

Modeling the Delivery of Large Wood to Streams with Light Detection and Ranging (LIDAR) Data¹

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Abstract

A remote sensing technology called Light Detection and Ranging (LIDAR) was used to assess the characteristics of streamside forest structure and predict the delivery of wood to over 55 stream kilometers in a 28-square kilometer study area. The LIDAR data correlated with canopy height ($R^2 = 0.65$) and stand average basal area ($R^2 = 0.45$). The model predicted that 83 percent of wood delivered to streams originated within 20 meters of the channel and that 95 percent came from within 30 meters of the channel.

Introduction

Modeling the rate of large wood delivery to streams over large areas is not practical because the forest structure information required is frequently unavailable. Recent advances in remote sensing technology can now provide resource managers with the ability to characterize the structure of streamside vegetation and model the loading of wood to streams. The objective of this study was to use Light Detection and Ranging (LIDAR) data to model the delivery of wood to streams within the study area. This was accomplished by first transforming raw point elevation measurements to gridded surfaces. These surfaces were then compared to ground-based forest structure information in order to determine if the LIDAR data accurately characterized forest structure. The LIDAR data was used for two of three variables needed in a wood delivery model.

Large wood is an integral part of many stream ecosystems in the Pacific Northwest. A wide variety of organisms have life histories associated with wood located in the active channel. It is a substrate for photosynthetic organisms such as green algae, cyanobacteria, diatoms, liverworts, mosses, and trees (Harmon and others 1986). Large woody debris jams often create low velocity lateral habitats, which provide resources and refugia for juvenile fish (Moore and Gregory 1989). Streams with large pieces of wood in the active channel better retain dissolved and particulate carbon than those without large wood (Bilby 1981, Bilby and Likens 1980). In addition to the chemical and biological interactions mentioned above, large wood is a key factor in determining the geomorphic response of a stream to the

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physical disturbances that shape the channel. There is a positive relationship between pool volume and the amount of large wood in the channel (Carlson and others 1990). Energy dissipation of streamflow caused by the presence of wood dams causes the formation of upstream gravel bars (Lisle 1986).

Most large wood delivered to streams originates in the streamside vegetation. In fact approximately 80 percent of the wood in western Oregon Cascades streams was delivered from within 20 m of the active channel (McDade and others 1989, Van Sickle and Gregory 1990). Murphy and Koski (1989) reached similar conclusions for some Alaskan streams, but the distance of origin was less than that reported in the previously mentioned studies. Difference in tree height is the likely cause of this disparity.

Timber harvesting adjacent to streams has, in many cases depleted the source of large wood pieces. Consequently many of these streams now have fewer large pieces than streams with undisturbed riparian stands (Bilby and Ward 1991). In some cases the harvested stands supply a greater number of wood pieces. These pieces, however, are smaller and highly mobile compared to downed wood in the streams of old-growth forests (Evans and others 1993, McHenry and others 1998).

Estimating the delivery of wood to streams by means described in traditional methods requires detailed information on stand structure (i.e., the height of every tree and its distance from the stream) (Minor 1997, Van Sickle and Gregory 1990). Alternatively, loading may be estimated by surveying a stream over a period of years and recording wood inputs (McDade and others 1989). This information is not readily available for many forested streams. In cases where the required information is available, it is often limited to very small spatial extents. This study seeks to determine whether a remote sensing technology called Light Detection and Ranging (LIDAR) can provide information necessary to predict wood delivery to streams over a wider spatial extent than is practical with ground-based methods.

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 subcoregion 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 and others 1997).

The McDonald Forest comprises approximately 48 square kilometers and within its boundaries are more than 30 different tree species, including *Abies grandis*, *Pseudotsuga menziesi*, and *Quercus garryana*. The majority of stands in the McDonald-Dunn Forest are either coniferous or a coniferous/hardwood mixture. Only 13 of 179 stands are greater than 200 years old, and the median stand age is roughly 60 years. The LIDAR flight line and the 28 square kilometer study area include portions of the McDonald-Dunn Forest as well as some privately owned land. Approximately 55-kilometers of stream occur within the study area, most of which are first-order and second-order streams. The largest stream, Soap Creek, is fourth-order and lies on the eastern boundary of the study area.



