Pacific
Northwest
Research
Station

Science Update

MONITORING FORESTS AT THE SPEED OF LIGHT


Tom Iraci

IN SUMMARY

Airborne laser scanning is a technology developed in the last 15 years. Commonly referred to as **li**ght **d**etection **a**nd **r**anging, or lidar, these systems can map ground with up to a 6-inch elevation accuracy in open, flat terrain. Lidar is being rapidly adopted for topographical and flood-plain mapping and the detection of earthquake faults hidden by vegetation, among other uses. Most analysis begins with a process known as “bare-earth filtering”—laser scan data about trees and buildings are stripped away to leave just the bare-ground data. These discarded data, however, are extremely valuable for many forestry uses.

Scientists from the Pacific Northwest (PNW) Research Station and University of Washington, along with other partners, have been using lidar data to describe vegetation. In just the last 5 years, scientists have discovered that lidar can characterize the forest along with the contours of the land, providing accurate data on forest characteristics such as canopy height, stand structure, growing-stock estimates, wildlife habitat, and biomass.

Lidar can be a revolutionary technology in forestry. Although lidar will never replace getting out on the ground, data that used to be available only for a few plots or selected stands may be routinely available for an entire forest, currently at a cost of about $1 to $2 per acre. In a few years, the use of lidar scans may be as commonplace as the use of aerial photos and topographic maps today. Learn more inside about how lidar works and what it offers.

USDA United States Department of Agriculture
Forest Service
Pacific Northwest Research Station
http://www.fs.fed.us/pnw
Issue 12
December 2005

What is lidar?

Lidar uses laser light to measure distances. It is used in many ways, from estimating atmospheric aerosols by shooting a laser skyward to catching speeders in freeway traffic with a handheld laser-speed detector. Airborne laser-scanning technology is a specialized, aircraft-based type of lidar that provides extremely accurate, detailed 3-D measurements of the ground, vegetation, and buildings (see sidebar on page 4 on "How Lidar Works"). Developed in just the last 15 years, one of lidar's first commercial uses in the United States was to survey powerline corridors to identify encroaching vegetation. Additional uses include mapping landforms and coastal areas. In open, flat areas, ground contours can be recorded from an aircraft flying overhead providing accuracy within 6 inches of actual elevation. In steep, forested areas accuracy is typically in the range of 1 to 2 feet and depends on many factors, including density of canopy cover and the spacing of laser shots. The speed and accuracy of lidar made it feasible to map large areas with the kind of detail that before had only been possible with time-consuming and expensive ground survey crews.

Federal agencies such as the Federal Emergency Management Administration (FEMA) and U.S. Geological Survey (USGS), along with county and state agencies, began using lidar to map the terrain in flood plains and earthquake hazard zones. The Puget Sound Lidar Consortium, an informal group of agencies, used lidar in the Puget Sound area and found previously undetected earthquake faults and large, deep-seated, old landslides. In other parts of the country, lidar was used to map highly detailed contours across large flood plains, which could be used to pinpoint areas of high risk. In some areas, entire states have been flown with lidar to produce more accurate digital terrain data for emergency planning and response.

Lidar mapping of terrain uses a technique called "bare-earth filtering." Laser scan data about trees and buildings are stripped away, leaving just the bare-ground data. Steve Reutebuch, team leader for Silviculture and Forest Models at PNW Research Station, first began his lidar research in forests in 1997 to find out how much accuracy was lost in lidar flights over areas with heavy forest cover. He wanted to better understand the level of error in lidar mapping of the ground through forest canopy, to be used in analyzing terrain maps in forested areas. He and his University of Washington collaborators found that the data thrown away by geologists were a rich source of information for foresters, a finding that has been well corroborated by lidar forestry research groups around the world.

What kinds of data did lidar yield about forests?

