# Vegetation Structure and 3-D Reconstruction of Forest Canopies Using Echidna® Ground-based Lidar

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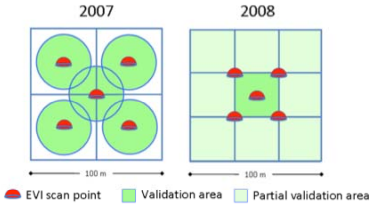
## Overview

Our research uses a ground-based, scanning lidar instrument to retrieve forest canopy structural information, including stand height, mean tree diameter, basal area, stem count density, woody biomass, leaf area index, and foliage profile, and links this information to airborne and spaceborne lidars to provide large-area mapping of structural and biomass parameters.

The terrestrial lidar instrument, Echidna®, developed by CSIRO Australia, allows rapid acquisition of vegetation structure data that can be readily integrated with downward-looking airborne lidar, such as LVIS (Laser Vegetation Imaging Sensor), and spaceborne lidar, such as GLAS (Geoscience Laser Altimeter System) on ICESat, to provide large-area maps and inventories of vegetation structure and carbon stocks.

First-generation algorithms for processing Echidna® data focus on retrieving the location, size, and spacing of tree trunks and on the foliage profile of the stand. To the right are some results for lidar scans using the Echidna® Validation Instrument (EVI), an engineering prototype. The results include comparison of stand height, LAI, biomass, DBH, and stem density derived from the EVI with contemporaneous field measurements for New England hardwood/conifer and Sierra Nevada conifer stands.




Sample design. A 1-ha area was sampled at each site (stand). In 2007, the area was divided into 4 subplots, and in 2008 into 9 subplots. We acquired EVI scans and ground stem measurements in validation areas as shown in the diagrams. At each scan point, we also acquired 13 hemispherical photos and LA-2000 measurements to validate LAI retrievals.

A proper Auzzie echidna.

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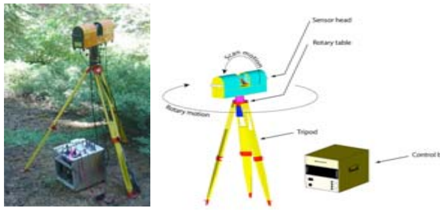
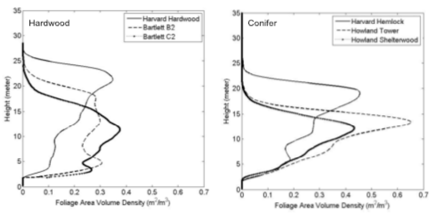
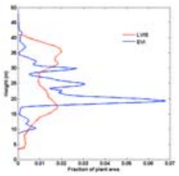



Echidna® ground-based lidar. Lidar pulses strike a rotating mirror at an angle of 45°, providing a scan through zenith angles of ±130° in a vertical circle. As the instrument rotates on its vertical axis, data from all azimuths are acquired.

Examples of EVI data for a hemlock stand at the Harvard Forest in Massachusetts (top image) and a giant sequoia-red fir stand at Sequoia National Forest in California (bottom image). The images are in a *plate carrée* projection that displays the data by azimuth angle (*x*-axis) and zenith angle (*y*-axis).




Foliage profiles (leaf area with height) retrieved from EVI scans at 6 sites, 5 scans per site. Among the hardwood sites, Harvard Hardwood is tallest, with an open understory. The Bartlett stands are shorter with more understory. The conifer sites show sharply peaked profiles with little or no understory layer. The curves fit a model of leaf area that increases with conifer crown width until the crowns touch and intersect, when leaf area is at its peak.

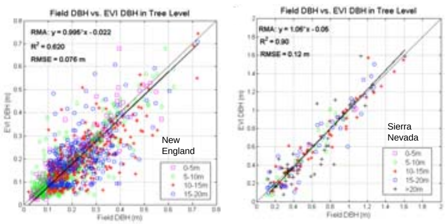



Foliage profiles acquired from under the canopy (EVI) and above the canopy (LVIS) show different features. Here we see profiles from the center scan at Sierra site 305, pictured in the right column. The LVIS profile, for a nominal 20-m diameter footprint, is smoother but shows less understory. The EVI profile, based on a 0–10° zenith ring above the instrument, shows the influence of nearby crowns and branches. The LVIS footprint is centered about 6 m away from the instrument location.

