation less than 5 meters tall will necessarily return only one signal because of the limit on the rate at which return signals can be processed.

To test this hypothesis, an analysis was conducted to determine the number of non-first return signals within a one-acre circle (equivalent to a 36-meter radius) of each 1.5 meter grid cell. First, a grid was generated in which each cell contained a LIDAR point density value equal to the number of non-first return points in a 0.4 hectare (one-acre) circle. First return points were excluded from this analysis because nearly every surface in the study area could generate a first return coordinate (unlike water, for example, which will not return a signal because the laser pulse is absorbed by the surface). Since both canopy and ground can generate first returns, these signals are not informative indicators of the amount of reflective surface available as a consequence of variation in forest structure. Higher order return signals are meaningful indicators of the potential number or layers of reflective surfaces because not every vegetative surface is capable of generating multiple returns (e.g., vegetation less than five meters tall).

The number of non-first return points per hectare was calculated for every grid cell across the study area. These values were then compared to forest structure metrics contained in the StandPoly GIS data set. Initially, all stands within the study area were selected for this comparison. Several stands were subsequently deemed inappropriate for inclusion in this analysis because their boundaries extended beyond the spatial extent of the study area. This exclusion is justified because the stand level statistics, in these cases, were generated based on ground plot information collected outside of the area scanned by the LIDAR instrument. Therefore, only stands completely within the study area were selected for this analysis. A visual inspection of the 64 stands selected for the analysis showed that none was within 36 meters of the study area boundary, thus the search radius for the density grid was always within the boundary of the LIDAR flight line. The basal area for these stands was compared to the number of non-first return points per hectare in these areas. Basal area is used here as a relative measure of density. A positive relationship between this ground-based stand density metric (i.e., stand average basal area) and non-first return point density was observed (fig. 10).

Based on the relationship between ground-based stand density and the number of non-first return LIDAR points, grid values of non-first return points per hectare were converted to a grid values of stand average basal area using the following equation:

Basal Area = (ln (non-first return grid / 36.59)) / 0.0248 Equation 3.

The resulting grid contained the stand average basal area in square meters per hectare.

Because the units for wood delivery, W_d, come from the rate of tree fall, R_f, and because this metric is used as a relative measure of density, I cancelled the units of measurement associated with Equation 3 using the following equation:

D = (Basal Area m^2 / 1 ha) / (1 ha / 10,000 m^2) Equation 4.

The result of this equation is a unitless measure of density for every grid cell in the study area. This grid was then used in the wood delivery rate model as a surrogate for the standard density metric.

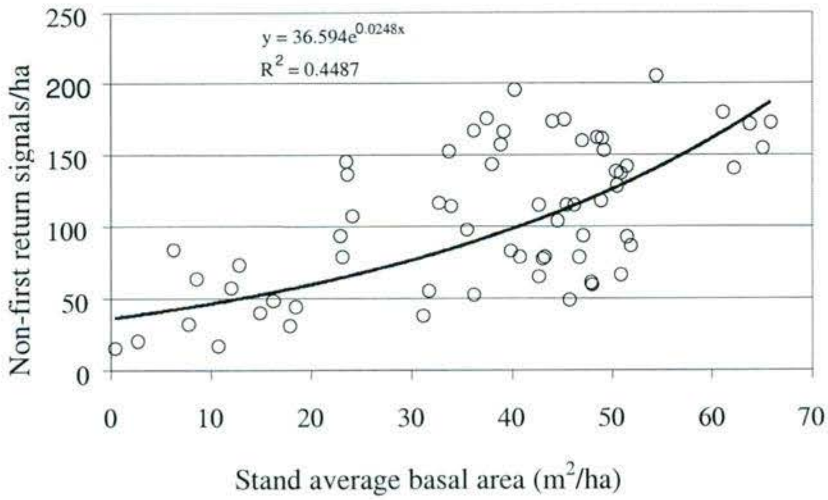

Figure 10. Stand average basal area vs. non-first return point density.

<u>Rate of Fall, R_f, Component</u>

No direct estimate of the rate of tree fall in the McDonald-Dunn Forest was available for this study. In a previous study, Van Sickle and Gregory (1990) used tree mortality as an approximation of the probability of tree fall, although mortality underestimated the actual rate of tree recruitment in the study streams by a factor of seven. Given certain assumptions, however, mortality can be used as rough approximation of tree fall. ORGANON, a model designed to predict the growth of individual trees in a stand, is capable of estimating mortality for all trees less than 110 centimeters in diameter (fig. 11). For this study I assumed that the estimated mortality

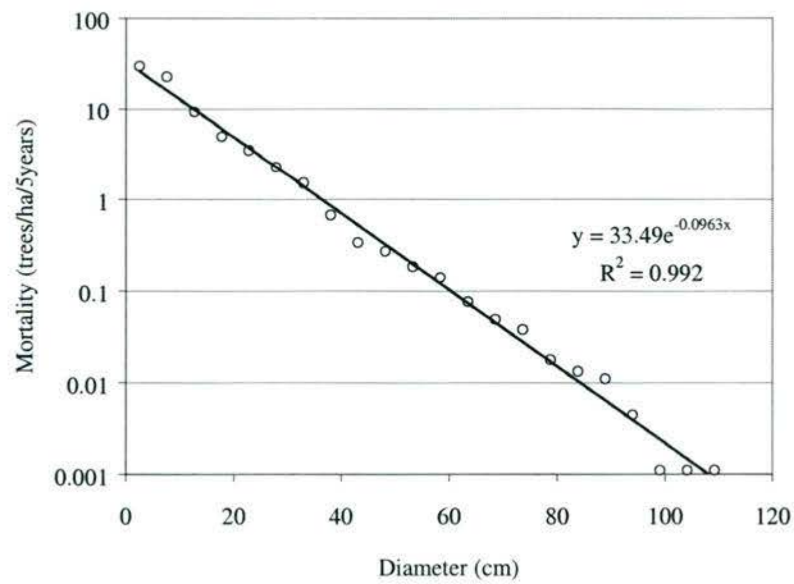

Figure 11. Mean mortality as a function of tree diameter.

equaled tree fall, thus no trees were snags after mortality. The ORGANON model, operation guidance, specifications, and input data files for stands in the McDonald-Dunn Forest are available at http://www.cof.orst.edu/resfor/mcdonald/purpose.sht.

The ORGANON input files are stand level aggregations of the ground plot data. Data from thirty stands within the study area were randomly selected as input files for ORGANON. The model is designed to run with more than 50 trees per stand; therefore, twenty of the initial 30 stands that did not meet this requirement were discarded. Growth over an arbitrarily-selected 25 year period, or five growth cycles, was calculated for each of the remaining ten input files. ORGANON estimated the mortality of every tree in the input file and reported the average values by diameter class. I then computed stand averages from the ORGANON diameter class mortality values (Table 4). Because mortality was highly variable from stand to stand, average mortality was calculated for all ten stands and assumed to be uniform across the study area. This value was used as a surrogate for the rate of tree fall. Despite this assumption, it is recognized that mortality is highly variable, site specific, and age specific.

Table 4. Average Mortality by Stand

Stand #	Mortality[1]
61103	56.049
60802	56.148
60513	81.259
60811	111.901
70501	133.457
60402	198.346
60403	209.58
51101	259.951
51001	325.062
60901	334.272
Average / 25yrs	176.603
Average / 5yrs	35.321

Number of trees/hectare for 25 year period.

Wood Delivery Rate Model Methodology

The wood delivery rate, W_d, was calculated by multiplying the cell values in the P_s and D grids by the surrogate for rate of fall, (i.e., R_f; see Equation 1). Both P_s and D are unitless numbers, and R_f supplies the rate information for the wood delivery model. Two potential tests of this model are:

1. Does the model predict the percent of wood delivered from the streamside vegetation to streams as a function of the distance from the stream, and
2. Does the model predict loading rates similar to those derived from other studies?

The analyses designed to test these questions are described below.

