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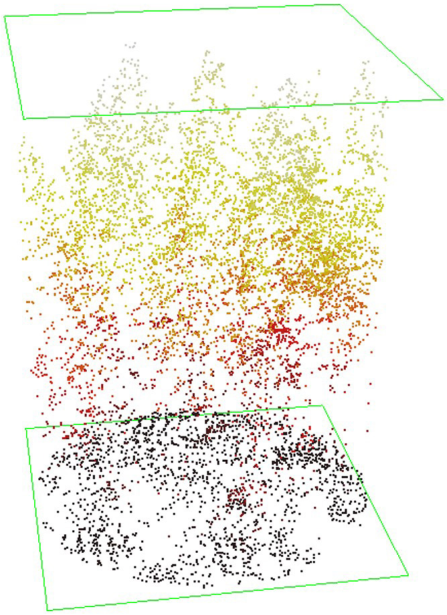
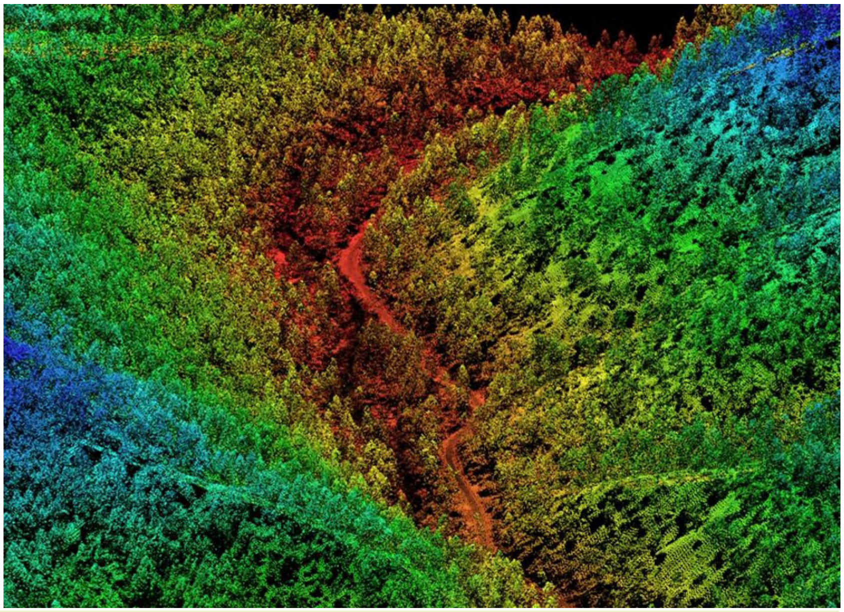
Where's the Biomass? A New Approach for Quantifying Biomass and Carbon in the Western United States

The Multiple Use Sustained Yield Act of 1960 mandates the U.S. Forest Service to manage its 193 million acres of national forest for multiple uses that include "outdoor recreation, range, timber, watershed, and wildlife and fish." These uses benefit society in tangible and less tangible ways: Protecting watersheds produces clean water for cities and exposure to nature improves an individual's quality of life.

Because climate change directly impacts each of the uses outlined in the Multiple Use Sustained Yield Act, per the 2012 Forest Service Planning Rule, the U.S. Forest Service must concurrently mitigate and adapt to climate change when managing for these multiple uses. An underlying foundation of this work is knowing the distribution of aboveground biomass across the landscape to inform management decisions. For instance, climate change and the consequently longer fire seasons may increase the risk of severe fires where there are heavy loads of accumulated fuel, which is more often referred to as biomass outside the fire community. Thus, biomass





The first LiDAR systems became available in the 1970s. Combining it with global positioning system (GPS) advances in the early 1990s made it a powerful yet mostly unexplored tool to measure forests. Collecting LiDAR data requires outfitting an airplane with an airborne laser scanning system (ALS). As the airplane flies above the landscape, light in the form of a pulsed laser is directed at the ground. After the light strikes a physical surface, whether a branch, a shrub, or the ground, the light returns to the sensor. The time elapsed for the laser pulse to return to the sensor, which occurs at the speed of light, can be translated into distance. These return signals are processed along with the real-time GPS and aircraft position data to create a 3D point cloud of the landscape, which can then be rendered in mapping software into a map of the landscape that depict physical attributes. For example, this map shows the elevation gradient of the landscape, with red being the lowest point and blue being the highest point (illustration: J. Evans).

maps can by used to inform decisions on where to place fuel treatments.

Inventory datasets are readily available from which the distribution of aboveground biomass may be calculated, but there are limitations in their application. Forest inventory data available through the Forest Inventory and Analysis (FIA) program do not capture immediate changes of wide-scale disturbance, such as wildfire or insect outbreaks. Aerial photography is regionwide but doesn't provide quantifiable forest measurements. Light detection and ranging (LiDAR) datasets can provide quantifiable forest measurements, yet these are often only available for a specific area at a single snapshot in time, since LiDAR data are expensive to collect.