Figure 1—The study area in the McDonald-Dunn State Research Forest near Corvallis, Oregon.

LIDAR Technology

LIDAR is a remote sensing technology capable of characterizing a variety of vegetation structure metrics. Studies have shown LIDAR capable of accurately measuring mean canopy height (Magnussen and Boudevyn 1998, Naesset 1997), timber volume (Naesset 1997, Nilsson 1996), basal area (Lefsky and others 1997, Means and others 1999), and biomass (Lefsky and others 1999, Nelson 1997). LIDAR is also used for characterizing topography (Garvin 1996). LIDAR technology is based upon the general principle that a portion(s) of an emitted laser pulse will reflect to its source. Because the travel rate of a pulse is constant (i.e., the speed of light), concurrently emitted pulses with different return times must have differing travel distances. Portions of these pulses reflect back to a sensor on the airplane. Because the position and orientation of the sensor is known for each emitted pulse, every returning signal has a unique set of three-dimensional coordinates.

The LIDAR unit used for this study is a scanning system. Approximately 15,000 pulses per second were emitted in a sinusoidal pattern (*fig. 2*) from an airplane at an altitude of 2,000 m. The footprint, or size of the laser pulse upon reaching the earth, was approximately 0.5 m in diameter. The spacing between pulses over bare earth was approximately 6 m, and the width of each scan was approximately 4,500 m. Because the same pulse can generate several returning signals, the distance between points, in the horizontal plane is often less than 6 m. Multiple returns are generated when some portion of a laser pulse is intercepted by a reflective surface and returned to the airborne sensor. The uninterrupted portion of the pulse can generate additional return signals if reflective surfaces are encountered.

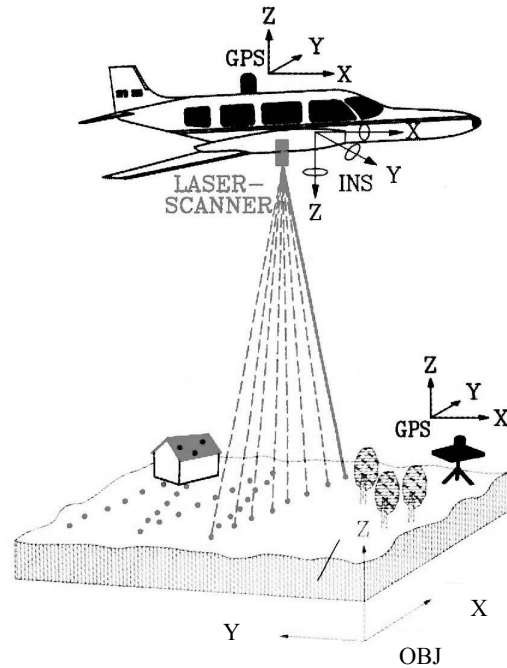


Figure 2—Airborne laser scanner.

Methods

The objective of this study is to use LIDAR data to model the delivery of wood to streams within the study area. To accomplish this, LIDAR was first transformed to gridded surfaces representing the ground and canopy surface. These surfaces were then compared to ground-based forest structure information in order to determine if LIDAR accurately characterized forest structure. LIDAR was then used to derive two of three variables in a probabilistic wood delivery model.

Airborne Data Collection

Airborne data were collected in October 1998. The number of returning signals was highly variable. A single returning signal was most common. Second and third returns were also very common but respectively less frequent. Fourth or fifth returns were captured in rare instances.

Number of return signals for study area:

Signal return order	No. of signals
1 st	992,208
2 nd	200,611
3 rd	27,784
4 th	2,068
5 th	89

One explanation for the decreasing number of signals with return order is technological. There was a limit on the speed at which return signals were assimilated. The scanning equipment is capable of capturing only one signal every 0.2 nanoseconds. Once a signal was recorded, additional capture was precluded for a time that equated to approximately 5 m of travel distance. Therefore, only vegetation greater than 5 m in height can generate multiple returns from a single pulse.