Age Class Cumulative Frequency

The cumulative frequency distribution of wood delivered to a stream as a function of distance from the stream coincides with values reported in other wood delivery studies (McDade 1988, Murphy and Koski 1989, McDade et al. 1990, Robison and Beschta 1990, Van Sickle and Gregory 1990). Two different spatial resolutions were used to calculate cumulative frequencies in this study. A study area curve was generated as a preliminary assessment of model performance. Additional curves were then generated at the stand level to determine if the known variations in forest structure could be detected. Aerial photographs, stand polygon data, and visual inspection of the source areas in the study area were used to select four stands of different forest structure and age. Each of the five cumulative frequency distribution curves presented in this study were calculated individually. Because it would have been difficult and time consuming to calculate cumulative frequency distribution curves for every stand in the study area, curves were calculated only for the four stands chosen and the for total study area.

Wood Delivery Rate Estimates

Of the 194 stands in the study area, nineteen were selected to evaluate the rate at which wood was delivered to streams in the model. Stands were excluded from the analysis if they did not contain streams. Stands were also excluded from the analysis if the StandPoly boundary intersected any part of the wood delivery source area because wood delivery, in these polygons, would be underrepresented in the modeled rate per hectare. The wood delivery rate was summed for each stand and divided by the total source area within the stand. The area of the selected polygons varied; consequently, the total source areas for each of the streams in the nineteen stands also varied depending on the length of the stream and the area of the stand. To standardize for differences in the size of the selected stand polygons, the delivery rate was divided by the total source area (for each stand).

The delivery rates obtained in this study were compared to the delivery rates reported in Lienkaemper and Swanson (1987). These "comparison sites" were located in the Cascades ecoregion (Pater et al. 1997), (fig. 12) in 500-year-old conifer forests stands. The Cascade sites are higher in elevation and receive more precipitation than the McDonald-Dunn Forest sites. These Cascade forests were produced by differing environmental conditions that may influence the result of any comparison. However, these two forest types also have structural similarities (especially the older forests) that may make a comparison useful. Many of the tree species, such as Douglas fir

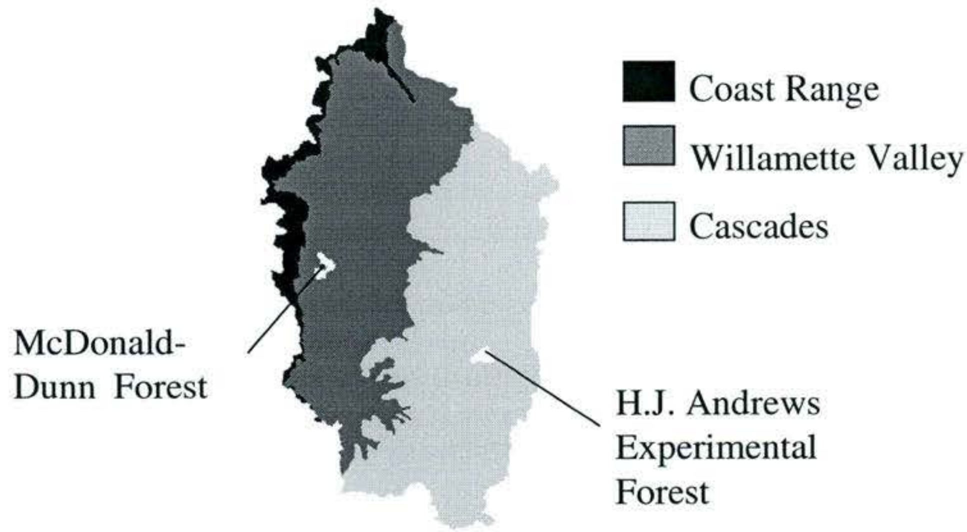

Figure 12. Ecoregions of the Willamette Basin and study sites used for comparison of model results.

(*Pseudotsuga menziesii*), are common to both study areas. Trees in the comparison sites are likely to be larger than trees in the McDonald Forest. This size difference should result in larger source areas for the comparison sites because trees can reach the streams from greater distances.

Lienkaemper and Swanson (1986) recorded the number of trees entering five streams over a period of seven to nine years. From this information, I calculated the number of trees entering the stream per hectare of source area over a five-year period. I assumed that all the trees entering the comparison site streams had origins less than 35 meters from the channel (McDade et al 1990). This may be a conservative estimate considering that McDade (1988) found trees falling in the stream from distances greater than 60 meters in some cases.

Source Area Evaluation Methods

Source Area Ratio Model Description

The objective of this part of the study was to determine if the LIDAR data could be used to identify the source area for trees falling in streams. The probability that a tree will fall in a stream is a function of tree height, z, and perpendicular distance, d_p, to the stream (see Equation 2, p. 29). The source area for a stream includes the area between the edge of the stream and the furthest perpendicular distance to a tree that could potentially fall into the stream. The LIDAR canopy height grid was used to identify locations along the stream network where the tree height of the grid cell was greater than the perpendicular distance to the stream (fig. 13).

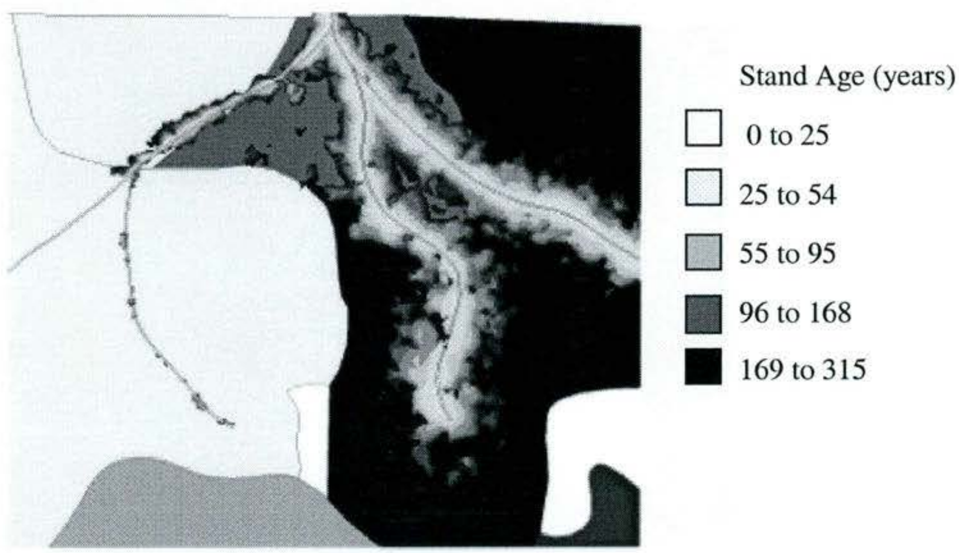

Figure 13. Source area size by stand age.

Source area ratio is defined as the area of streamside forest that can potentially deliver wood to a stream divided by the length of stream. Source area ratios in this paper are reported as the area of streamside forest in square meters divided by the length of stream in meters. A ratio was used in this study because stream length varies widely in the 19 stands selected for analysis. The ratio is a means of normalizing the source area within stands so that comparisons between stands are meaningful.

Source Area Ratio Methodology

Conceptually, the source area for an older stand with tall trees will extend a greater perpendicular distance from the stream than will a young stand with short trees. Consequently, streams flowing through taller, older stands should have greater source areas per length of stream (source area ratios) than streams through shorter, younger stands. Stands were selected to test this hypothesis if 1) they contained streams and 2) the potential wood delivery source area did not intersect a stand boundary. Nineteen of the 95 stands containing streams were chosen for this analysis. The predicted source area within each of the nineteen stands was divided by total the length of stream within the stand boundaries. The ratio of source area to stream length was then compared to stand level statistics such as stand age, mean height of the forty tallest trees, and the mean height of the dominant and co-dominant trees in the stand.

Key Piece Source Area Model

Key Piece Source Area Model Description

The objective of this part of the study was to quantify the proportion of the source area that could potentially deliver wood of a given height or diameter class to a stream. Because very large pieces of wood may have greater influence on channel characteristics and stream function than small pieces (Benke and Wallace 1990, McHenry et al. 1998), it is useful to identify the potential source areas for various size classes of trees.

Canopy Height Classes

Given that no universally agreed upon definition exists for key piece size, this study examined both the source area and the loading rate for a range of values. Five canopy height classes were included in this analysis: total canopy surface, canopy surface greater than 10 meters, canopy surface greater than 20 meters, canopy surface greater than 30 meters, and canopy surface greater than 40 meters. Grids for each of these surfaces were generated from the LIDAR canopy height grid. Then the probability of a tree falling in a stream, P_s, was calculated for each height class surface. These were each then multiplied by the density grid, D, and rate of fall grid, R_f, to produce a unique loading value, W_d, for all the cells in each height class grid.

