

Quantifying and Visualizing Canopy Structure in Tall Forests: Methods and a Case Study

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*The mighty trees getting their food are seen to be wide awake,
every needle thrilling in the welcome nourishing storms, chanting
and bowing low in glorious harmony, while every raindrop and snowflake is seen as a
beneficent messenger from the sky.*

—John Muir, *Our National Parks*, 1901

Introduction

In 1970, one of the first canopy research projects began in an old-growth *Pseudotsuga menziesii* forest. The goal was to assess the biomass and surface area of its entire canopy as part of an ecosystem-level study of forest dynamics. Supported by the International Biological Program, ten tall *Pseudotsuga* trees were climbed, and every branch was mapped and estimated for foliar biomass and leaf area. This pioneering research used rock-climbing techniques (e.g., lag screws and webbing ladders) to gain access to the tree crowns (Denison et al. 1972). The study generated an unprecedented amount of within-canopy structure data. At that time, however, such large datasets were difficult to handle. Most of the original data are now available only on obsolete punch cards; only a small portion have been analyzed and published (Pike et al. 1977; Massman 1982). Although canopy access techniques and data management methods have greatly evolved, the data collected for that study remain the most detailed ever collected on the crown structure of *Pseudotsuga menziesii*.

Since then, other researchers have pursued similar goals in other forests. Modern techniques for gaining access to forest canopies are diverse and varied (Moffett and Lowman 1995, Mitchell et al. 2002). With nearly a dozen canopy cranes and scores of canopy walkways and towers maintained around the world, access is no longer limited to the adventurous (Nadkarni 1995). However, rope-based techniques remain the best way to gain the particular type of canopy access to trunks and branches of tall trees required by researchers who study canopy structure.

Mapping the three-dimensional (3-D) structure of trees has been achieved from the ground using lasers with some success (Sumida et al. 2001; Nychka and Nadkarni 2003). These techniques involve mapping the 3-D coordinates (x, y, z , or d, α, θ) of each bifurcation, or node, within the tree down to some minimum size. The primary limitation is that mapping each bifurcation within a tree is possible only with small trees and trees whose structure is not hidden by foliage or epiphytes. Larger trees can be mapped with canopy cranes, but access to the near-bole space within tree crowns is often restricted—the bulk of the measurements must still be taken

remotely. A further limitation to mapping 3-D structure as nodes and segments is that the resultant tree is a stick-figure shape—there is no thickness to the segments.

Many aspects of tree physiology, epiphyte ecology, and stand-level forest dynamics can greatly benefit from whole-tree estimates of surface area, wood volume, and biomass. Surface area estimates are needed to determine carbon production for trees with photosynthetic bark and to estimate epiphyte habitat with tree crowns (Pike et al. 1977; Lyons et al. 2000; Ellyson and Sillett 2003). Although most conifers carry much of their volume within a single stem, others—along with most angiosperm trees—contain much of their wood volume in branches within the crown. To assess these accurately requires knowing branch diameters within the tree, an extremely difficult task from the ground or even from the gondola of a crane.

Biomass estimates in forests require quantification of components such as trunks, branches, and foliage. In tall-stature forests, this has been accomplished by felling one to many trees for samples. While the crowns of large trees are destroyed in the felling process, a small proportion of branches may be relatively undamaged. These can often be sufficient to develop regression equations for various components with the crown, but not for whole-tree estimates.

Forest ecologists need a comprehensive, nondestructive sampling regime to obtain accurate whole-tree estimates of 3-D structure for any forest type. In this chapter, we propose a three-tiered approach to obtain 3-D structural information in forests:

1. **Stand Mapping:** To gain information on the forest as a whole and to put individual trees in a stand-scale perspective;
2. **Crown Mapping:** To gain detailed 3-D information on individual trees; and
3. **Analyses:** To scale up from subsamples to whole-tree and stand levels.

We follow this protocol with a case study comparing two very tall but structurally dissimilar forests: a *Eucalyptus regnans* forest in southern Australia and a *Pseudotsuga menziesii* forest in the Pacific Northwest of North America. We present this comparison to illustrate the power and diversity of these techniques, many of which are being presented here for the first time.