A brand-new Carbon Monitoring System (CMS) project overcomes many of these limitations for calculating biomass and promises to be a valuable resource to support both the 2012 Forest Service Planning Rule and the U.S. Forest Service's Shared Stewardship Initiative's objectives.

Harnessing the Power of Remoting Sensing

This CMS project draws upon 18 years' worth of LiDAR research undertaken by a team led by Andrew Hudak, a research forester at the U.S. Forest Service Rocky Mountain Research Station (RMRS). When he joined the station, Hudak decided LiDAR would be a research focus. "LiDAR at that time was a cutting-edge way to do forest measurements," he says. "It's poignant that in 2003 I received $50,000 in RMRS funding through the Agenda 2020 Program to start my first LiDAR project, and now it's 2020."

The goal of the Agenda 2020 program was to encourage Forest Service scientists to work with private timber industry partners to develop tools to inform forest management decisions. One of Hudak's first research projects was developing methods to translate a LiDAR-derived 3D point cloud of Moscow Mountain and the St. Joe Woodlands in north-central Idaho into quantifiable forest attributes. These areas totaled nearly 84,000 hectares of mixed-conifer forestland owned by Bennett Lumber Products, Inc., and Potlach Forest Holdings, Inc.

"The data that comes from a LiDAR acquisition of an area can be literally gigabytes of data—billions of points in space," explains Benjamin Bright, a geographer with RMRS with Hudak's team. "Through software and statistical modeling, we can reduce the data to more usable pieces of information."

Through regression and imputation modeling, they related field-measured forest characteristics to LiDAR point clouds and satellite measurements. Models were then applied across landscapes to generate 2D maps of stand attributes of interest, such as the distribution of Douglas-fir or grand fir tree densities for a given area, or forest biomass.

"The map products created from LiDAR data are a high-resolution

SUMMARY

The 2012 USDA Forest Service Planning rule requires that National Forests incorporate mitigation and adaptation strategies in response to climate change into their forest management plans. An underlying foundation of this work is knowing the distribution of aboveground biomass across the landscape. Climate change may put some areas with high biomass at greater risk for carbon emissions from wildfires, whereas other areas with reduced risk of wildfire may be preferred locations to manage for increased carbon storage.

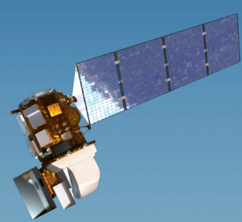
With a grant from National Aeronautics and Space Administration's (NASA) Carbon Monitoring System (CMS) Program, Andrew Hudak, a research forester with the Rocky Mountain Research Station, led a team to develop aboveground biomass maps for Idaho, Oregon, Washington, and western Montana. These annual maps, which span the years 2000–2016, will be useful for developing carbon budgets for National Forests and identifying areas needing fuel treatments to reduce wildfire risk.

Building upon the success of the project, NASA provided additional funding for Hudak and his team to create maps of other forest attributes, such as basal area, volume, and canopy fuels. The goal is to map biomass and other forest attributes of interest to forest managers annually for the whole western United States, from 1984 through 2020.

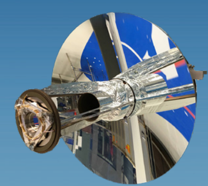
How Are We Measuring Forests?

FROM SPACE

Satellite images have global coverage and are useful for making broad-scale maps. They can be calibrated with finer-scale airborne or field data.



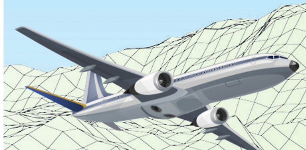
On July 23, 1972, the first Landsat satellite was launched. Its mission: to monitor and study the Earth. In 2021, Landsat 9 is expected to launch.



The Global Ecosystem Dynamics Investigation (GEDI) is a LiDAR system mounted on the International Space Station. It was commissioned on March 25, 2019 and will remain on the Station for two years (photo: NASA/Roscosmos).

Forestry is inherently a ground-based discipline, because it has always required boots on the ground to inventory a forest. By measuring individual trees in a specified plot size, foresters can statistically calculate a number of stand attributes, such as the number of trees, or the basal area of each tree species, for the area measured. The introduction of imagery, collected first by airplanes and later by satellites, enabled foresters to make estimations for larger forested areas faster than could be achieved solely by field inventories.

This doesn't mean satellites will ever replace field-based inventory crews. The on-the-ground measurements are invaluable because they provide ground-truthing for the LiDAR-derived models, such as those developed for this CMS project.



FROM THE AIR

Airborne LiDAR provides dense coverage of height in a small area. Biomass can be modeled from matching ground measurements.

ON THE GROUND

Forest Inventory and Analysis field crews and terrestrial LiDAR provide fine detail about species, biomass, and height.