For this part of the analysis, the criteria used to select ground-based forest structure information for comparison to LIDAR derived surfaces were identical to those used for the source area ratio analyses. Three analyses were performed to compare the LIDAR derived surfaces to ground based forest structure information. First, the source area ratio for each height class was compared to stand age. Second, I computed the area of each height class surface and compared it to the area of the entire canopy height surface. Third, because piece diameter may be an important determinant of instream function (Benke and Wallace 1990, McHenry 1998), diameter classes were calculated for the height class surfaces. The area of each height class surface was then calculated and compared to total canopy surface area.

Diameter Class Calculations

As mentioned previously, the height and diameter of every tree within a ground plot was recorded. A least squares regression was performed on the measurements of tree height and tree diameter in order to derive an equation that could be used to convert the canopy height surfaces to diameter class surfaces. This was achieved by selecting all the trees measured (n = 83) from five stands, without regard to species, and plotting tree height against diameter at breast height (fig. 14). The height and diameter of snags were measured in the field and were therefore included in this analysis to allow for more direct comparison with my model results, which also included snags.

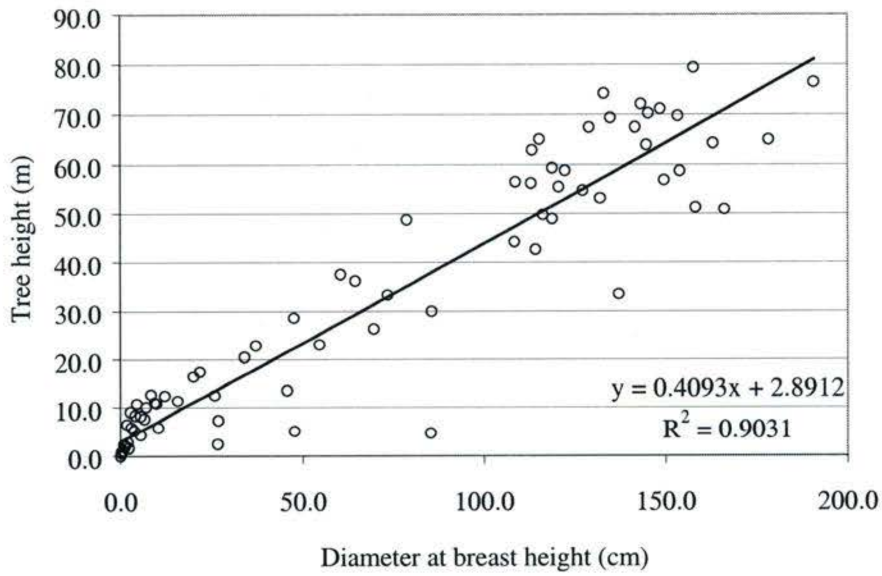

Figure 14. Least squares regression of tree height and tree diameter.

Method Summary

Airborne LIDAR data collected for the McDonald-Dunn Forest was transformed from its raw state into a canopy height grid. Values in the canopy surfaces were checked against ground based forest structure data. The LIDAR data were then transformed for use as the P_s and D components of the wood delivery rate model. The LIDAR data were also used to calculate the area from which streams could recruit wood pieces. These values were then compared to ground based forest structure measurements.

CHAPTER IV

RESULTS

Overview

There are three questions that this research attempted to answer. First, can the wood delivery model accurately predict the rate at which wood is delivered to streams? Second, can LIDAR be used to identify the potential source areas for the delivery of wood to streams? Third, can LIDAR data be used to identify potential source areas for large or "key pieces"?

Wood Delivery Rate Model Results

This study modeled the rate at which trees fall into streams. As mentioned previously, no tree fall data were collected for this study; however, I did perform two evaluations of the wood delivery rate model using results from other studies. First, I estimated the amount of wood delivered to streams over time as a function of distance from the stream, and I compared the McDonald-Dunn Forest values to values reported for streams in southeastern Alaska and the western Cascades of Oregon. Second, I compared the actual delivery rates per unit area in the McDonald-Dunn Forest relative to delivery rate values for five stream reaches in the western Cascade Mountains.

Cumulative Frequency Distributions

Cumulative frequency distribution curves, or the percentage of wood pieces delivered to stream as a function of distance to the stream, are commonly used to describe wood delivery to streams (McDade 1988, Murphy and Koski 1989, McDade et al. 1990, and Van Sickle and Gregory 1990). The results of five cumulative frequency distribution curves from the McDonald-Dunn Forest are presented here. The first is a curve representing wood delivery for all streams within the study area. The remaining curves represent wood delivery to streams from four stands of varying age structure. The cumulative frequency curve for the entire study area predicted that 83% of the wood delivered to streams would originate from within 20 meters of the channel, and 95% would originate from within 30 meters (fig. 15). McDade (1988) found that in 29 streams in western Washington and Oregon, 70% of the wood in streams originated within 20 meters of the channel, and 90% originated within 30 meters (fig. 16). In southeast Alaska, 99% of the wood originated from within 30 meters (Murphy and Koski 1989). It should be noted that the other study sites were located in different ecoregions than the McDonald Forest. Tree height can be influenced by environmental conditions specific to each ecoregion may differ from region to region even among trees of the same species. Because trees in the western Cascades are taller, more wood can be delivered to streams from greater distances, thus reducing the relative contribution from distances close to the stream. Wood in the Willamette Valley Foothills or southeast Alaska is likely delivered from shorter distances because the trees in these forests are not as tall. Consequently, the relative contribution, expressed as a percentage of the total, are greater at shorter distances.

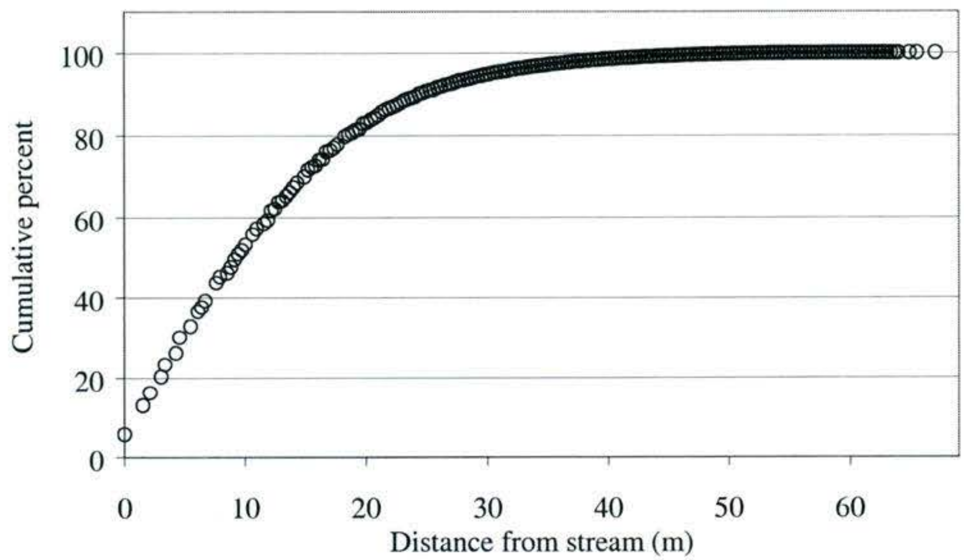

Figure 15. Wood delivery in the McDonald-Dunn Forest as a function of distance from the stream.