Reutebuch chose the Blue Ridge study site, a roughly 2-square-mile area within Capitol State Forest, for lidar research. Capitol State Forest covers 90,000 acres near Olympia, Washington, and is managed by the Washington Department of Natural Resources (DNR). The Blue Ridge site was the location of a

Key Findings

- Lidar can provide high-resolution digital data of landforms and topography, even through forest cover. The resulting digital terrain models are far more detailed and accurate than existing topographical maps.
- Lidar can supply data on the percentage of canopy cover in a forest and variations in canopy height across the forest. Intensity data can be used with canopy height models to separate hardwood from conifer canopy areas.
- Lidar can map forest stand structures over the landscape in enough detail to supply data for canopy height models, growing-stock estimates, wildlife habitat models, crown fire behavior models, and any other resource models where spatial arrangement, stand density, biomass loadings, and tree height are important data inputs.
- Lidar data can be matched with other digital imagery and with existing orthophotographs to detect changes in forests over time, such as tree growth and loss of trees through windthrow.
- The all-return data sets from lidar flights can be used for a wide range of specialized analyses in natural resource management. Current lidar data sets provide baseline data that could be used in the future to monitor changes in forests.

Purpose of PNW Science Update

The purpose of the *PNW Science Update* is to contribute scientific knowledge for pressing decisions about natural resource and environmental issues.

PNW Science Update is published several times a year by:

Pacific Northwest Research Station
USDA Forest Service
P.O. Box 3890
Portland, Oregon 97208
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Our mission is to generate and communicate scientific knowledge that helps people understand and make informed choices about people, natural resources, and the environment.

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Tom Iraci

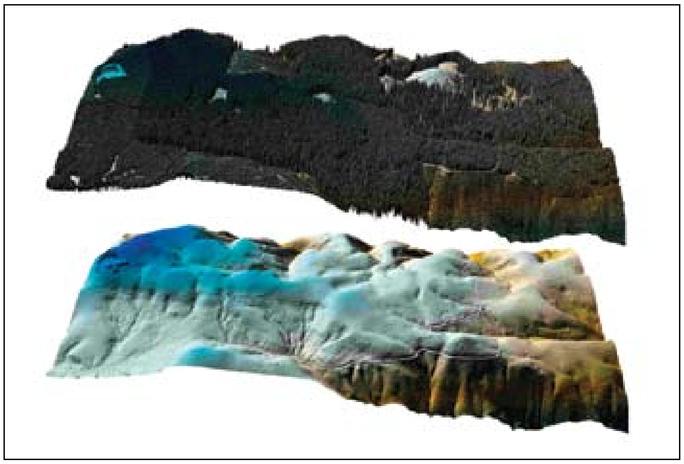
Most of the Blue Ridge study area in Capitol State Forest was covered with 70-year-old stands of Douglas-fir in 1998 as the study began. This stand is a no-harvest control unit.

large study on silvicultural regimes, being conducted under a partnership between his team's scientists and local DNR managers. Designed to study silvicultural options for young-growth Douglas-fir forests, the study treatments included commercial thinning, patch cuts, group selection, creation of two-age stands, clearcut harvest, and uncut stands.

Most of the area was covered with 70-year-old Douglas-fir stands in 1997 before the study. The larger trees were mostly Douglas-fir with some hemlock and western redcedar; the largest trees were reaching 40 inches diameter at breast height. A few pole-sized trees and western hemlock seedlings were scattered throughout. For the silvicultural options study, data were gathered on the stands 1 year before the treatments, 1 year after treatments, and every 5 years thereafter.

"I realized that the Blue Ridge study area would be ideal for testing lidar in forested terrain," says Reutebuch. "We would be able to take advantage of the existing plot data." The detailed stand data, treatments that would create varying canopy densities, and posttreatment monitoring created controlled, well-documented conditions for testing lidar.

Reutebuch worked with the silvicultural options group to include lidar in the research plan. The first lidar flight was in 1998, a month before the treatments began; the second lidar flight was in early 1999, after treatments were completed and before the growing season; and the third was in late 2003, at the end of the growing season. The latter two flights covered a five-growing-season span, and they also gave scientists a chance to compare a leaf-off scan, done before deciduous trees leafed out for the year, with a leaf-on scan, done while leaves were still on the deciduous trees. Thus scientists would be able to test lidar results under this variation in conditions.



Steve Reutebuch

Scientists found that lidar could map the ground surface accurately through mature forest canopies, not only in open areas. This graphic shows a perspective-view of both the canopy-level (top) and ground-level (bottom) lidar surfaces in the Blue Ridge study area, collected in a single flight in 1999.