Ground Data Collection

Two ground-based data sets were used in this study. The first was a set of ground plots, and the second was a stand-level aggregation of ground plot data. The ground plot data used in this study were collected as part of an ongoing forest inventory at the McDonald-Dunn Forest. Data collection occurred between July 1997 and February 1998. All sample plots have a variable radius. Tree size and distance from a reference center point determine the radius of these plots. All trees equal to or greater than 20-centimeters in diameter at breast height (DBH) and located within 6.1 m of the plot center were automatically included in the sample. Large trees located beyond the 6.1 meter threshold were included in the sample if the DBH was sufficiently large. Either prisms or relaskops were used to identify trees for inclusion in the sample (Oregon State University 1999). Among the recorded measurements were DBH and tree heights. Tree heights were recorded for all living and dead trees within the plot.

The stand data used in this study were derived from the ground plot data and digital orthophotographs. Ground plots with similar characteristics (e.g., height, age) were grouped together and stand boundaries were digitized around those clusters based on the features observed in the photographs. These groupings contain the attribute summaries of information collected at the plot level including, but not limited to, basal area. Since not every ground plot was sampled every year, where current stand information was missing, 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. The return interval for sampling an individual ground plot is typically less than 10 years but can vary from 1 to 15 years.

Airborne Data Transformation

Each LIDAR return signal contains a unique three-dimensional coordinate. Ground elevation return signals were separated from return signals generated by the vegetation via a proprietary processing algorithm (Renslow, pers. comm.). Generally described, this process works as follows: 1) last return signals are separated from non-first return signals, 2) a Triangulated Irregular Network surface (TIN) is created from these points, 3) points obviously above the ground were removed on the basis of visual inspection, 4) the process is repeated until all points above the ground were removed. Digital orthophoto stereo pairs were used to verify the categorization of these signals. Triangulated Irregular Network surfaces (TINs) were computed from the x, y, and z coordinates of the ground and first return LIDAR point files. A TIN is a set of non-overlapping, adjacent triangles intersecting the points with three-dimensional coordinates (*fig. 3*). The TINs in this study were used to generate gridded surfaces called lattices. Lattices are similar to TINs in that the mesh points contain elevation information. The spacing and resolution of these two data models, however, is very different. The mesh points of a TIN contain information from the

original point files. Mesh points do not exist between the original raw point locations. In the conversion from TIN to lattice, mesh points are created at regular intervals. Interpolation is used to calculate the mesh point elevation where the distance between original points is greater than the resolution of the created lattice. The principle advantage of a lattice over a TIN is that calculations can be performed on lattices, whereas this capability is not available for TINs. After creation of the lattices, the ground elevation surface was subtracted from the first return elevation surface. The result of this calculation was a new lattice for which each cell contained a canopy height value. The cell size for each of these surfaces is approximately 1.5 m.

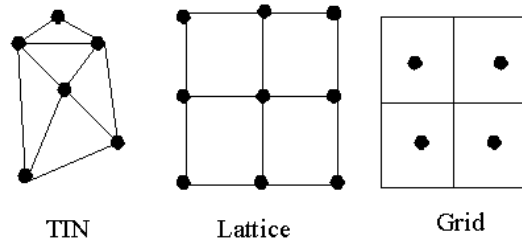


Figure 3—Data model structure.

Thirty-two ground plots in a 929-hectare section of the southwestern portion of the study area were selected and compared to the canopy height grid. This section of the study area was selected because it contained the full range of forest structure characteristics, from very old to very young. Ground plots located adjacent to roads or clear cuts were excluded from the analysis because of uncertainties regarding the geographic location of the plot's GIS data set. The heights of individual trees in each ground plot were averaged, and the values were plotted against the laser-derived canopy height (*fig. 4*).