3-D Structural Mapping Protocol for Forests

Stand Mapping

Site selection varies greatly with study objectives. In our work, sample areas at each site were located in large, relatively flat blocks of forest with plot boundaries located well away from clear-cut edges to reduce confounding factors such as edge influences, slope, and aspect. Ideally, each potential study site has geographic information system (GIS) and/or aerial photos available. Stands are discrete, homogeneous blocks of forests that are defined locally. In coniferous forests, stands are often identifiable from aerial photos or even detailed satellite imagery. In other forests, this may have to be done through ground-based reconnaissance. Stand boundaries are obtained or generated using GIS, and the resulting GIS-generated polygons are used as the study site.

At each site, transects are the sample units and are used as replicates. Maximum tree height measured during reconnaissance is used to determine transect size. Transects must be large enough to capture the stand-level variability but small enough to maximize efficiency. The transect dimensions are 3×0.3 times the dominant tree height, following Kuiper (1994) and Van Pelt (1995). For example, a stand in which the dominant tree height is 50 m is sampled by 150 m \times 15 m transects. The number of transects used at a given site will vary depending on resources and time, but three or four usually suffice. Transects are located inside stand polygons with random starting points and directions. These are then located on the ground using GPS and surveyed in with rebar at the recorded endpoints.

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A metric tape is stretched down the center of the plot and staked at either end with rebar. Any piece of dead wood (greater than 5 cm) intercepted by the tape is measured. Measurements may include species, diameter, decay class, piece length, and beginning and end points where each log intersects the tape. Diameter is measured perpendicular to the central axis of the log at the interception point. These data are used to calculate log volume in the entire plot (Harmon et al. 1986).

Shrubs are sampled in a subplot centered on the whole plot. Width of the subplot is one-tenth that of the whole plot (i.e., 0.03 times the mean height of canopy dominants). Species, X-value, basal diameter, and height can be recorded for shrubs and trees with diameter at breast height (DBH) less than 5 cm and taller than 50 cm. DBH (rather than basal diameter) is recorded for large shrubs.

All trees within the plot greater than 5 cm in diameter at breast height are mapped and measured for DBH. The DBH is measured at 1.37 m above the high point of ground (i.e., ground level on the uphill side of the tree). The species, status (live or dead), and a unique identification number are recorded for each stem. For each stem, the perpendicular distance between the center of the stem and the tape is recorded as the Y value. One side of the tape is chosen to have positive Y values, the other to have negative. The value on the tape perpendicular to the center of the stem is recorded as the X value. Compasses are set perpendicular to the direction of the transect to maintain accuracy in the Y value measurements.

Data sheets and a stem map are prepared from these initial measurements for double-checking in the field. This two-step process allows one to correct errors of location, identification, and measurement. A laser range finder (e.g., Impulse 200LR, Laser Technologies, Inc.) is used to measure total tree heights and heights of crown bases. The crown base is defined as the point above which living foliage surrounds more than one-third of the trunk. Crown radii are measured from the center of the trunk to the tip of the longest living branch. For large trees, or trees with highly asymmetrical crowns, eight or more radii must be measured; one radius in each cardinal direction suffices for most trees.

In each stand, a subset of trees of each species is chosen for stem volume measurements. The random sample must include the full range of tree sizes. A survey laser is used to measure trunk diameters every 3 m along the entire stem. These data are used to supplement those collected during crown mapping (see below) to develop regression equations that predict trunk volume from height and DBH. In the case of trees with large buttresses, basal maps must be prepared for each stem to be converted to a functional diameter (see the Analyses section below).

Crown Mapping

Several trees of each species are randomly chosen for detailed study. Again, these should span the size range of the species. Single rope techniques are used to gain access to tree crowns and permit climbers to measure directly locations and dimensions of all reiterations and branches. Very tall trees in old-growth forests are accessed via a bow that is used to shoot an arrow over sturdy branches in the crown. A vertical range up to 85 m is possible with this technique. The arrows are tied to fishing filament (14- to 20-lb test), which is attached to a spinning reel on the front of the bow. If the shot misses, or the arrow goes over undesired or unsafe branches, the arrow is lowered to the ground, untied, and the filament is retrieved.