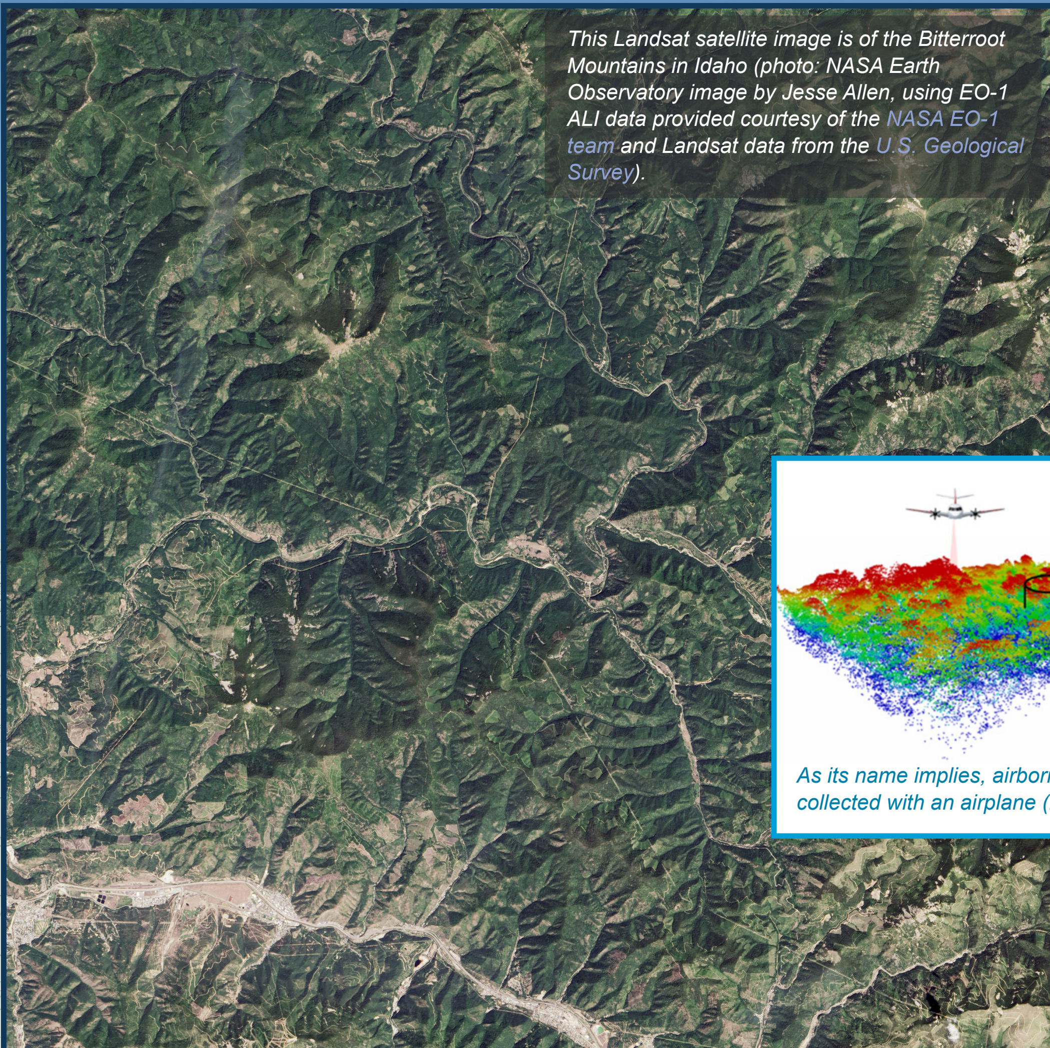
FIA

Across the United States, Forest Inventory and Analysis program crews collect field measurements that can include tree diameters, type of tree species, and amount of understory vegetation. Since its start in 1930, the FIA program's mission is to "make and keep current a comprehensive inventory and analysis of the present and prospective conditions of and requirements for the renewable resources of the forest and rangelands of the US."

How Are We Measuring Forests? (continued)

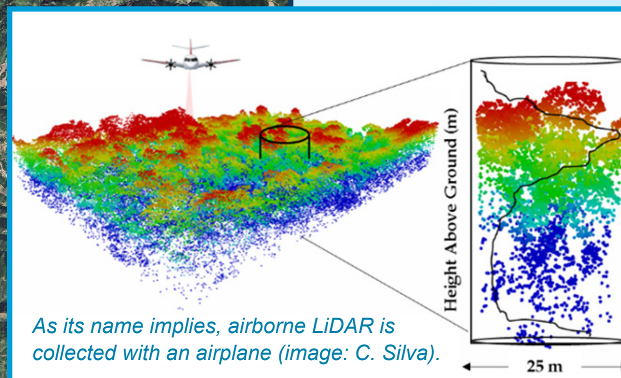
Landsat and LiDAR visualizations

Landsat



This Landsat satellite image is of the Bitterroot Mountains in Idaho (photo: NASA Earth Observatory image by Jesse Allen, using EO-1 ALI data provided courtesy of the NASA EO-1 team and Landsat data from the U.S. Geological Survey).