The rate of large wood delivery, to streams, predicted by the model in this study was compared to wood delivery rates observed in the Western Cascades ecoregion (Lienkaemper and Swanson 1987). Five hundred-year-old conifer forests surrounded the streams in the Cascade study. The Cascade sites are higher in elevation and receive more precipitation than the McDonald-Dunn Forest. Differing environmental conditions may influence the result of any comparison. However, these forests (especially the older forests) have structural similarities that may make a comparison useful. Many of the tree species such as Douglas-fir (*Pseudotsuga menziesii*) are common to both study areas. Trees in the Cascade sites are likely to be larger than trees in the McDonald Forest, resulting in larger source areas.

Lienkaemper and Swanson (1986) recorded the number of trees entering five streams over a period of 7 to 9 years. From this information I calculated the number of trees entering the stream per hectare of source area over a 5-year period. I assume that all the trees entering the Cascade streams had origins less than 35 m from the channel (McDade and others 1989). This may be a conservative estimate considering that McDade (1988) observed evidence of trees falling into streams from distances greater than 60 m.

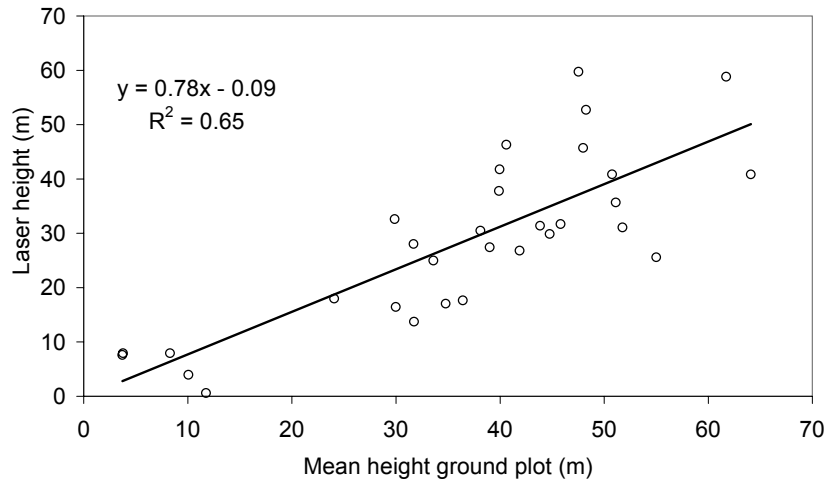


Figure 4—Ground plot height vs. laser height.

The Wood Model

Unlike most wood delivery models, data used in this study are not tree specific. LIDAR data do not provide information about individual trees. Instead, LIDAR defines a surface(s) that approximates tree height. The resolution of each of these surfaces is approximately 1.5 m. Therefore, the model in this study describes the probability that a given cell will deliver wood to a stream. Delivery of wood to streams is characterized by the equation:

$$W_d = P_s D R_f \quad (1)$$

The delivery of wood to a stream is represented by (W_d) and is expressed as the number of trees falling in a stream per hectare over a 5-year period. P_s equals the probability that a tree will fall in a stream given the height of the tree and its distance from the stream. D is a relative measure of tree density and is unit-less. R_f , the rate of tree fall, equals the average number of trees that fell per hectare over a 5-year period.

Probability of Falling in a Stream

The probability of a tree falling in a stream is a function of tree height and distance from the stream. It is assumed that the direction of tree fall is random. The probability of a given grid cell contributing wood to a stream (P_s) is based on the trigonometric function:

$$P_s = (\arccosine (z / h)) / 180 \quad (2)$$

in which the variable z equals the perpendicular distance to the stream and h equals the height of a given cell. A geographic information system (GIS) was used to obtain both variables for this equation. Using GIS, a grid was created to compute the shortest perpendicular distance to a given segment of the stream network. It was not possible to calculate the distance to two streams. Therefore, it is necessary to assume that when a tree falls it always falls in the nearest stream. A visual assessment of the study area showed that only a small number of canopy height grid cells could

potentially contribute to two streams (i.e., near confluences); thus, this was not expected to affect the model results.

Density

Density in the wood delivery models (Minor 1997, Van Sickle and Gregory 1990) is the number of trees per unit area. In this study an alternative approach was taken because of the inability to discern individual trees with this LIDAR data set. I hypothesized that a relationship between the density of LIDAR return signals, per unit area, and forest density might exist.