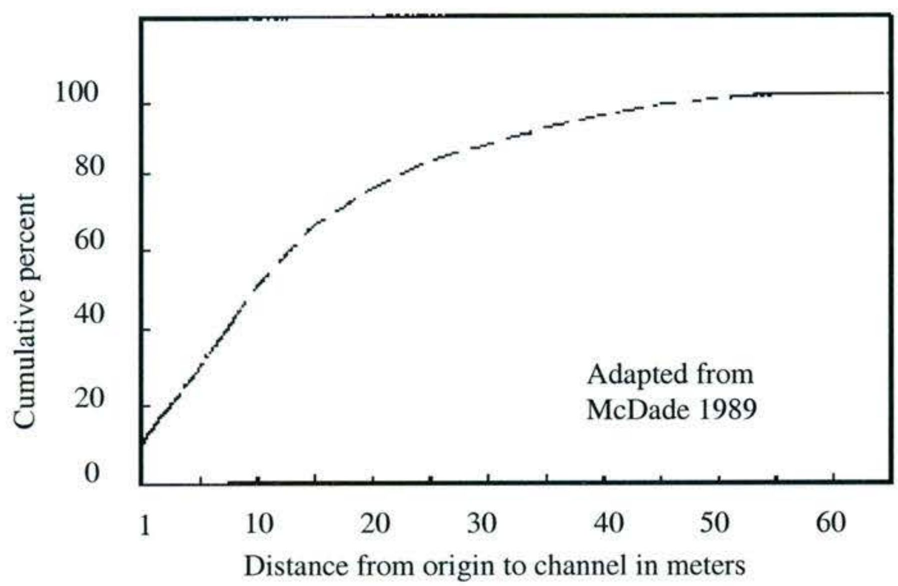

Figure 16. Wood delivery in Western Oregon and Washington as a function of distance from the stream.

This point is further illustrated by comparing stands with different forest structures in the McDonald-Dunn Forest to very tall stands in the western Cascade

Mountains (fig. 15). Consider that the study sites described by McDade (1988) were described as either old growth (greater than 200 years old) or mature (between 80 and 200 years old). The median age of the McDonald-Dunn Forest stands in this study was approximately 59 years (Table 3). Only 13 of 195 of the McDonald-Dunn Forest stands were over 200 years in age.

Streams flowing through four stands with differing streamside forest structure characteristics were selected for this part of the analysis, and cumulative frequency distribution curves were computed for each. The curves varied greatly between age classes (fig. 17). The wood delivery rate model predicted that older stands would deliver more trees per hectare and that they would have larger source areas for delivery, as evidenced by the greater delivery distances (Table 6). Trees were predicted to reach the stream from greater distances in 214-year-old stand than in the agricultural land. Only

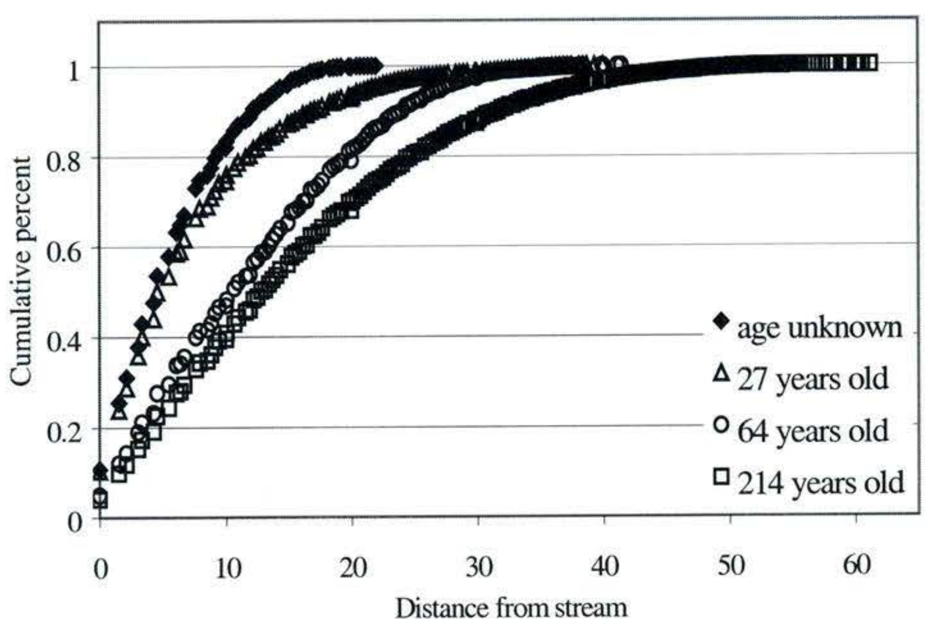

Figure 17. Cumulative percent of wood delivered as a function of distance from the stream in four stands in the McDonald-Dunn Forest.

about 3% of the wood delivered in the 214-year-old stand was predicted to originate from greater than 40 meters. The greater source area for 214-year-old stand is a function of the presence of older and taller trees. In contrast, 100% of the trees predicted by the model to be delivered to streams in agricultural land came from within 20 meters of the stream. Roughly 70% of the predicted trees delivered came from that same distance in the 214-year-old stand with taller trees. The model also predicted that shorter stands would deliver fewer trees per hectare over a 5-year period than taller stands (Table 5).

Table 5. Cumulative frequency distribution for stands of different age classes.

	Percent of total delivery			
Distance from stream	Agricultural land (age unknown)	70803 (27 years old)	20406 (64 years old)	50904 (214 years old)
10 meters	82.0	74.6	47.0	39.6
20 meters	99.8	92.9	79.1	68.0
30 meters	100.0	98.5	97.3	87.3
40 meters	100.0	100.0	100.0	96.5
Total wood delivery (trees/ha/5yrs)	4.02	3.55	5.97	22.06

The cumulative frequency distributions predicted by this model, closely approximated those observed by McDade (1988) for forests of similar ages. For the 214-year-old stand in this study, my model predicted that 68% of wood delivered would come from within 20 meters of the channel. McDade (1988) observed that in old growth forests (over 200-years-old), 70% of the wood delivered came from within 20 meters. My model predicted that 87% of the wood would come from within 30 meters; McDade (1988) observed that 90% of the wood originated from within that same distance.

Delivery Rates

While my model appears to be capable of producing cumulative frequency distributions of wood delivery similar to values reported in other studies, predictions for delivery rates vary more than values in other studies. Of the nineteen stands selected to analyze the rate at which wood is delivered to streams in the McDonald-Dunn Forest, five are comparable in age to the sites in the western Cascades. The wood delivery rate model in this study appears to produce higher wood delivery rates for streams in several stands than the western Cascades sites. The predicted wood delivery rates for five stands (30206, 60314, 60513, 30715, and 30809; Appendix B) are three to fourteen times higher than the greatest observed rate in the western Cascades. Although the average wood delivery rate for the 19 selected stands in the McDonald-Dunn Forest was nearly three times greater than the mean of the western Cascades sites, these samples were not statistically different. A two-sample t-test, assuming unequal variances, did not indicate a conclusive difference because of the large variance in the McDonald-Dunn Forest wood delivery rates (Table 6).

Although sensitivity analysis of the wood delivery rate model was beyond the scope of this study, future efforts to modify or improve the delivery rate model should include such an analysis.

Table 6. Two sample t-test assuming unequal variances.

	Western Cascades	McDonald-Dunn Forest
Mean	2.34182	6.767856
Variance	0.289129	123.933
Observations	5	19
Pooled Variance	101.4523	
Hypothesized Mean Difference	0	
Df	22	
t Stat	-0.87426	
P(T<=t) one-tail	0.195711	
t Critical one-tail	1.717144	
P(T<=t) two-tail	0.391421	
t Critical two-tail	2.073875	

Source Area Identification

Source Area Ratios by Structure Type

This part of the study examined the relationship between stand age and the source area from which streams could potentially recruit wood. The source areas in this section are reported as a ratios of the area of potential wood delivery in square meters divided by the length of stream in meters in a stand. This ratio is referred to as the source area ratio.