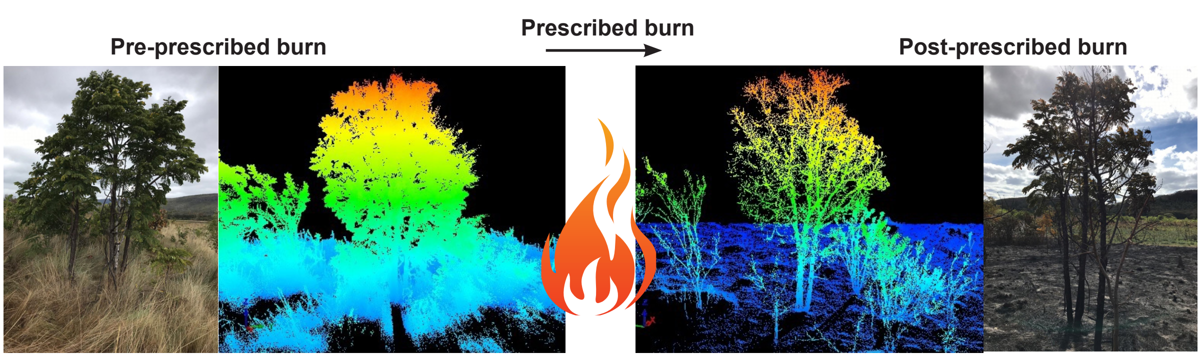
Airborne LiDAR



As its name implies, airborne LiDAR is collected with an airplane (image: C. Silva).

Terrestrial LiDAR

Terrestrial LiDAR uses the same technology as airborne LiDAR but the equipment is located on the ground (images: C. Silva and P. Almeida).



representation of the ground surface or forest characteristics," says Bright. "For a lot of applications that's what people want to know, whether they care about erosion, geology, or forest vegetation."

When the team published their first findings in 2006, the modeling approach demonstrated a tangible use of LiDAR to generate forest inventory data beyond what could be cost-effectively collected via field crews. "This modeling approach is now done operationally," Hudak says. "That's how you can assign estimates across the whole landscape; two predictive modeling approaches in particular, regression and imputation, are now widely used by foresters."

Building upon this success, Hudak and the team turned their attention to whether LiDAR, if collected in subsequent years, could be used to calculate changes on the landscape, such as increases in basal area or tree density. Although satellite imagery could capture significant disturbances, such as wildfire or timber harvests, it wasn't sufficiently sensitive to capture the annual growth of trees; it's why foresters relied upon ground-based inventories to monitor these changes.

In 2009, Hudak returned to Moscow Mountain, where LiDAR was reflown and 89 plots were remeasured. From these data, a 2009 model was developed and compared against the 2003 model to determine if changes in biomass could be estimated. The shift from quantifying the basal area of trees or species distribution on the landscape to quantifying aboveground biomass was feasible since there are well-established allometric equations to convert tree diameter measures to biomass. By validating estimates of biomass change against stand inventory data, Hudak and the team determined that LiDAR could capture landscape changes over time and these changes could be displayed as a map with sufficient accuracy to satisfy managers.

"The map products created from LiDAR data are a high-resolution representation of the ground surface or forest characteristics. For a lot of applications that's what people want to know, whether they care about erosion, geology, or forest vegetation."

—Benjamin Bright

"Foresters used to think that you have to remeasure trees on the ground to track changes across the landscape, but we found you can do a lot with remote sensing and modeling," Hudak explains.

As Hudak and his team continued to push the envelope of LiDAR's uses, state and federal agencies,

MANAGEMENT IMPLICATIONS

- Currently available datasets, such as FIA plot data and Landsat images of forest cover, don't capture vertical forest structure that relates to aboveground biomass, whereas this Carbon Monitoring System (CMS) used LiDAR to capture local forest structure in its modeling.
- The 2012 Forest Service Planning Rule requires the agency to mitigate and adapt to climate change. The aboveground biomass maps available through the CMS may be used to inform a variety of land management decisions, such as carbon sequestration and fuel treatment projects.
- More information and links to the CMS datasets are available at https://www.fs.usda.gov/rmrs/tools/carbon-monitoring-system-aboveground-biomass-estimates-pacific-northwest-inland-northwest-and
- The 2000–2016 forest aboveground biomass maps that Hudak's team created for the Pacific and Inland Northwest are available at https://daac.ornl.gov/CMS/guides/CMS_AGB_NW_USA.html.
- The 2000-2016 pinyon-juniper woodland aboveground biomass maps that Hudak's team created for the Great Basin are available at https://daac.ornl.gov/CMS/guides/CMS_Great_Basin_Biomass.html.

KEY FINDINGS

- A brand-new Carbon Monitoring System (CMS) developed by RMRS and other researchers promises to be a valuable resource to support the U.S. Forest Service's Shared Stewardship Initiative's goals and policy makers calculating carbon budgets. Remote sensing data and Forest Inventory and Analysis (FIA) data were used to build the underlying biomass model and verify the model outputs, respectively.
- The reference data upon which this CMS is based are timeless because the tree measurements and LiDAR measurements represent conditions that are present somewhere on the landscape even as the forest changes because of annual growth, mortality, and disturbance.
- The next generation of maps available in this CMS will include other stand attributes such as canopy fuels and basal area, and these maps will cover the western United States.

and tribes were funding LiDAR-collecting missions of their own. The result was many independent datasets across the northwestern U.S., and the team found the goal of their next research project.