Because first return signals are so numerous (one flight line of approximately 6-miles in length contained more than 5-million first return points) and because even clearcuts generate first returns, these points were eliminated from the density analysis. A grid was created to represent the density of non-first return points per unit area. The point density computation counted every LIDAR point within a 0.4-hectare area (equivalent to a circle 36m in diameter). The results of this analysis were converted to points per hectare that were then compared to stand averages for basal area (*fig. 5*). Basal area was used here as a relative measure of density. I then used the relationship observed in *figure 5* and equation 3 to assign the stand average basal area to every grid cell in the study area.

$$\text{Basal Area} = (\ln (\text{dnst-grd} / 36.594)) / 0.0248 \tag{3}$$

This equation yielded the basal area in square meters per hectare. The fraction of basal area (*BA*) per cell was calculated as:

$$D = (BA \text{ m}^2 / \text{ha}) * (1 \text{ ha} / 10,000 \text{ m}^2) \tag{4}$$

This value was used as density in the total loading calculation.

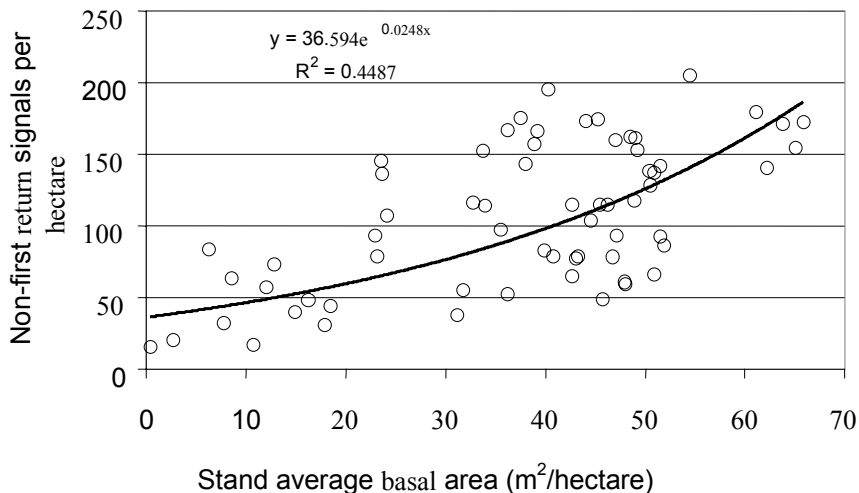


Figure 5—Basal area vs. non-first return signals.

Rate of Fall

No direct estimate of tree fall was available for this study. Van Sickle and Gregory (1990) used mortality as a rough approximation of the probability of tree fall. ORGANON, a model designed to predict the growth of individual trees in a stand, is also capable of estimating mortality for all trees less than 109-centimeters in diameter. I assume for this study that the probability of tree fall equals mortality, thus no trees were snags after mortality. ORGANON and input files for every stand in the McDonald Forest are available at the Web site: <http://www.cof.orst.edu/resfor/mcdonald/purpose.sht>.

The data from 30 stands within the study area were randomly selected as input files for ORGANON. The model is designed to run with greater than 50 trees per stand. Twenty of the initial 30 stands did not meet this requirement and were discarded. Growth over a 25-year period was calculated for each of the remaining input files:

Stand No.	Mortality ¹
61103	56.049
60802	56.148
60513	81.259
60811	111.901
70501	133.457
60402	198.346
60403	209.580
51101	259.951
51001	325.062
60901	334.272
Average/25 yrs.	176.603
<u>Average/5yrs.</u>	<u>35.321</u>

¹ Number of trees/hectare for 25-year period.

The average mortality of all 10 stands was calculated for a 5-year period and applied uniformly across the study area as an approximation for the rate of fall (R_f). A uniform R_f was used in the wood delivery model, though it is recognized that mortality is highly variable and site specific. The 5-year time period was chosen because the results of this model will be compared to data collected in the western Cascade Mountains over a similar time interval.