A number of stream reaches did not yield expected results. For example, the source area ratio for the stream in a 136-year-old stand (stand number 60314, Appendix 2) was low in comparison to other stands of similar age classes (fig. 18). A visual inspection of digital orthophotos for this area revealed that the stream in this stand flows along the edge of a clear cut. Although there is vegetation along both sides of the stream, it is shorter than the vegetation in the rest of the stand. This stand was included in Figure

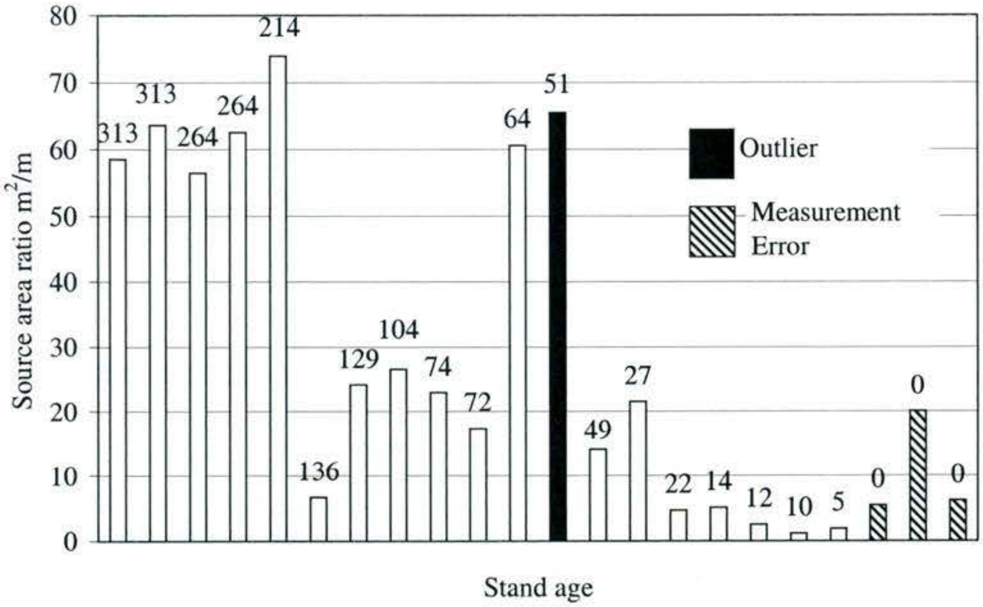

Figure 18. Source area ratios by stand age.

18 but was considered an outlier and was, therefore, excluded from the analyses in Figures 19 and 20.

The stream reach in the 51-year-old stand (stand number 20106, Appendix 2) had an unusually large source area for its age class (fig. 18). This is likely a combination of three factors. First, the stream reach in this stand is short relative to the other stream reaches in this analysis (57 meters long in comparison to the median stream length of 439 meters for all nineteen stands). Second, the headwaters of this stream were located within the stand. The potential wood delivery area therefore "wraps" around the head of the stream, thus increasing the area of potential tree recruitment per meter of stream length. Third, nearly 3% of the canopy height surface within the source area is greater than 30-meters tall (Appendix 3). This is a greater percentage of tall trees than some stands that are much older.

Three of the stands in Figure 18 are listed as having an age class of zero. The LIDAR data and visual inspection of digital orthophotographs indicate that at least some streamside vegetation is present. In these cases, the established ground plots are outside the riparian zones; consequently, this vegetation was not measured. These stands were excluded from the comparison of source area ratio to the mean height of the dominant and co-dominant trees and to stand age (figs. 19 and 20).

Despite these anomalies, the results of the source area analysis indicate that older stands have larger source areas. From an analysis of scatterplots, I detected a fairly strong relationship between the source area ratio and stand level forest structure metrics such as mean height of the dominant/co-dominant trees (fig. 19) and age class (fig. 20).

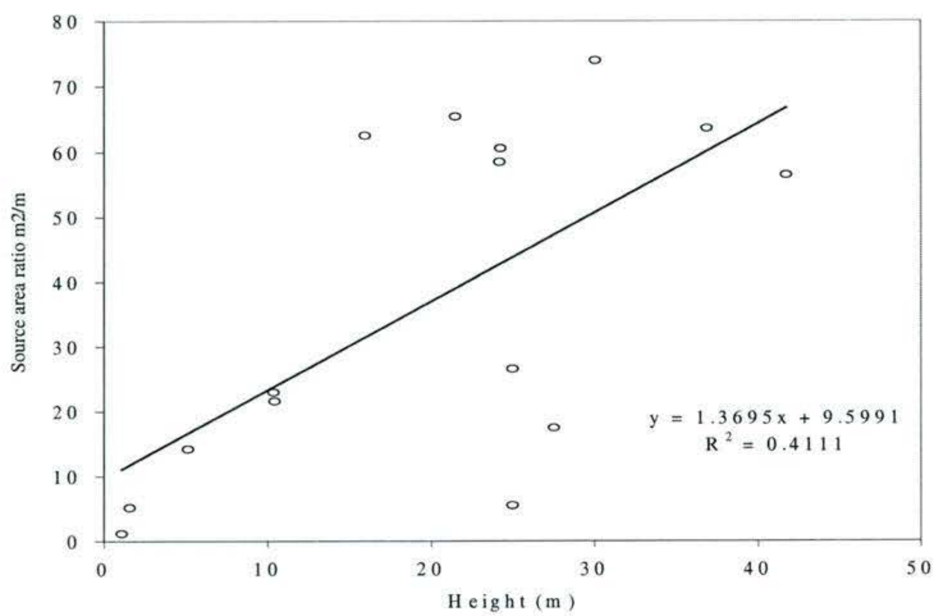

Figure 19. Ratio of source area to stream length vs. mean height of the dominant and co-dominant trees.

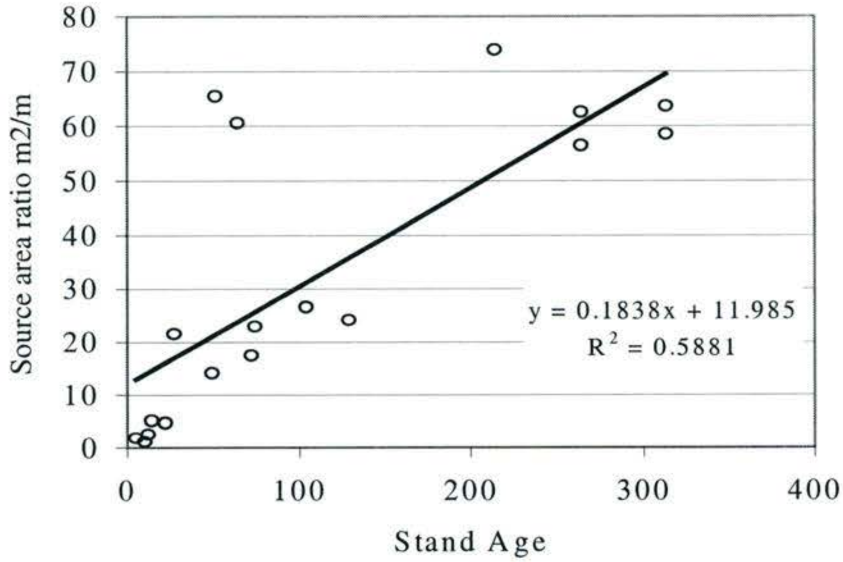

Figure 20. Ratio of source area to stream length vs. stand age.

Identification of Key Piece Source Areas

The objective of the key piece source area analysis was to identify the area in the streamside vegetation occupied by trees greater than five selected height classes. These classes were chosen to represent a continuum of potential wood delivery sizes within the streamside vegetation because the size of "key" wood pieces varies from stream to stream and location to location. Selecting grid cells above a predetermined height from the canopy height grid, allowed me to create a range of height class surfaces. A GIS was used to calculate the area of each of the five height class surfaces. The height classes used in this analysis were: 1) total canopy surface, 2) canopy surface greater than 10-meters in height, 2) canopy surface greater than 20-meters in height, 3) canopy surface greater than 30-meters in height, and 4) canopy surface greater than 40-meters in height. In the following section I describe myanalysis of the source area ratios of each height classe, the percentage of each height class with respect to the total canopy surface, and the potential of the study streams to recruit wood pieces of specified diameters.

Source Area Ratio and Key Piece Height Classes

Seven of the nineteen stands included in this part of the study had streams with source area ratios greater than $50m^2/m$ (fig. 21, Appendix 3). The remaining streams all had source area ratios less than $30m^2/m$. In five streams with source area ratios greater than $50m^2/m$, trees taller than 40 meters occupied at least $5m^2/m$ of the total surface area. For stands that had source area ratios of $30m^2/m$ or less, not more than $1m^2/m$ of the total surface was predicted to have trees over 40-meters tall. Only ten of the nineteen stands studied could potentially recruit wood taller than 40-meters.