The first objective for lidar was to test its accuracy in mapping the ground surface under varying canopy densities. "I didn't expect lidar to map the terrain very well through heavy cover," comments Reutebuch. "I thought there'd be big differences in

How Lidar Works

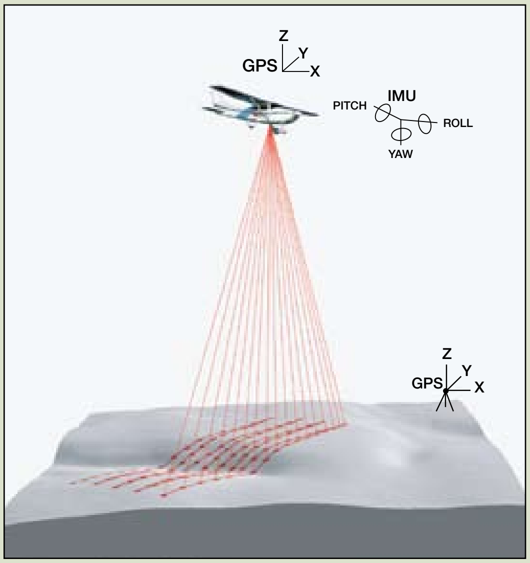
The use of lasers has become commonplace, from laser printers to laser surgery. In airborne-laser-mapping lidar, lasers are taken into the sky. Instruments are mounted on a single- or twin-engine plane or a helicopter.

Airborne lidar technology uses four major pieces of equipment (see figure below). These are a laser emitter-receiver scanning unit attached to the aircraft; global positioning system (GPS) units on the aircraft and on the ground; an inertial measurement unit (IMU) attached to the scanner, which measures roll, pitch, and yaw of the aircraft; and a computer to control the system and store data. Several types of airborne lidar systems have been developed; commercial systems commonly used in forestry are discrete-return, small-footprint systems. “Small footprint” means that the laser beam diameter at ground level is typically in the range of 6 inches to 3 feet.

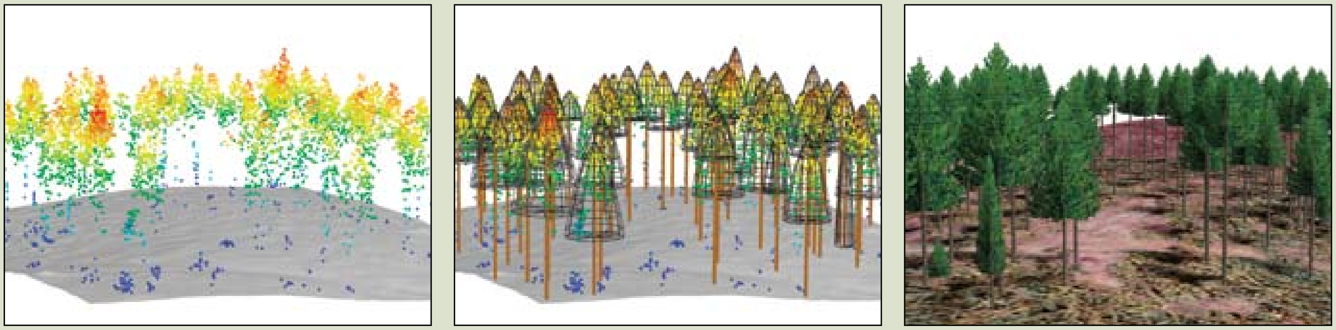
The laser scanner on the aircraft sends up to 100,000 pulses of light per second to the ground and measures how long it takes each pulse to reflect back to the unit. These times are used to compute the distance each pulse traveled from scanner to ground. The GPS and IMU units determine the precise location and attitude of the laser scanner as the pulses are emitted, and an exact coordinate is calculated for each point. The laser scanner uses an oscillating mirror or rotating prism (depending on the sensor model), so that the light pulses sweep across a swath of landscape below the aircraft. Large areas are surveyed with a series of parallel flight lines. The laser pulses used are safe for people and all living things. Because the system emits its own light, flights can be done day or night, as long as the skies are clear.