Results

The cumulative frequency of wood delivered to streams, as a function of distance from the stream, is a value commonly reported in wood delivery studies (McDade 1988, McDade and others 1989, Minor 1997, Van Sickle and Gregory 1990). This study found that 83 percent of the predicted wood delivered to streams came from within 20 m of the channel, and 95 percent came from within 30 m of the

channel (*fig. 6*). Murphy and Koski (1989) found that 99 percent of the wood in southeast Alaska came from within 30 m of the channel. McDade (1988) reported that roughly 90 percent of wood delivery to streams in 29 old growth forests in Oregon and Washington originated within 30 m of the stream. It is not surprising that the cumulative frequency distribution curves presented in this study report greater cumulative percentages from shorter distances than those reported in McDade (1988) because the stands in the McDonald-Dunn Forest, on average, are much shorter. Only thirteen of 179 stands studied were greater than 200 years old. The median age of the stands within the study area was approximately 60 years.

The model in this study also predicted the rate at which large wood enters streams. These predictions were compared to values reported by Lienkaemper and Swanson (1987). Predictions from the McDonald-Dunn Forest closely match those of the H.J. Andrews Research Forest (*table 1*). The values for Lookout Creek may be lower than expected due to the presence of a road in the source area. The value reported for the McDonald-Dunn Forest is the mean of the entire study area. Further investigation of loading rates from specific stream segments and from various stand structure types is needed.

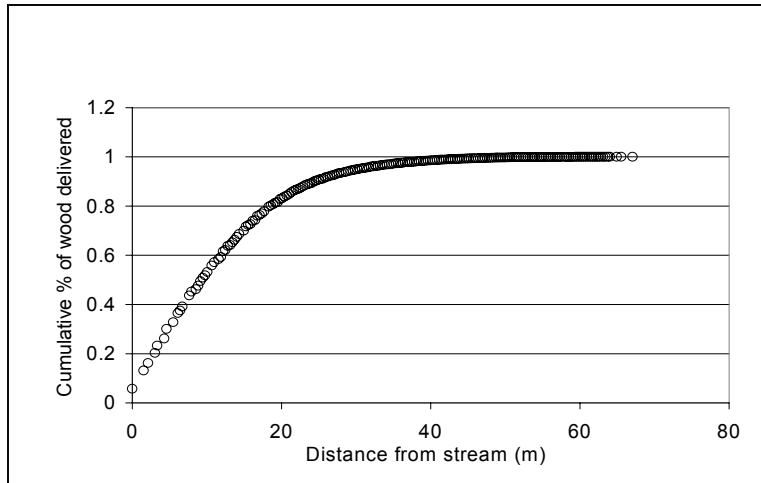


Figure 6—Wood recruitment as a function of distance from the stream for the entire study area.

Tables 1—Loading Rate Comparison between H.J. Andrews Research Forest and McDonald-Dunn Forest.

Location	No. of years	Reach length	Width ¹	Area (ha)	No. of trees added	Trees/ha	Trees/ha 5-yr. period
ws-9 ²	8	170	70	1.19	6	5.0420	3.1513
ws-2 ²	8	146	70	1.022	4	3.9139	2.4462
Mack Creek ²	9	332	70	2.324	10	4.3029	2.3905
Upper Lookout ²	9	483	70	3.381	12	3.5492	1.9718
Lower Lookout ²	7	350	70	2.45	6	2.4490	1.7493
McDonald-Dunn Forest ³							3.0035

¹ Assumed source-area based from McDade and others 1989.

² Numbers derived from values reported in Lienkaemper and Swanson 1986.

³ Average for entire study area.

Discussion

The ORGANON mortality values used in this study were not spatially explicit. ORGANON calculated mortality values for a wide range of age classes. With the aid of height regression equations, mortality could be applied variably across the landscape based on the canopy height observed in each grid cell. This approach might be warranted because Headman and others (1996) found that loading rates varied with stand age, indicating that mortality is lowest for moderately aged stands. Further, this study utilized only a small portion of the total number of stands. As illustrated, mortality varies from stand to stand. Mortality values could potentially be associated with the geographic location of each stand. Because this approach would not be practical in remote areas with little stand data, it was not pursued in this study.