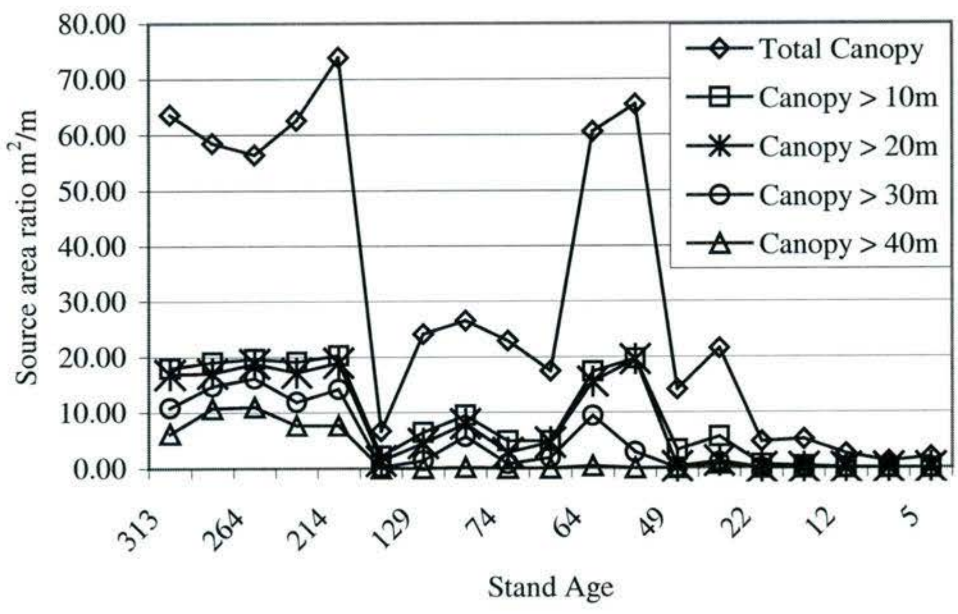

Figure 21. Source area ratio by canopy height interval.

Canopy Surface Height Class Area Percentages

The total amount of area with forest canopy that contributed wood to streams for all nineteen stands was 29 hectares. Only 3 hectares, or roughly 10% of the total area, included vegetation taller than 40 meters. Ninety-seven percent of that 3 hectares came from the five tallest stands. Streamside forests in young stands (0 to 80 years), mature stands (80 to 200 years), and old growth stands (greater than 200 years) were compared, revealing that 82% of the source area in the young forests was less than 10 meters tall (fig. 22). Approximately 70% of the source areas in the mature and old growth stands were occupied by vegetation less than 10 meters tall. On average, 14% of the canopy height surface in old growth stands was occupied by trees over 40 meters tall. None of the canopy area in the young or mature stands was occupied by vegetation over 40 meters

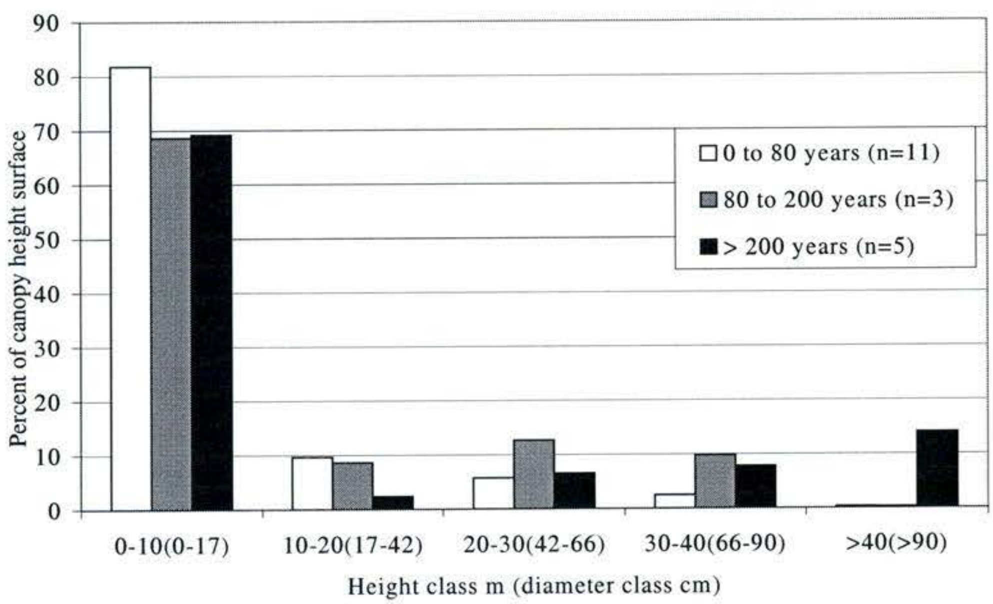

Figure 22. Average percentage of canopy height surface within a given height class interval by stand age.

tall, although 3% of stand 070803 (27 years old) did have vegetation over 40 meters tall.

Canopy Surface Height Class and Wood Diameter

While the height, or length, of a piece of wood delivered to a stream is important, length is not the only factor that determines the function of wood in streams. The diameter of a wood piece is also an important indicator of the relative stability of that piece in a stream. McHenry et al. (1998) found that logs greater than 80 centimeters in diameter did not change position in large floods. Benke and Wallace (1990) reported similar findings for wood pieces greater than 40 centimeters in diameter. I used a height/DBH least squares regression to derive a function for which, given a known height, an approximate DBH could be calculated. I then used this function to calculate approximate DBH for each of the four canopy surface height classes (fig. 23, Appendix 4).

Only five of the 19 stands in this analysis could potentially deliver wood greater than 90 centimeters in diameter to the streams (fig. 23). On average, trees in old growth stands with DBH greater than 90 centimeters were predicted to occupy 14% of the source area (fig. 22). Only five of the nineteen streams modeled did not have the potential to recruit wood from the 66-centimeter diameter class. In stands over 200-years old, 28% of the predicted source area was occupied by trees greater than 42 centimeters in diameter, whereas this diameter class was predicted to occupy only 23% and 9% of the source area for mature and young stands respectively (fig. 24).

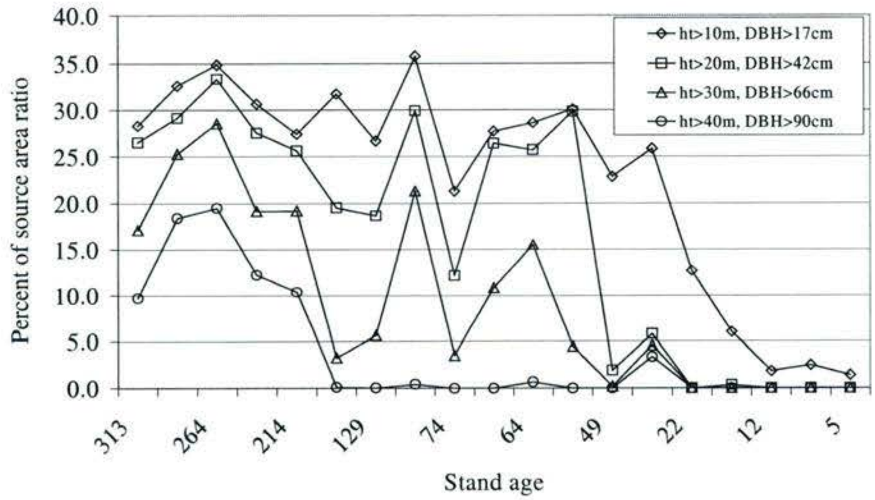

Figure 23. Percent of source area ratio, in individual stands greater than a designated height or diameter class.