Thus, with distance and location information accurately determined, the laser pulses yield direct, 3-D measurements of the ground surface, vegetation, roads, and buildings. Millions of data points are recorded, so many that “lidar creates a 3-D data cloud,” explains Reutebuch. After the flight, software calculates the final data points by using the location information and laser data. Final results are typically produced in weeks, whereas traditional ground-based mapping methods took months or years.

The first acre of a lidar flight is expensive, owing to the costs of the aircraft, equipment, and personnel. But when large areas are covered, the costs can drop to about $1 to $2 per acre. The technology is commercially available through a number of sources.



Bob McGaughey

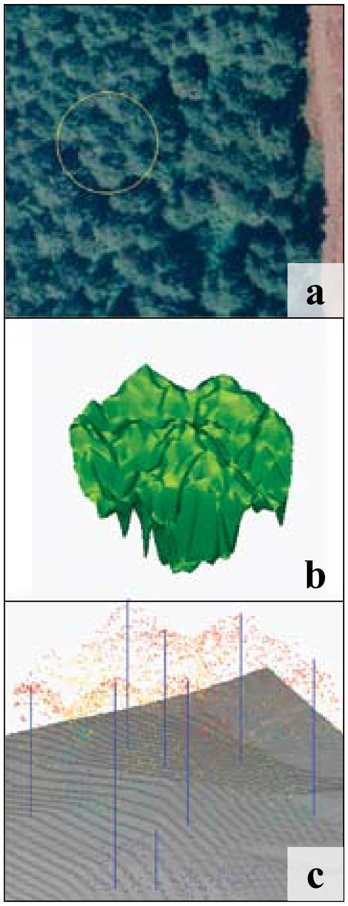


The lidar point cloud includes direct measurements of various canopy elements including stems, branches, and foliage. This series of images shows the lidar data for above-ground vegetation, tree objects inferred from the data, and a visual simulation of the tree objects and terrain rendered with PNW Research Station’s EnVision software.

Bob McGaughey

accuracy between the clearcut and the uncut 70-year-old stand. But it turned out that the average error was about the height of my boot, or 9 inches. We were blown away by how well we could map this terrain through this cover.” Accuracy was statistically the same in the clearcut and the 70-year-old stand.

This highly accurate lidar ground surface was generated by filtering out only those points that hit the ground by using a bare-earth filtering process. Other agencies using lidar had simply thrown away the data from points that reflected from vegetation. But Reutebuch and his colleagues, Bob



Lidar can map the shape of the forest canopy. This figure shows (a) a large-scale aerial photo, with the plot circled in yellow; (b) detailed canopy surface model for the plot, generated from lidar data; and (c) estimated individual tree stem locations and heights from lidar data. This capability should be particularly useful for gathering more information about canopies in old-growth forests.

Bob McGaughey

McGaughey, a research forester for PNW Research Station, and Hans-Erik Andersen, University of Washington Precision Forestry Cooperative, had an idea. Reutebuch explains, "We thought maybe we could do something with all these measurements of canopy."

The team found that lidar had enormous potential for supplying information about the forests themselves, including data on stand and individual tree characteristics. Lidar produced accurate estimates of individual tree heights in the overstory, with results within 3 feet of the photogrammetrically measured results. It also estimated crown diameter. With lidar data on individual tree crowns, scientists could generate a detailed canopy surface model. Average stand height could also be estimated from the data.

Lidar's accuracy was comparable to stand inventory results from traditional methods. Once fully validated, lidar could potentially provide detailed, accurate assessments of stand characteristics and growth across an entire forest.

Next the scientists worked on estimating stand characteristics with lidar, which measures the location of reflecting surfaces within the stand, including foliage and branches. They found strong relations between lidar data and field-measured data for dominant height, stem volume, biomass, and basal area. (Basal area is defined as the cross-sectional area of all trees in a stand, as measured at breast height; the pretreatment basal area for the Blue Ridge stands ranged from 227 to 255 square feet per acre.) Also, intensity data, or the reflectance strength, from each lidar pulse, combined with information on canopy height, showed potential for distinguishing hardwood and conifer canopy areas. Thus lidar looked promising for estimating stand characteristics.