"We were interested in trying to develop a model using LiDAR and inventory data and then apply that model to other areas where inventory data hadn't been collected," says Patrick Fekety, a research associate at Colorado State University and member of Hudak's team.

"In other words, what we were studying was the spatial transferability of the LiDAR data, Fekety elaborates. Could the model generate estimates of forest attributes across an entire region that met the threshold of accuracy needed by land managers?

Using six LiDAR datasets collected on National Forest and private forestland in northern Idaho, along with forest inventory plot data from the same area, Hudak and his team built a model that was validated against an excluded field inventory dataset.

"We found that the model's accuracy wasn't as great when we compared it to a LiDAR unit without field data," explains Fekety. "Of course, we would have a better model if we had the field data, but from a practical standpoint, the model was sufficient."

Of the significance of their findings, Fekety says, "People had always suspected you could use LiDAR to supplement missing field inventory data. It makes sense that you can make that leap."

The next idea to test from this research was that maps of forest attributes could be created for an entire region, not just the specific area where LiDAR was flown.

"At the scale of the National Forest, that's really useful because that's the level where planning occurs," Hudak says. "I'm not sure if there is a national forest in the West that has complete LiDAR coverage, but that may not be necessary."

In 2014, when Hudak heard that NASA's CMS program was seeking to leverage commercial off-the-shelf LiDAR datasets for carbon-related projects, he saw an opportunity to make an even greater leap: Develop a biomass model for the entire northwestern United States.

How to Map Biomass

In 2010, Congress created NASA's CMS. "It's an initiative that funds projects to use existing and newly collected remote sensing data to develop data products to help in the measurement, reporting, and verification of carbon stocks and fluxes," explains Edil Sepulveda, a staff research scientist and member of the Applications team at NASA's Goddard Space Flight Center. "Essentially, we're measuring and monitoring carbon around the world," he adds.

Specifically, for his CMS project, Hudak and the team would use aboveground biomass measurements contributed by USFS managers and other stakeholders in the northwestern U.S. and create maps of the distribution. "These maps will be needed because managing for biomass carbon is coming," says Hudak.

As with all his LiDAR research projects, Hudak would develop a new application of LiDAR—not only would the team spatially map the aboveground biomass but also temporally. This would be accomplished by combining LiDAR with Landsat imagery.

"When you maintain the association between both sets of data in a reference database, both the tree measurements and LiDAR measurements, it makes them timeless," Hudak explains. "They represent conditions somewhere on the landscape, and in combination with the Landsat imagery, they can be used to give us actual observations to tie to changing conditions."

Hudak drew upon his connections within the remote-sensing community at state and federal agencies and tribes to find the LiDAR datasets. One of Fekety's tasks was making sense of the voluminous data.

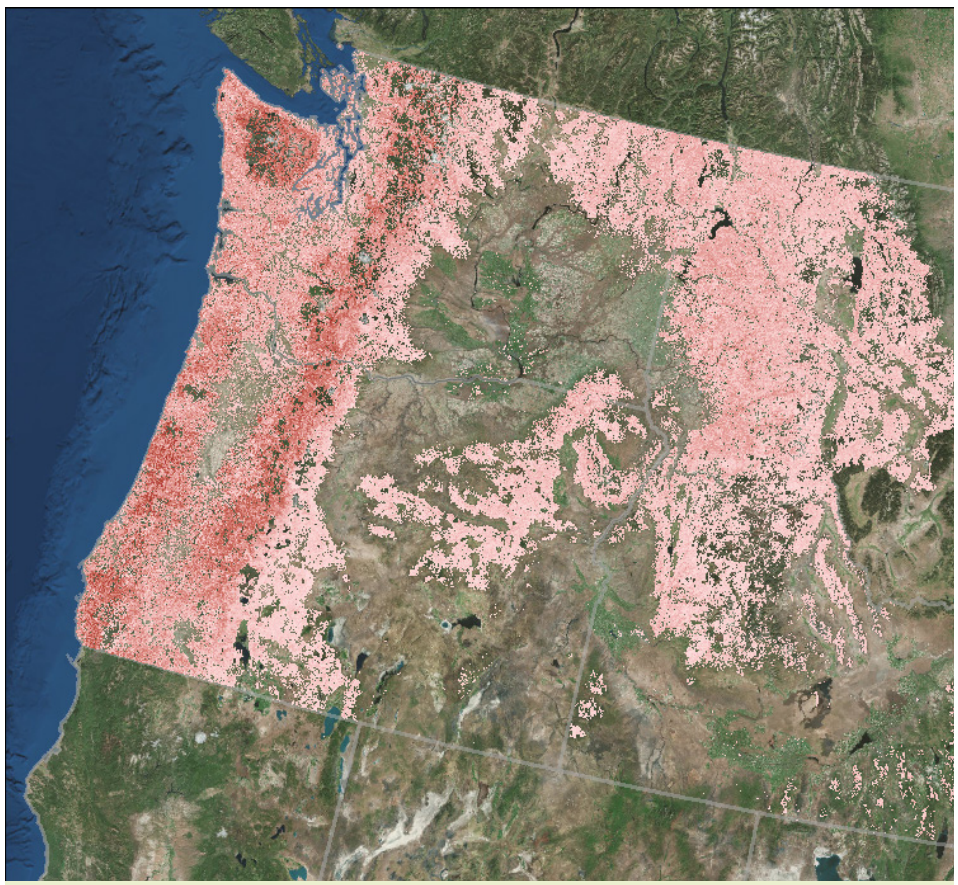
"One of the big challenges for us was finding as much data as we can across the Pacific Northwest where people have established these forest inventory plots within LiDAR units and compile that data into a common dataset that we could use within our CMS project," Fekety says. "It's not an exciting task, but it's necessary to ensure the data are all in the same format."