After a successful shot, the filament is used to pull a nylon line followed by a climbing rope (9 mm) over the branches. When both ends of the rope are on the ground, one end of the rope is anchored with a knot and the other end is climbed via single rope technique (Perry 1978). Once the branch supporting the climbing rope is reached, rope techniques developed by arborists are used to gain access to progressively higher branches (Jepson 2000). A pulley is secured near the treetop with a webbing sling through which the climbing rope is passed and lowered to the

ground along two clear paths on opposite sides of the crown. By double-tying the midpoint of the rope above the pulley, a team of two climbers can gain access to all parts of the crown for recording data. Between climbing sessions, the rope is replaced by the nylon cord.

A metric tape is stretched from average ground level to the treetop. If the tape cannot be anchored on the ground, it is tied to a nearby tree or shrub at the proper height. Metal tags are attached to the main trunk at 5-m intervals for use as future benchmarks in height measurements of trunks, limbs, and branches once the metric tape has been removed. The tree's total height is recorded to the nearest decimeter, and main trunk diameters are measured at each tag. Near the base of large trees, additional diameters are often needed for accurate estimation of wood volume.

Reiterated trunks are defined as accessory trunks arising from the main trunk, other reiterated trunks, or limbs (Sillett 1999; Sillett and Van Pelt 2000). They are vertically oriented stems with their own branches and are architecturally indistinguishable from freestanding trees except for their locations within the crown of the larger, supporting tree. This follows the terminology of Hallé et al. (1978), but in the narrow sense of using this term only for complete reiterations. The following data are recorded for each reiterated trunk: basal diameter, base height, base distance, base azimuth, top height, top distance, and top azimuth. Distances and azimuths are referenced to the center of the main trunk. If the reiteration is more than 5 m tall, or if there are structural anomalies, additional diameters, distances, and azimuths are measured.

Limbs are defined as large branches that arise from the main trunk and give rise to reiterated trunks. They consist of limb segments, and they terminate in other limb segments or reiterated trunks. Branch segments are defined as accessible sections of large branches that arise from the main trunk and give rise to other branch segments or branches. Limbs behave differently from branches physiologically and are thus kept separate on data sheets. Both limb segments and branch segments receive the same measurements: the diameter at each end is measured as well as the height, distance, and azimuth of each end. Smaller branches can also arise along the length of a branch segment, but larger branches and trunks will cause the branch segment to be divided into additional segments.

Limb segments, branch segments, and branches are named according to their origins. For example, a branch consists of two segments and four branches (see Figure 3-1). The first branch segment is named M-1 because it arises from the main trunk (M). Branch segment M-1 gives rise to branches 101 and 104 as well as branch segment 1-2. The origin of branch 101 is listed as 1 on the data sheet because it arises from the distal end of branch segment M-1. Branch segment 1-2 gives rise to two branches, 102 and 103. Their origins are listed as 2 on the data sheet because they arise from the distal end of branch segment 1-2. Branch 104 is too small to deflect the branch segment significantly, so its origin is listed as M-1 on the data sheet. To know exactly where branch 104 originates, the distance along the branch segment M-1 is also recorded on the data sheet.

Each branch receives a unique number within a given tree. The following measurements are taken for each branch greater than 2 cm in diameter: basal height, basal diameter, extension (i.e., slope-corrected horizontal distance from trunk to branch tip), percent foliated, azimuth from trunk, overall slope, and curvature. Overall slope is measured in degrees, positive (up) or negative (down), in five-degree increments. A two-letter code is used to further describe curvature. The first letter refers to the shape of the portion of the branch near the trunk, and the second letter refers to the shape of the rest of the branch. There are three different designations (O = orthotropic, upward tending, G = geotropic, downward tending, and N = neutral), resulting in nine possible codes (see Figure 3-2).

Each branch is classed as either original or epicormic. Original branches are those formed when the treetop was at the height of the branch (i.e., piths of original branches are continuous with the pith of the trunk). Epicormic branches are those formed below the top of the tree (i.e., they originated from the cambium). However, the process of epicormic branching often



Figure 3-1 Photo of a climber with limb segments

results in many trees, these branches are more epicormic than original. The entire epicormic branch is recorded.