The team compared the lidar data clouds from early 1999 and late 2003 and found that lidar successfully estimated the differences in growth among the treatment units. Lidar data, which were confirmed by traditional ground-based measurements, found that the unthinned control unit of mature trees had a total height growth of 3 to 9 feet over the five growing seasons, and remaining dominant trees in the heavily thinned stand had less height growth but greater expansion in their crowns. The 35-year-old stand in the study area had total height growth of 9 to 15 feet, considerably more height gain than the mature stands.

Lidar's accuracy, then, was comparable to stand inventory results from traditional methods. But labor-intensive traditional methods can be done on only selected plots or stands, because of the expense. Lidar, once fully validated, could potentially provide detailed, accurate assessments of stand characteristics and growth across an entire forest. Reutebuch realized that lidar would be a revolutionary technology in forestry.

Tom Iraci

In Capitol State Forest, lidar's accuracy has been comparable to traditional field survey methods for some stand characteristics such as canopy height, stem volume, basal area, and biomass.

How can information generated by lidar be used?

Lidar is rapidly emerging as a useful, effective source of high-resolution data for many resources. It has strong potential to be used in forest inventory and silvicultural work, fire and fuels management, wildlife habitat classification, stream mapping, and other resource management work. For each type of use, field work on the ground is necessary to rigorously evaluate the accuracy of lidar for that use before it can be adopted as a standard technique. Research is already underway testing lidar in different forest types and for different applications.

Forest inventory and silvicultural work. Second-growth, managed forests cover millions of acres in the Pacific Northwest. Agencies and landowners conduct thinning and other silvicultural actions in these forests, including variable-density thinning designed to develop stands with more structural complexity. Forest managers need to collect forest information and monitor growth and yield on these forests, yet they have limited funds. Lidar is a technology that could be used for efficient evaluation of stand structures before and after thinning.

The USDA Forest Service's Forest Inventory and Analysis (FIA) Program has been described as "the Nation's forest census." The program collects inventory data on all forest land in the country and analyzes the data to assess current conditions, evaluate changes, and predict future trends and conditions. Andersen, McGaughey, and Reutebuch are working with Ken Winterberger of the PNW Research Station's FIA Program to test the use of lidar for collecting similar inventory information. So far they have a pilot study underway in Alaska, with plans to expand research to Washington and Oregon, if successful in Alaska. Lidar may be particularly useful for inventory plots in remote areas. As lidar becomes more widely validated, it has potential for monitoring changes in forests over time and across landscapes, something that would be prohibitively expensive now.

Fire and fuels management. Fire hazard, excessive fuel loads, and large wildfires are major concerns in many Western States. Managers are addressing these issues with fuel treatment and risk reduction projects and, after fires, with recovery and restoration projects for burned areas.

Reutebuch and his colleagues have used the Capitol State Forest study to test the use of lidar for mapping canopy fuels. No quick, accurate methods exist for estimating canopy fuels, which play a big role in wildfire behavior and rate of spread, and the research team thought that lidar, an airborne technology, might estimate those fuels very well. The Joint Fire Sciences Program funded the project.

Tom Iraci

Increasingly, second-growth forests are managed to develop wildlife habitat as well as to grow wood. Lidar promises to be a useful tool for monitoring structural complexity in forests.

The team found that in Capitol State Forest, lidar was indeed highly accurate for estimating canopy height and fairly accurate for estimating crown fuel weight, crown bulk density, and canopy base height, variables that affect crown fire behavior. They are also testing lidar's estimation of canopy fuels at Fort Lewis in the Puget Sound area and in mixed pine and fir stands in eastern Washington's Mission Creek area to see if correlations are found in other forest types.

Lidar data on canopy fuels may help fire managers predict fire spread and intensity, especially for catastrophic crown fires, and may be useful for quickly assessing fuel loading and fire risk over large areas.

The lidar-produced estimates of canopy fuels can potentially be used to develop maps showing canopy fuel levels over a landscape and as input into fire-behavior models. When further validated, lidar data on canopy fuels may help fire managers predict fire spread and intensity, especially for catastrophic crown fires, and may be useful for quickly assessing fuel loading and fire risk over large areas. Research studies must test lidar in different forest types before the technique can be validated and become fully operational in those types.