After nearly 4 years of developing and testing models, Hudak and his team successfully produced aboveground biomass maps spanning the years 2000–2016. The mapped biomass estimates were then calibrated with field plot data collected by FIA to minimize the model bias.

"When we did bias corrections and saw the trendline of what FIA was predicting for the forest biomass compared to what our maps were predicting, it was surprising how close that relationship was," explains Fekety.

A significant feature of the CMS is that "the maps capture current conditions while the reference database is designed so we can continue to add new plot measures and LiDAR as they're collected," says Hudak. "It will continue to expand and become a more robust representation of the conditions out there."

Bright assisted with archiving the biomass maps into NASA's Oak Ridge National Laboratory Distributed Active Archive Center where they are available for download (https://doi.org/10.3334/ORNLDAAC/1719). Also archived and available are the biomass maps that were derived from the LiDAR datasets contributed by the stakeholders and used to train



The maps produced by the Carbon Monitoring System show the distribution of forest biomass across the Pacific Northwest. Powering this system are numerous LiDAR and field inventory datasets collected by academic researchers, state and federal agencies, private industry, and tribes (image: Oak Ridge National Lab Distributed Active Archive Center (ORNL DAAC)).

the regional model (https://doi.org/10.3334/ORNLDAAC/1766).

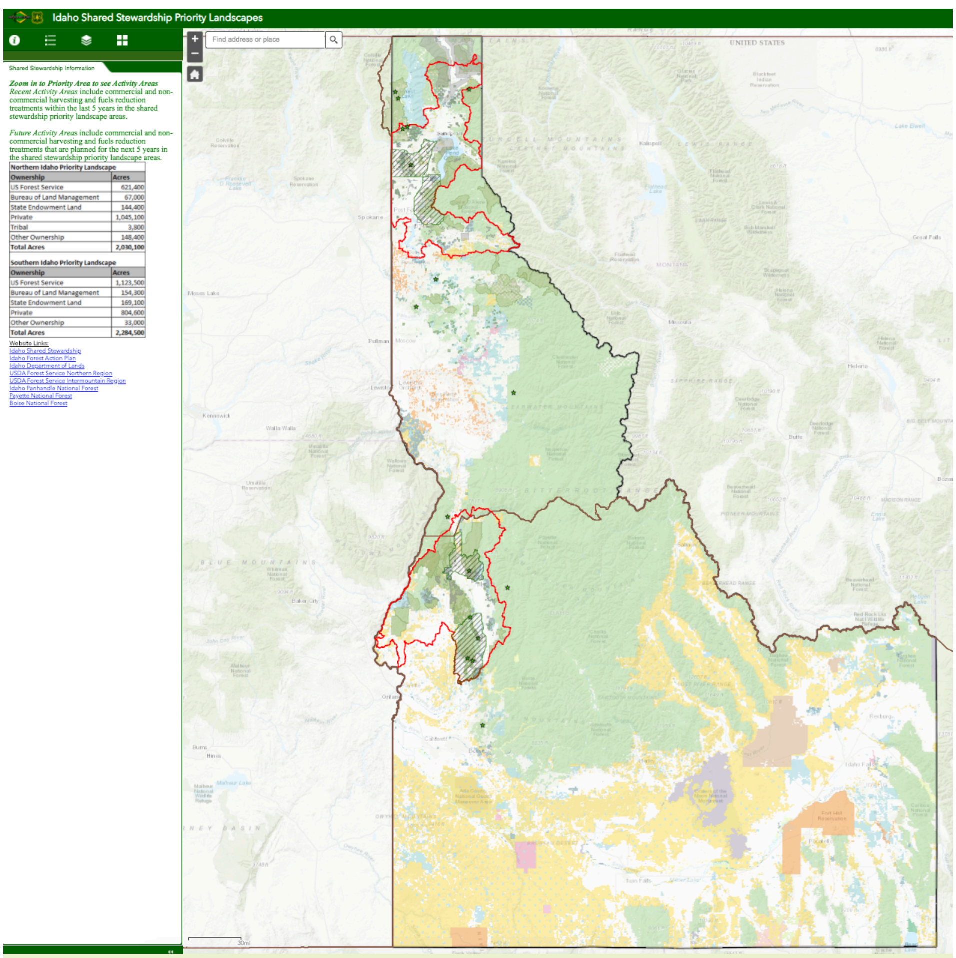
Applying This Approach in Shared Stewardship

One early user of these CMS data products was Kevin Halverson, a regional analyst with the Intermountain Interregional Office. The aboveground biomass maps cover all of Idaho, including two priority landscapes selected through a Shared Stewardship Agreement that was signed on December 18, 2018 between the state of Idaho and the U.S. Forest Service. The southern shared stewardship area was of particular interest to Halverson because it's filled with overstocked forests, which means high levels of aboveground biomass that pose a high wildfire risk to both communities and potential loss of timber.