On young trees, live axes are typically programmed to record parameters of the branch, such as the percent of foliage, the distance to become asymmetric, and the number of branches requiring

1. Number of live axes
2. Total axis length
3. Number of live axes

Live axes are defined as

A *foliar unit* is defined as a stem and foliage. In some tree species, the previous method of sampling, a sub-sample of the ground for

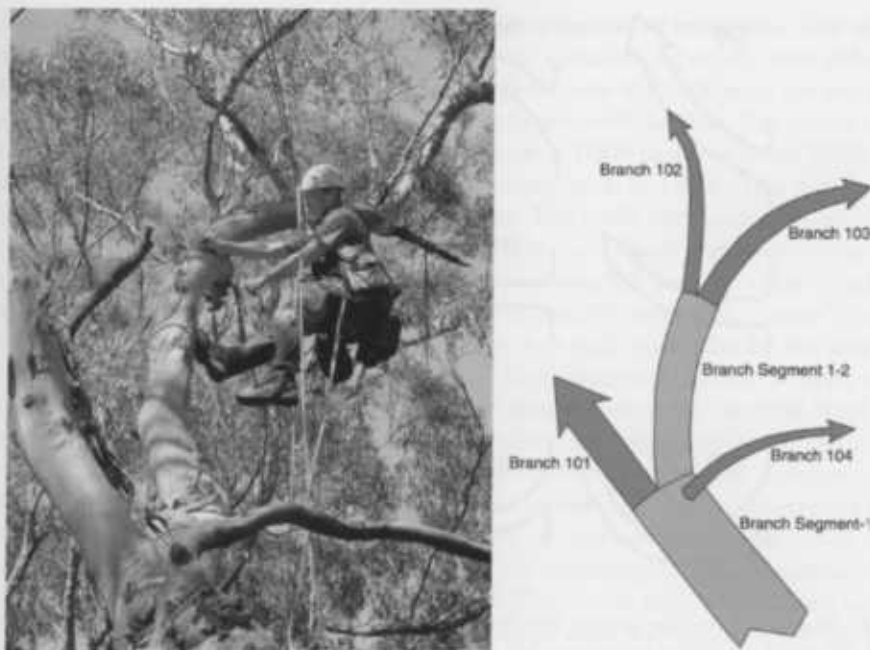


Figure 3-1 Photo of terminal end of limb segment being measured and a diagrammatic illustration of same system with limb segments and branches delineated.

results in many branches originating from the same location (Ishii and Wilson 2001). On old trees, these branch systems can become very well developed, sometimes containing a dozen or more epicormic branches emerging from a single locus on the trunk. In these instances, the entire epicormic system is given one number, but all of the branch parameters are separately recorded.

On young trees or older trees of many species, branches are simple and conform to a genetically programmed architectural model (Hallé et al. 1978). On such simple branches, biomass parameters of the branch can be predicted from measurements of basal diameter, extension, and percent of foliage cover. As trees age, branches sustain damage from disturbances and reiterate to become asymmetric and individualistic (Ishii et al. 2002). Biomass estimates of these complex branches require three additional measurements:

1. Number of bifurcations in which both forks exceed 4 cm in diameter;
2. Total axis length greater than 4 cm in diameter; and
3. Number of foliar units (see below).

Live axes are distinguished from dead axes, and their lengths are estimated to the nearest 0.5 m.

A *foliar unit* is a species-specific, naturally occurring unit that consists of repeating clusters of stems and foliage that can be counted to quantify foliage on individual branches. This modifies previous methods used to quantify foliage in *Pseudotsuga menziesii* (Pike et al. 1977; Massman 1982). In some tree species, leaf density within a foliar unit varies from tree to tree and along the height gradient, so calibration is needed to maintain accuracy and repeatability. At the beginning of the study, the crew assembles in a tree to discuss the foliar unit for that particular species. Also during sampling, a subset of randomly chosen foliar units are removed from each tree and brought to the ground for further calibration. These destructive samples are then brought to the laboratory