One of the largest wildfires in recent years was the Biscuit Fire, which burned nearly a half-million acres in southwest Oregon in 2002, much of it in rugged mountains. A landscape-scale study is being implemented on 36,000 acres of the burned area. Developed by Bernard Bormann, PNW Research Station Ecosystem Processes Program, and the Biscuit Fire recovery team, the study is designed to compare different postfire management strategies for restoring habitat for old-growth-associated species. The three experimental pathways designed by Bormann are used in the study to test much-debated management approaches toward salvage of dead trees, reduction of fuel, tree planting, and natural regeneration.

The lidar research team, in collaboration with Bormann's Sustainable Ecosystem Productivity team, had a lidar flight done over the study area in summer, 2004, two years after the fire and before the three experimental pathways were started on the ground. The lidar flight detected tree mortality, canopy cover, and canopy structure at the individual tree scale—over an area of 36,000 acres. Without lidar, that kind of detailed information could only have been obtained for selected plots or stands.

Lidar data provided valuable documentation of baseline conditions across the study area before management experiments began, and the scientists hope to use lidar in monitoring study results in the years following completion of the salvage treatments. The lidar flight also covered the PNW Research Station long-term ecosystem productivity experiment, which was partly burned. With a grant from the National Commission for Science on Sustainable Forestry, an independent nonprofit group, Bormann's team is comparing lidar data with extensive ground data from these stands to find out to what extent lidar can be used to calculate indexes of biodiversity.


Tom Iraci

A 36,000-acre study is testing management approaches for postfire forest restoration over some of the half-million acres burned in 2002 by the Biscuit Fire. Lidar offers a way to get detailed data on canopy structure changes across the study area; these data would not be available any other way.

Terrain maps. Topographic maps have existed for decades, of course. Lidar data can be used to create digital terrain models or DTMs, which show the landforms much as a topographic map would. However, lidar-derived DTMs offer far more detailed information than traditional topographic maps. "County and state agencies and FEMA are using lidar to map earthquake faults, detect road slippage, monitor erosion, and map areas vulnerable to flooding," comments Reutebuch.

Natural resource professionals could use lidar to locate streams under forest canopies and to estimate the changes in stream channels after floods. They could also use DTMs to monitor erosion in upland areas and get detailed information on landslides.

Lidar is very useful for breaking out hardwood and softwood cover over the landscape and mapping other wildlife habitat features in forest canopies.

Ecological research. The shape of the forest—canopy depth and structure—affects the forest ecology in many ways. A number of studies are under way in forests ranging from eastern hardwoods to tropical jungles.

Tom Iraci

Characterizing changes in stream channels is labor-intensive work. Although lidar would not replace field crews, it could greatly expand the miles of stream on which data are collected.

Subtle differences in canopy structure can be critical habitat features for some wildlife species. Lidar is very useful for breaking out hardwood and softwood cover over the landscape and mapping other wildlife habitat features in forest canopies. The lidar research team is exploring these capabilities in the Fort Lewis area, where managers are testing restoration strategies for Oregon white oak, which provides critical habitat for the threatened western gray squirrel.

Scientists are using lidar as one tool in their studies of canopy structure in Pacific Northwest conifer forests. Early results suggest that canopy characteristics such as the roughness or bumpiness along outer edges, canopy gaps, porosity, and top-heaviness or bottom-heaviness seem to make a difference for functions such as carbon exchange between trees and air, respiration, and transmittance of sunlight. Lidar is also a promising tool for estimating aboveground biomass, an important factor in modeling carbon dynamics of forests, which in turn are a critical factor in global carbon dynamics.

Tom Iraci

Many scientists around the world are now using lidar to study forest canopies, including old-growth forests in the Pacific Northwest.

What steps would help lidar reach its full potential in forestry?

"Lidar is being widely applied by other people," Reutebuch says, "and it provides unprecedented data." The mapping community has adopted lidar as a standard ground-surface mapping technology, but they consider lidar data reflected from vegetation to be "noise" and they throw it out. "People in the natural resource community could get these data, but they often aren't asking for the data—yet."