"Vegetation maps are quite important when you're trying to target areas on the landscape for either doing wildfire hazard reduction or timber treatments," Halverson explained. "The vegetation is important for determining whether there is value in the timber or what that wildfire behavior is going to be like."

Halverson worked with the Boise National Forest and Payette National Forest to compile the relevant data they need to make decisions as to what treatment options are needed and where they will be located.

The CMS is "part of that toolbox in that catalogue of data layers that we're looking at to help advise this process," said Halverson.



On the Idaho Department of Land's website is an interactive map that allows users to view the designated priority areas, where current restoration projects are underway, and where future projects are planned. The map is available at https://www.idl.idaho.gov/forestry/shared-stewardship/.

The Next Frontier in Forest Mapping

The prototype CMS had barely been finalized before Hudak received another 3 years of funding for phase 2, which is even more ambitious. Not only will Hudak's team expand the aboveground biomass maps to the western United States and over a longer time frame (1984–2020), they will also map other forest attributes, such as basal area and volume.

To create these wall-to-wall maps, the team will include data from the Global Ecosystem Dynamics Investigation (GEDI), a sampling LiDAR system mounted on the International Space Station. "This is a gamechanger in that we never had a spaceborne LiDAR designed for forestry," explains Hudak.

"Unlike commercial airborne imaging lidar systems, GEDI will provide sample data. Although there had been an earlier

The USDA Forest Service and NASA—A Powerful Partnership

NASA may be synonymous with exploring outer space, but furthering our understanding of Earth is a focus of many of its missions. Since the launch of the first Landsat satellite, the agency has collected extensive global datasets on Earth's atmosphere, vegetation, and surface features.

In spring 2019, the inaugural USFS-NASA Applications Workshop held in Salt Lake City, Utah, brought together NASA personnel and researchers from the Forest Service and other government agencies, academia, and Distributed Active Archive Centers (DAACs). Key workshop goals were sharing the breadth of remote sensing data available from NASA's missions, learning agency land management goals and information needs, and exploring opportunities for collaboration.

The workshop began as an initiative between the Forest Service and mission applications leads at NASA Goddard; NASA's Soil Moisture Active Passive (SMAP) and ICESat-2 missions provided logistical support, and the Forest Service provided in-kind support. According to Everett Hinkley, the national remote sensing program manager for the Forest Service's Geospatial Management Office, over the years there have been research collaborations between NASA and the Forest Service researchers, but these collaborations were in most cases on an ad hoc basis.

"NASA has a lot of great Earth-observing capabilities, and I don't feel that we're fully leveraging those data products," explains Hinkley. "I am not even fully aware of the different missions and data products, but I continue to learn more through our continued collaboration."

At the workshop, NASA research scientists gave presentations on four new missions: SMAP, ICESat-2, GEDI, and the upcoming NASA-ISRO Synthetic Aperture Radar (NISAR). These four missions use different remote sensing technologies to collect complementary vegetation, atmospheric, carbon flux, soil moisture, and elevation datasets worldwide.

One of the biggest benefits of the workshop was "creating an awareness of the data products," says Sabrina Delgado Arias, a research scientist and applications lead for the ICESat-2 mission. "Some attendees were already familiar with the data products available, but the workshop provided an opportunity to go in depth as to the functionality of what these missions can do."

A deliverable of the workshop was creating a key opportunities document that will guide future research needs. "From the breakout sessions, we were able to gather information on Forest Service decision support needs and what they're currently using to inform those needs," Arias explains. "Then we looked at NASA relevant data products and tools that could be used to address those needs, whether or not they are already using these data products, and ways to close any barriers or gaps for NASA data product integration."

Hudak was among the 107 attendees at the workshop but also contributed to planning. A key takeaway for him was seeing the connection of his CMS data products and how managers might use the biomass maps to inform management decisions. "What dawned on me was if the utility of the product isn't obvious and it doesn't make managers jobs easier, they're not going to bother with it," he says.

A second in-person USFS-NASA Applications Workshop has been replaced by virtual meetings. "We want to focus on getting a sense of the top priority action areas where we can target support to make the data operational for the Forest Service," Arias explains.