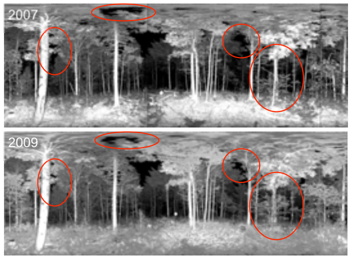
| Parameter | Source | Site 23 | Site 99 | Site 168 | Site 301 | Site 305 | Site 338 | Site 406 | Site 801 | Site $R^2$ | Plot $R^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Arithmetic mean of DBH (m) | Field | 0.41 ±0.02 | 0.30 ±0.01 | 0.37 ±0.01 | 0.37 ±0.02 | 0.58 ±0.02 | 0.44 ±0.03 | 0.60 ±0.02 | 0.87 ±0.09 | 0.95 | 0.65 |
| | EVI | 0.41 ±0.03 | 0.30 ±0.03 | 0.38 ±0.03 | 0.49 ±0.02 | 0.66 ±0.06 | 0.52 ±0.08 | 0.59 ±0.05 | 1.00 ±0.06 | | |
| Stem count density (trees/ha) | Field | 110 ±29 | 421 ±79 | 570 ±86 | 231 ±64 | 284 ±40 | 347 ±65 | 256 ±27 | 125 ±12 | 0.91 | 0.76 |
| | EVI | 127 ±18 | 521 ±47 | 543 ±57 | 196 ±40 | 254 ±41 | 338 ±46 | 260 ±28 | 156 ±16 | | |
| Above-ground biomass (t/ha) | Field | 115± 64 | 221 ±34 | 1088 ±92 | 361 ±60 | 1214 ±150 | 647 ±28 | 833 ±80 | 2664 ±250 | 0.92 | 0.74 |
| | EVI | 100 ±63 | 233 ±43 | 818 ±72 | 224 ±33 | 922 ±136 | 711 ±52 | 603 ±108 | 1950 ±212 | | |
| LAI | LAI-2000 | 0.73 ±0.23 | NA | 2.22 ±0.46 | 0.76 ±0.17 | 1.35 ±0.47 | NA | 2.43 ±0.28 | 2.18 ±0.44 | 0.91 | 0.82 |
| | EVI | 0.65 ±0.24 | NA | 2.46 ±0.3 | 0.58 ±0.14 | 2.03 ±0.5 | NA | 2.59 ±0.26 | 2.42 ±0.47 | | |
| | Hemi | 0.64 ±0.25 | NA | 2.14 ±0.19 | 0.61 ±0.16 | 1.82 ±0.3 | NA | 2.39 ±0.08 | 2.28 ±0.19 | 0.99 | 0.96 |
| Dominant species | | Jeffrey pine | White fir, incense cedar | Red fir | Red fir | Red fir | Red fir | White fir, sugar pine | Red fir, giant sequoia | | |

Values are site means ± standard deviation, 5 scans per site.

Comparison of structural parameters retrieved by EVI with field measurements, Sequoia National Forest in Sierra Nevada of California. Data are averages for 5 scans at each of eight sites. Standard deviations are based on values for these 5 scans.




Diameter at breast height is retrieved well by the EVI. Different colors show data in specific distance ranges. Because the EVI acquires data at constant angular resolution, EVI-retrieved diameter becomes less accurate with distance. At New England sites (left), the $R^2$ value is 0.62 overall, but the regression slope and intercept are very close to 1 and 0 m, respectively. In Sequoia National Forest stands (right), $R^2$ is 0.90, and the slope and intercepts are also very close to 1 and 0 m. Giant sequoia trees are not included in the regression.

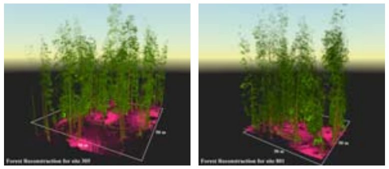



| | Mean of DBH (m) | Stem count density (tree/ha) |
|---|---|---|
| Field 2007 | 0.221±0.01 | 629 |
| Field 2009 | 0.224±0.01 | 599 |
| EVI 2007 | 0.210±0.01 | 732 |
| EVI 2009 | 0.215±0.02 | 671 |

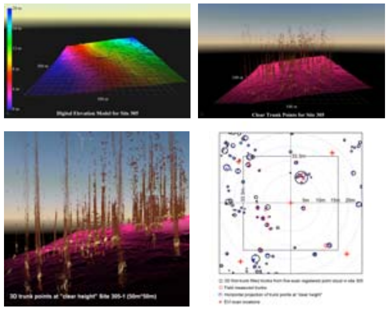
These scans of the Howland shelterwood site in 2007 and 2009 show that the Echidna® lidar can detect small growth increments. In these two *plate carrée* projections of mean lidar returns, the gaps between crowns visibly shrink and small trees show growth during the two-year interval (red ellipses). Based on ground measurements, mean DBH in the plot increased by 0.3 cm, while EVI finds the difference to be 0.5 cm. The stem count density decreases as diameters increase.

## Point Cloud Processing

The peak intensity and its location within each waveform were used to create a point cloud dataset for each of the lidar scans at a site. The point cloud records each scattering event and its apparent reflectance within an *x*-, *y*-, *z*-coordinate space. By carefully locating the position of each scan point and then finding trees and objects viewed by multiple scans, we merged the point clouds to create a 3-D reconstruction of the stand within the 50 m by 50 m inner plot area. Scattering events were then classified into trunk, leaf and ground and used in creating the color images below.



These reconstructions, based on merging multiple scans, show a stand of high-elevation red fir (left) and a stand including giant sequoias (right) in the Sequoia National Forest, near Fresno, California. Using a simple classification algorithm based on the shape of the return lidar waveform and its vertical position, each point is classified into trunk (brown), leaf (green), or ground (magenta).



Further processing of the point cloud, shown here for the red fir site, uses the ground points to fit a digital elevation model for the site (upper left), which is then used to identify trunk returns between 01.75 and 2.25 m above the ground. When these are projected onto a stem map, they fit stem locations very well (lower right), with $R^2$ values for retrieved vs. measured DBH of 0.97. Height and crown size, identified by similar processing techniques, were also retrieved well with $R^2$ values of 0.98 and 0.81 respectively.

The three-dimensional forest stand reconstructions can be displayed as fly-through videos. The computer display shows these for the two stands above as well as a deciduous forest stand in Massachusetts scanned in 2009.