"Today, we are in a position with lidar similar to where our predecessors were with aerial photography in the early 20th century," Reutebuch continues. "By 1930 it was obvious that aerial photography was providing new data on the extent, composition, and volume of forests, yet it took another 20 years for agencies to develop flight specifications and cooperative, cost-sharing agreements to allow periodic wide-area photography."

Coordinated collection of lidar data could provide the data needed for many aspects of natural resource planning, along with baseline data for monitoring changes in forests at the tree, stand, and landscape levels.

In 2005, it is obvious that lidar provides unprecedented 3-D geo- and biospatial data. Coordinated collection of lidar data could provide the data needed for many aspects of natural resource planning, along with baseline data for monitoring changes in forests at the tree, stand, and landscape levels. Currently, various local, state, and federal agencies are flying lidar projects for single-use needs such as flood risk mapping or earthquake fault detection, without consideration for how the data could be used in forestry. Many of these contracts do not even require delivery of all lidar data returns, and the vegetation data are lost or must be purchased separately from the vendor.

Some essential steps are needed for lidar to be fully used in forestry. Reutebuch explains the work to be done. First, there is an immediate need to develop standards and specifications for data collections so that lidar vegetation and terrain data are more widely available for use by local, state, and federal natural resource management agencies. Several organizations (USGS National Digital Elevation Program, FEMA, and the American Society for Photogrammetry and Remote Sensing) have worked together to produce standards for lidar topographic mapping.

Standards and specifications for lidar missions would cover sensor settings, flight specifications, and delivered products, ensuring that the end products are useful for forestry needs. The FEMA standards for flood hazard mapping are a good starting point on which natural resource management agencies could build more comprehensive standards.

"There are several simple, easily understood, and widely recognized lidar-derived forest mapping products that many agencies and specialists would find useful," Reutebuch comments. He lists five products that could be easily generated.

- **High-resolution maps of landforms and terrain.** These DTMs could be used for hydrologic and erosion process modeling, landscape modeling, road and harvest planning and design, and geographic information system analysis.
- **Canopy height models.** These models would provide stand structure data over the landscape for estimates of growing stock, input for wildlife habitat and fire behavior models, and other resource planning uses.
- **Canopy cover maps.** These maps would provide detailed, digital images of canopy cover and gaps.

Someday, lidar technology might even change how we think about landscapes.

- **Lidar intensity images.** These images can be matched with other digital imagery and existing orthophotographs for monitoring changes over time in forests, such as changes in hardwood-softwood cover and tree mortality.
- **All-returns data sets.** The all-returns data sets would be baseline data for future use and would be available for future monitoring and change detection projects that haven’t been imagined yet, similar to how scientists reanalyze old satellite-collected data as new algorithms are developed.

“Someday, lidar technology could give us inventory data for the whole landscape, not just for a grid of plots,” Reutebuch says. “It might even change how we think about landscapes.”

Tom Iraci

Forest canopies are perhaps the least understood part of forests. Lidar can shed some light on how canopies develop and function.

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For Further Reading

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Art director — Frank Vanni
Layout — Pilar Reichlein

PNW Science Update
U.S. Department
of Agriculture
Pacific Northwest
Research Station
333 SW First Avenue
P.O. Box 3890
Portland, OR 97208-3890
Official Business
Penalty for Private Use,
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Got Science?

The PNW Research Station's top research findings and accomplishments for 2005 include:

- The condition of watersheds and streams improved slightly in the Northwest Forest Plan area over the first decade under the Plan.
- The barriers and opportunities for sustainable wood production in the Pacific Northwest will be related to future markets, harvest potential, land use changes, and sustainable forestry options, rather than to traditional sustained yield outputs.
- The Fuel Characteristic Classification System was formally released in late 2005 and can be downloaded from the Web (www.fs.fed.us/pnw/fera/fccs).

Check our Web site for publications related to these and other 2005 accomplishments. The full report on the 2005 Science Accomplishments of the Pacific Northwest Research Station will be available in February 2006.

PNW Research Station: http://www.fs.fed.us/pnw