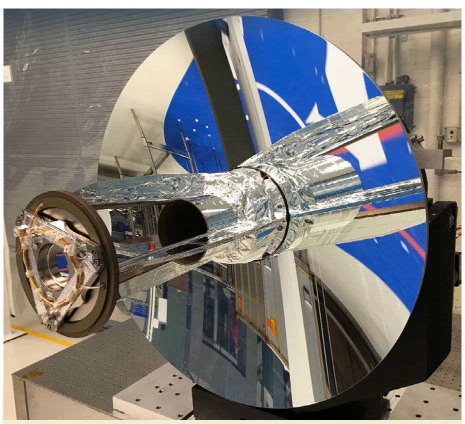
The first day of the 2019 USFS-NASA Applications Workshop was described as intense because of the amount of information that participants learned about each of the four missions. The next 2 days allowed the participants to discuss the research opportunities that were possible using NASA's data.

This year's workshop is virtual, but the organizations are excited about what the discussions will hold. "There's this natural synergy that exists between us and NASA," says Hinkley (photo: Madison Worthy, USDA Forest Service).

spaceborne sampling LiDAR system, known as the Ice Cloud, and Land Elevation Satellite (ICESat), its footprint size was 70 meters and only worked well for forestry applications on flat terrain; complex terrain made it difficult to separate ground from canopy within such a large footprint," Hudak says.

GEDI has a footprint ~25 meters in diameter, which approximates the size of a typical forest inventory plot; this simplifies combining field inventory plot measurements and GEDI LiDAR samples with wall-to-wall imagery in integrated models.

Deliverables of phase 2 will be annual maps of biomass, basal area, and volume for the entire western United States. A reason for producing maps of basal area and volume is that they are common measurements used by foresters to quantify the trees on the landscape, and they are also easy to obtain. Measuring a tree's diameter can generate its basal area and another calculation can convert tree diameters to volume.



The Global Ecosystem Dynamics Investigation (GEDI) LiDAR is the highest resolution LiDAR system ever deployed from space. Pictured is the 80-cm telescope that will collect the returned pulses. The system was launched on December 5, 2018 and began formally collecting sample data in spring 2019. The University of Maryland is leading the project in collaboration with the NASA Goddard Space Flight Center.

Unlike many aerial-based LiDAR systems that store the pulse returns as discrete points, GEDI is a full waveform LiDAR, which means all the returned energy is recorded as a continuous signal. The returned energy signal resembles a wave, hence its name. As with aerial LiDAR, researchers can measure surface topography, canopy cover, vertical structure, and canopy height (photo: R. Dubayah).

How Many Scientists Does It Take to Map Biomass Across the U.S. West?

The Rocky Mountain Research Station may be leading this CMS project, but its success is owed to many collaborators across the United States. Meet the research team working on Phase 2.

Arjan Meddens, Washington State University: Because of his remote sensing background, Meddens understands the science of how mapping products are created, as well as how to engage stakeholders and identify their mapping needs. "The reason for doing a stakeholder approach is to get them involved. Then they are already aware of the data they contributed and they're looking for the product," explains Hudak. "They're invested in it."

Robert Kennedy, Oregon State University: All the Landsat time series images need processing. Many of these steps have been automated and can be accessed by the public on Google Earth Engine.

Jody Vogeler, Colorado State University: Not all of the western United States is forested. In fact, a significant portion of it is rangelands, especially in the Great Basin, little of which has been flown with LiDAR. In this case, National Agricultural Imagery Program (NAIP) data is being used instead. Began in 1987, the NAIP program acquires aerial photographs of the lower 48 states on a 2-year cycle.

"We get tree cover estimates in pinyon-juniper woodlands from imagery and then convert from tree crown cover to biomass," says Andy Hudak, research forester with RMRS. "This method doesn't work well in dense forests where the tree crowns overlap, but in a rangeland with scattered pinyon pine and juniper trees with less biomass, this method works pretty well."

Van Kane, University of Washington: To create the aboveground biomass map of the western United States requires processing and stitching together forest canopy height and density metrics from numerous LiDAR datasets so they can be used in the modeling process. Kane will also explore the utility of NAIP data for estimating biomass change in forests, given the 2-year frequency at which NAIP data are collected, whereas repeat lidar coverages remain rare.

Chad Babcock, University of Minnesota: This is where the brand-new Global Ecosystem Dynamics Investigation (GEDI) sample data are being integrated into Hudak's phase 2 CMS. Forest structure measurements obtained from GEDI will help fill in the gaps between existing field plots and LiDAR datasets. "It's going to significantly improve the estimates between where airborne LiDAR has been flown," Hudak says. "It's going to make the maps more consistent and accurate locally."

To accomplish these goals, the team grew to include seven other co-principal investigators who bring expertise in processing the GEDI samples to relate to the Landsat imagery time series and building the models to predict the forest attributes.

It's anticipated that the work will take 3 years, and since Hudak received first-year funding in November 2019, land managers will have to wait a few years until these new products are available. And when they are, there will be users ready for their release.

"When these maps are available for Region 4, they will help tell a good story of what has happened in the last 3 decades", said Halverson.

FURTHER READING

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Where's the biomass? https://www.fs.usda.gov/rmrs/science-spotlights/got-biomass-questions-there's-map

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About the Science You Can Use Bulletin

The purpose of SYCU is to provide scientific information to people who make and influence decisions about managing land.

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