The delivery rate value reported in this study was a mean for all 55 stream kilometers. The delivery rates reported in the Lienkaemper and Swanson (1987) study were for comparatively short stream reaches of a few 100 meters. Most of the stands in the McDonald-Dunn Forest are much younger and shorter than those studied at the H.J. Andrews Forest. Although these results are encouraging, further evaluation of model predictions for shorter stream reaches in the McDonald-Dunn Forest is warranted.

Conclusion

A strong correlation was observed between the ground plot forest structure metrics and laser derived canopy height. A relationship was also observed between the stand average basal area and the number on non-first return LIDAR points. The cumulative frequency distribution curve and the wood delivery rate predicted by this model are consistent with the conceptual frameworks established in other studies. Additional research is needed to refine the ability of this technology to assess the wood delivery potential of streamside forests, but initial results are promising.

Although the scope of the modeling in this study was limited to wood delivery, LIDAR technology shows great potential as a tool in the study of stream ecosystems. Some potential applications are stream shading studies, litterfall modeling, quantification of the area of streamside forests that can potentially deliver wood to streams, and a number of topographic applications. Because LIDAR data can be collected over such large areas, it shows great promise as a watershed assessment tool.

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References

- Bilby, Robert E.; Likens, Gene E. 1980. **Importance of organic debris dams in the structure and function of stream ecosystems.** *Ecology* 61(5): 1107-1113.
- Bilby, Robert E. 1981. **Role of organic debris dams in regulating the export of dissolved and particulate matter from a forest watershed.** *Ecology* 62(5): 1234-1243.
- Bilby, Robert E.; Ward, James W. 1991. **Characteristics and function of large woody debris in streams draining old-growth, clear-cut, and second-growth forests in southwestern Washington.** *Canadian Journal of Fisheries and Aquatic Science* 48: 2499-2508.
- Carlson, J. Y.; Andrus, C. W.; Froehlich, H. A. 1990. **Woody debris, channel features, and macroinvertebrates of streams with logged and undisturbed riparian timber in Northeastern Oregon, U.S.A.** *Canadian Journal of Fisheries and Aquatic Sciences* 47: 1103-1111.
- Evans, Brent F.; Townsend, Colin R.; Crowl, Todd A. 1993. **Distribution and abundance of coarse woody debris in some southern New Zealand streams from contrasting forest catchments.** *New Zealand Journal of Marine and Freshwater Research* 27: 227-239.
- Garvin, James B. 1996. **Topographic characterization and monitoring of volcanoes via airborne laser altimetry.** In: McGuire, W. J.; Jones, A. P.; Neuberger, J., eds. *Volcano instability on the Earth and Other Planets*, Geological Society Special Publications No. 110: 137-152.
- Harmon, M. E.; Franklin, J. F.; Swanson, F. J.; Sollins, P.; Gregory, S. V.; Lattin, J. D.; Anderson, N. H.; Cline, S. P.; Aumen, N. G.; Sedell, J. R.; Lienkaemper, G. W.; Cromac, K. Jr.; Cummins, K. W. 1986. **Ecology of coarse woody debris in temperate ecosystems.** *Advances in Ecological Research* 15:133-302.
- Headman, Craig W.; Van Lear, David H.; Swank, Wayne T. 1996. **In-stream large woody debris loading and riparian forest seral stage associations in the southern Appalachian Mountains.** *Canadian Journal of Forest Research* 26: 1218-1227.
- Lefsky, Michael; Cohen, W. B.; Acker, S. A.; Spies, T. A.; Parker, G. G.; Harding, D. 1997. **LIDAR remote sensing of forest canopy structure and related biophysical parameters at the H.J. Andrews experimental forest, Oregon, USA.** In: Greer, J. D., ed. *Natural resources management using remote sensing and GIS*. Washington DC: American Society of Photogrammetry and Remote Sensing.
- Lefsky, Michael A.; Harding, D.; Cohen, W. B.; Parker, G.; Shugart, H. H. 1999. **Surface LIDAR remote sensing of basal area and biomass in deciduous forests of eastern Maryland, USA.** *Remote Sensing of Environment* 67: 83-98.
- Lienkaemper, G. W.; Swanson, F. J. 1986. **Dynamics of large woody debris in streams in old-growth Douglas-fir forests.** *Canadian Journal of Forest Research* 17: 150-156.
- Lisle, Thomas E. 1986. **Stabilization of a gravel channel by large streamside obstructions and bedrock bends, Jacoby Creek, northwestern California.** *Geological Society of America Bulletin* 97: 999-1011.
- Magnussen, S.; Boudewyn, P. 1998. **Derivations of stand heights from airborne laser scanner data with canopy-based quantile estimators.** *Canadian Journal of Forest Research* 28: 1016-1031.
- McDade, M. H. 1988. **The source area for coarse woody debris in small streams in western Oregon and Washington;** 69 p. M.S. thesis.