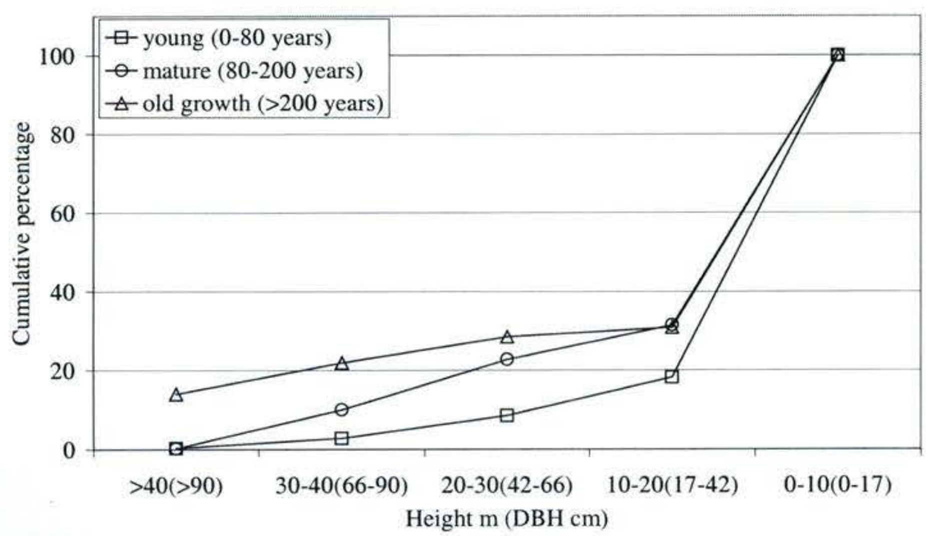

Figure 24. Cumulative percentage of source area occupied by trees of a given height or diameter class.

CHAPTER V

SUMMARY OF FINDINGS AND CONCLUSIONS

Overview

In this study, I used a new technology to assess forest structure characteristics important to the function of stream ecosystems. The wood delivery rate model I developed predicted cumulative frequency distribution curves similar to those found in other studies. The predicted delivery rates were highly variable among stands of similar structure characteristics and may overestimate the rate of wood delivery in some cases. The source area model was positively correlated to stand level ground data, and the key piece source area model determined the area of the streamside forests occupied by trees of selected height and diameter classes. In this chapter, I discuss the performance and results of these models and identify areas for potential future research.

The Rate of Wood Delivery

The cumulative frequency distribution curves in this study are consistent with those obtained in other studies for stands with similar structure characteristics (McDade 1988). The wood delivery rate model, on the other hand, seems to overestimate the delivery of wood in a number of stands. In some cases, the rate of wood delivery to streams in the McDonald Forest was eight to twelve times greater than values for the western Cascades sites. The average wood delivery rate of all nineteen stands was nearly three times greater than the largest rate for the western Cascades sites. The estimates presented in this study could be representative of true wood delivery rates in the McDonald-Dunn Forest. The variation in rate values might be indicative of different species in different environmental conditions in different ecoregions. Although there are currently no field data to substantiate my results, I suspect that the differences in the wood delivery rates predicted by this model and the wood delivery rates observed in the western Cascades are the result of modifications of the currently used models of wood delivery. These modifications and their influences are described in detail below. It should be noted that future efforts to model the wood delivery rate would benefit from the use of field data for verification of model results.

Limitations in the types of data that LIDAR can provide forced the modification of the standard delivery models. Recall that I was not able to discover a relationship between any LIDAR derived metric and the number of trees per unit area. If a correlation could be found between a LIDAR metric and stem count, then a probabilistic model could be constructed based upon the currently accepted conceptual framework. A review of the literature identified no studies examining a relationship between LIDAR and the number of trees per unit area. In this study, I used only one search radius to derive the basal area density metric, *D*. Further analysis would benefit from varying this search radius, for example, creating a point density grid equal in resolution to that of the ground plot data. It is possible that the search radius was too large to generate numbers that correlate well with ground plot data collected for a smaller spatial extent (recall that the radius of the ground plots was roughly 6.1 meters). It is also possible that the number of LIDAR points per unit area reflects stand height better than stand density. The correlation between the number of non-first return points and the StandPoly basal area may reflect the fact that taller stands have greater basal area per unit area. Also, stands with tall vegetation have more reflective surfaces than stands with shorter vegetation and can therefore produce a greater number of returns. Although I examined the relationship between non-first return point density and basal area in this study, a correlation was found between basal area and canopy height in other studies (Lefsky et al.1999, Means et al. 1999) indicating that basal area is also a function of height.

Had I been able to find a relationship between a LIDAR metric and the number of trees per unit area, I could have used the ORGANON mortality values to calculate a rough approximation of the probability of tree fall. In the model presented in this study, mortality is used to estimate the rate of fall. Standard wood delivery rate models use a unitless probability of fall. Further, the use of a universally applied mortality value limits the specificity of the rate delivery model. The wood delivery rate values, *Wd*, are simply a fraction of one uniform mortality value despite the fact that mortality is site specific and varies with age. Attempts to incorporate variable mortality values by age class in the wood delivery model were not successful. One further complication was that Van Sickle and Gregory (1990) found that the use of mortality in their wood delivery model resulted in the underestimation of the observed rate of tree fall by a factor of seven, although they did assume uniform probability of tree fall across all age classes. A variable estimate of mortality combined in a model with stem counts for density might produce better results.

The mortality model used in this study, ORGANON, would still have limitations under this scenario. First, ORGANON does not estimate mortality for any trees greater than 110-centimeters in diameter. Second, because ORGANON is calibrated for second growth stands, its application to forests without human disturbance is limited. Third, the McDonald Forest has been extensively studied and the data required for the ORGANON model were readily available. The measurements required to run ORGANON are numerous and might preclude utilization in areas where stand data are not readily available. The optimal solution for acquiring measures for the probability of fall for standard wood delivery models would be to collect field data on tree fall. For areas and situations where this is not possible, mortality estimates from models such as ORGANON may suffice.

Source Area Analysis

The source area for potential wood delivery is derived from a trigonometric function that calculates the probability of a tree falling in a stream based on the perpendicular distance to the stream and the height and distance of the tree from the stream (Equation 2). The source area ratio is a means of standardizing the source areas of forest stands surrounding streams of different lengths. The source area ratio predictions in this paper correlate to forest structure metrics and are consistent with the results that would be predicted by the widely agreed upon conceptual model regarding tree delivery to streams (McDade 1988, McDade et al. 1990, Van Sickle and Gregory 1990). The source area ratio metric is a useful diagnostic tool in the assessment of the potential of streamside forests to deliver wood to streams. The ratios presented in this paper assessed this potential at spatial extents encompassing several hundred meters. Although strong relationships were observed between various forest structure metrics and the ratio of source area to stream length, the resolution of the stand level data was too coarse to thoroughly test the accuracy of the finer resolution LIDAR derived source area boundaries. Given that a positive correlation was observed between the LIDAR data and fine resolution forest structure data (i.e., the ground plot data), it is reasonable to expect that source area ratios may be predicted on a scale of tens of meters. Unfortunately, few ground plots were located within the predicted source areas, and this level of accuracy could not be tested.

The source area ratio used in this study was a meaningful method of evaluating the potential of the streamside vegetation to deliver wood to a stream. Although, to the best of my knowledge, this metric has not been applied in any ground based study of streamside forest structure, this descriptive statistic may be a useful diagnostic tool to assess and quantify differneces in the potential for wood delivery between stands with different structures in the same locality or between stands in different ecoregions. The combination of LIDAR derived canopy surfaces and the source area ratio should provide resource managers with a tool to quantify differences in wood delivery potential for streamside forests over very large areas.

Key Piece Source Area Analysis

Another potentially important contribution that the LIDAR technology provides to resource managers is the identification of key piece source areas. While there is not a generally agreed upon definition of what constitutes a key piece, it may be useful to know whether or not a streamside forest can deliver wood of a certain length or diameter class to a stream. In fact, unless specific information is available regarding the size of key pieces in a stream, evaluation of canopy height classes may be a better approach for characterizing streamside vegetation than targeting a single height class or threshold. Of the nineteen stands evaluated in this study, only nine had the potential to deliver trees greater than 90 centimeters in diameter to a stream. Of these nine stands, only four had trees over 40 meters tall in at least 10% of the source area. Ninety percent of the source area for three of the young stands was less than 10 meters tall. This information, combined with knowledge of the local stream conditions, can inform resource managers regarding the wood delivery potential of streamside vegetation over large spatial extents.

Although this model provided useful information about forest structure characteristics, there are several opportunities to refine and improve upon the methods used in this study. For example, it is unlikely that a 40-meter tall tree with a 90-centimeter DBH located 35-meters from the active channel will deliver a wood of that diameter to the stream. If the tree is able to reach the stream, the top of the tree will fall in the stream while the large part of the bole will remain near the point of origin (McDade 1988). Therefore, in this study, the estimated source area containing trees with diameters larger than 40-centimeters is larger than the area that can actually deliver wood of that diameter to the stream. Although it was beyond the scope of this study, it may be possible to modify the key piece source area calculations such that only those trees capable of delivering the diameter class of interest to the center of the channel would be included in the area estimates. Further, it may be possible to use the LIDAR data to estimate the maximum and minimum diameter of the part of the tree that will reach the stream upon delivery (fig. 9).