- McDade, M. H.; Swanson, F. J.; McKee, W. A.; Franklin, J. F.; Van Sickle, J. 1989. **Source distances for coarse woody debris entering small streams in western Oregon and Washington.** Canadian Journal of Forest Research 20: 326-330.
- McHenry, Michael L.; Schott, Eric; Conrad, Robert H.; and Grette, Glenn B. 1998. **Changes in the quantity and characteristics of large woody debris in streams of the Olympic Peninsula, Washington, U.S.A. (1982-1993).** Canadian Journal of Fisheries and Aquatic Sciences 55: 1395-1407.
- Means, Joseph E.; Acker, Steven A.; Harding, D. J.; Blair, B. J.; Lefsky, Michael A.; Cohen, Warren B.; Harmon, M. E.; McKee, W. Arthur. 1999. **Use of large-footprint scanning airborne LIDAR to estimate forest stand characteristics in the western Cascades of Oregon.** Remote Sensing of the Environment. 67: 298-308
- Minor, Kathleen P. 1997. **Estimating large woody debris recruitment from adjacent riparian areas.** Corvallis: Oregon State University; 34 p. M.S. thesis.
- Moore K. M. S.; Gregory, S. V. 1988. **Response of young-of-the-year cutthroat trout to manipulation of habitat structure in a small stream.** Transactions of the American Fisheries Society 117: 162-170.
- Murphy, Michael L.; Koski, K. V. 1989. **Input and depletion of woody debris in Alaska streams and implications for streamside management.** North American Journal of Fisheries Management 9: 427-436.
- Naesset, Erik. 1996. **Determination of mean tree height of forest stands using airborne laser scanner data.** Photogrammetry & Remote Sensing 52: 49-56.
- Naesset, Erik. 1997. **Estimating timber volume of forest stands using airborne laser scanner data.** Remote Sensing of Environment 61: 246-253.
- Nelson, Ross. 1997. **Modeling forest canopy heights: The effects of canopy shape.** Remote Sensing of Environment 60: 327-334.
- Nelson, Ross; Oderwald, Richard; Gregoire, Timothy G. 1997. **Separating the ground and airborne laser sampling phases to estimate tropical forest basal area, volume, and biomass.** Remote Sensing of Environment 60: 311-326.
- Nilsson, Mats. 1996. **Estimation of Tree heights and stand volume using an airborne LIDAR system.** Remote Sensing of Environment 56: 1-7.
- Oregon State University, College of Forestry. 1999. **Research forests inventory manual.** Corvallis, OR.
- Pater, D. E.; Bryce, S. A.; Thorsen, T. D.; Kagan, J.; Chappell, C.; Omernik, J. M.; Azevedo, S. H.; Woods, A. J. 1997. **Ecoregions of western Washington and Oregon.** 1:1,350,000. United States Environmental Protection Agency.
- Van Sickle, John; Gregory, Stanley V. 1990. **Modeling inputs of large woody debris to streams from falling trees.** Canadian Journal of Forest Research 20: 1593-1601.