It may also be possible to use LIDAR to derive channel characteristics, such as constraint, slope, and stream width, that affect the behavior of wood pieces once they are in the stream. This physiographic information, combined with detailed forest structure information, has not historically been available over such large areas and would be very useful to resource managers.

Summary and Conclusion

In this study, I used LIDAR data characterize the height of the vegetation in the McDonald-Dunn Forest. I also found a relationship between the density of non-first return LIDAR points and the stand average basal area. As stated previously, few studies using small footprint LIDAR data have reported a relationship between any LIDAR metric and basal area. In studies that have found relationships between basal area and LIDAR data, height, not point density, was the related variable.

Most studies using LIDAR have been designed to test the accuracy of this technology's ability the measure ground elevation and forest height. Few studies, to date, have used LIDAR data for modeling exercises. In this study, I used LIDAR data to model the rate of wood delivery to streams, the source areas for potential wood delivery, and the percentage of source area capable of delivering "key" pieces of wood to the stream. The cumulative frequency curves obtained from the wood delivery rate model were similar to those reported in other studies. There was a correlation between the size of the source area ratios for the streamside forests and stand age, as well as the stand averages for the mean height of the dominant and co-dominant trees. The key piece analysis also produced results consistent with those that would be predicted by the prevalent conceptual model regarding streamside forests and the delivery of wood to streams.

Recent advances in LIDAR data acquisition and computer processing technology have increased the quality and accessibility of these data. I expect that the number and type of applications that use LIDAR data will increase as a result. This technology has great promise for the study of terrestrial ecosystems, including streams and their riparian areas. The source area identification portion of this study is relevant to, and could easily be applied to, watershed assessment activities currently underway in the state of Oregon. LIDAR also has the potential to aid in the study of stream shading and litterfall. Digital Elevation Models (DEMs) generated as a result of work in this study also have great potential for practical applications such as evaluation of channel slope, channel constraint, and possibly the location of floodplains and terraces.

This study is unique and important for several reasons. First, it is one of the few studies in which LIDAR data have been used to model ecosystem behavior. This will undoubtedly change as LIDAR data become more widely accessible. Second, this study demonstrated that LIDAR data could be used as a diagnostic tool over large spatial extents. Streamside forests are important indicators of instream conditions so the ability to model the source area for wood delivery over such large areas is a significant management tool. These advantages may lead to more widespread use of LIDAR data for the study and management of natural resources.

APPENDIX A

TREE SPECIES IN THE MCDONALD-DUNN FOREST

Scientific Name	Common Name
Abies amabilis	Pacific silver fir
Abies grandis	Grand fir
Abies pinsapo	Spanish fir
Abies procera	Noble fir
Acer macrophullum	Bigleaf maple
Aesculus hippocastanum	Horse chestnut
Alnus rubra	Red alder
Araucaria excelsa	Norfork Island pine
Arbutus menziesii	Pacific madrone
Calocedrus decurrens	Incense cedar
Castanea dentata	American chestnut
Chamaecyparis lawsoniana	Port Orford cedar
Cornus nuttallii	Pacific dogwood
Fraxinus latifolia	Oregon ash
Picea englemannii	Englemann spruce
Pinus contorta	Lodgepole pine
Pinus ponderosa	Ponderosa pine
Pinus sylvestris	Scot's pine
Populus trichocarpa	Black cottonwood
Prunus avium	Mazzard cherry
Prunus emarginata	Bitter cherry

Scientific Name	Common Name
Prunus species	Cherry
Pseudotsuga menziesii	Douglas fir
Pyrus malus	Apple
Quercus garryana	Oregon white oak
Robinia psueudo-acacia	Black locust
Taxus brevifolia	Pacific yew
Thuja plicata	Western red cedar
Tsuga heterophylla	Western hemlock

APPENDIX B

WOOD DELIVERY RATE COMPARISON

BY STAND

Stand number/location	Age	Loading	Stream length (m)
ws-91[1]	?	3.1513	170
ws-21[1]	?	2.4462	146
mack creek1[1]	?	2.3905	332
upper lookout1[1]	?	1.9718	483
lower lookout1[1]	?	1.7493	350
20604[2]	313	5.161019	567
30206[2]	313	26.56106	142
60210[2]	264	1.706221	1602
60605[2]	264	2.230019	437
50904[2]	214	1.478324	546
60314[2]	136	14.09772	623
60513[2]	129	43.4967	483
30715[2]	104	12.20206	160
30823[2]	74	3.043104	508
30809[2]	72	9.497894	160
20406[2]	64	1.112088	219
20106[2]	51	3.58564	56
30505[2]	49	1.583257	351
70803[2]	27	0.207244	1043
60311[2]	22	0.86519	623
60609[2]	14	1.546211	143
60707[2]	12	0.081835	1062
30507[2]	10	0.118169	723
60710[2]	5	0.015505	439

1. Western Cascades.
2. McDonald-Dunn Forest.

APPENDIX C

SOURCE AREA PER STREAM LENGTH BY HEIGHT INTERVAL

Stand number	Stand age	Total canopy	> 10 meters	> 20 meters	> 30 meters	> 40 meters
20604	313	63.64	18.02	16.87	10.89	6.18
30206	313	58.51	19.10	17.05	14.78	10.76
60210	264	56.47	19.71	18.83	16.13	11.00
60605	264	62.56	19.18	17.23	11.97	7.66
50904	214	73.94	20.27	18.95	14.18	7.67
60314	136	6.70	2.13	1.31	0.22	0.01
60513	129	24.14	6.43	4.50	1.36	0.01
30715	104	26.57	9.50	7.96	5.66	0.12
30823	74	22.96	4.88	2.80	0.80	0.00
30809	72	17.47	4.85	4.61	1.89	0.00
20406	64	60.59	17.35	15.57	9.39	0.40
20106	51	65.47	19.72	19.55	2.90	0.00
30505	49	14.18	3.24	0.26	0.03	0.00
70803	27	21.58	5.58	1.25	0.98	0.71
60311	22	4.72	0.60	0.00	0.00	0.00
60609	14	5.15	0.31	0.02	0.00	0.00
60707	12	2.55	0.05	0.00	0.00	0.00
30507	10	1.18	0.03	0.00	0.00	0.00
60710	5	1.91	0.03	0.00	0.00	0.00

APPENDIX D

PERCENT OF TOTAL SOURCE AREA RATIO
BY VEGETATION HEIGHT
AND DIAMETER CLASS

Stand number	Stand age	DBH >10 meters[1] (17 cm[2])	DBH >20 meters[1] (42 cm[2])	DBH >30 meters[1] (66 cm[2])	DBH >40 meters[1] (90 cm[2])
20604	313	28.3	26.5	17.1	9.7
30206	313	32.6	29.1	25.3	18.4
60210	264	34.9	33.4	28.6	19.5
60605	264	30.7	27.5	19.1	12.2
50904	214	27.4	25.6	19.2	10.4
60314	136	31.8	19.5	3.2	0.1
60513	129	26.7	18.7	5.6	0.0
30715	104	35.8	29.9	21.3	0.4
30823	74	21.3	12.2	3.5	0.0
30809	72	27.7	26.4	10.8	0.0
20406	64	28.6	25.7	15.5	0.7
20106	51	30.1	29.9	4.4	0.0
30505	49	22.9	1.9	0.2	0.0
70803	27	25.8	5.8	4.5	3.3
60311	22	12.7	0.0	0.0	0.0
60609	14	6.0	0.3	0.0	0.0
60707	12	1.8	0.0	0.0	0.0
30507	10	2.4	0.0	0.0	0.0
60710	5	1.4	0.0	0.0	0.0

1. Ratio of source area divided by stream length.
2. Approximate diameter at breast height based (DBH) based on DBH vs. height regression of 84 trees without regard to species, snags included ($R^2 = 0.9031$).

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