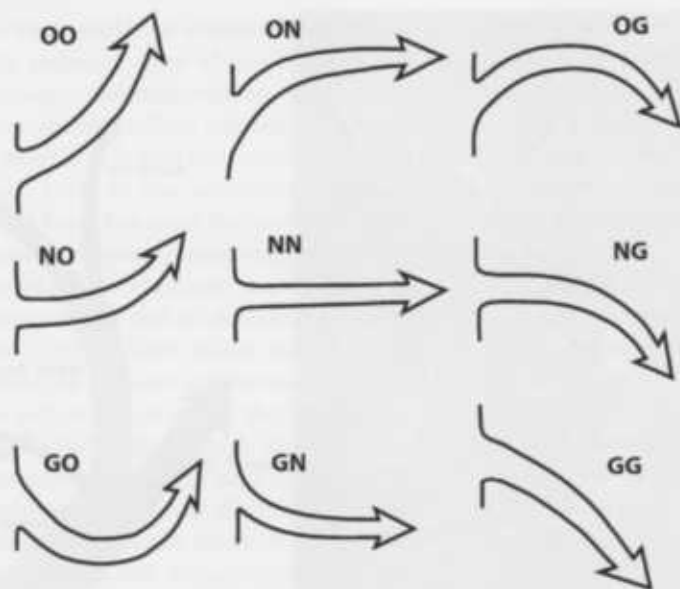


Figure 3-2 Diagrams of the nine possible branch-shape designations. The first letter refers to the basal half of the branch and the second letter refers to the outer half of the branch. O = orthotropic or upward tending, G = geotropic or downward tending, and N = neutral.

for dissection (see the Analyses section below). Trees in which the foliage on branches is sampled via foliar units do not need to have the percent foliated number recorded.

The spread, depth, and centroid of foliage on each branch are also estimated to improve visualizations and modeling of the crown mapping data since the foliage may not be centered on the branch. Spread is the greatest width of foliage associated with a branch in a horizontal plane perpendicular to the branch azimuth. Depth is the greatest length of foliage in a vertical plane. The centroid is the center of mass of all foliage associated with a single branch. Its location is defined in three dimensions by recording its height, distance, and azimuth relative to the main-trunk.

To account for all of the foliage on a tree, including leaves on branches less than 2 cm in diameter, live branches in 0 to 1 and 1 to 2 cm diameter classes are counted in 5 m height intervals throughout the crown. In the case of epicormic branch systems, these are given the branch number and height of that system. These data can be further refined by estimating the number of foliar units of these small branches aggregated by height intervals.

As mentioned above, trees with complex branches have a subsample of foliar units removed and brought to the laboratory for dissection. This will result in enough information to complete within-tree and between-tree comparisons. For trees with simple branches, this is not practical. Whole branches are very large in comparison to foliar units, so that the same amount of removal would be destructive to the forest and present a nearly insurmountable task in the laboratory. In these instances, a subset of branches is removed from the set of trees of the same species in the stand, so that the full range of branch sizes is sampled.

Analyses

Trees measured in the field with a laser as well as trees climbed and directly measured are used to develop species-specific equations predicting stem volume from height and DBH. On large

trees, DBH can vary with height in the region of many tropical trees. One method is to calculate a stem volume by taking the average diameter and area occupied by the stem. Another method is to calculate the volume by taking the average diameter and area occupied by the stem and then used with the volume of a cone or frustum. For a tree with measurement points by the trunk, the volume of the trunk is calculated as the volume of a frustum. For a tree with measurement points by the crown, the volume of the crown is calculated as the volume of a frustum.

The size of each tree is estimated by the volume of a conical shape (e.g., Hubbell and North 1996). The volume of a tree is estimated by the volume of a frustum. The volume of a tree is estimated by the volume of a frustum. The volume of a tree is estimated by the volume of a frustum.

Sample branches or foliar units (leaves) are dried, and weighed. The mass of branches is then divided by the number of branches to get the mass of a single branch. This mass is then divided by the volume of a branch to get the density of a branch.

To estimate leaf area, overlapping green leaves are measured. These leaves are then measured to get the leaf area. This allows the estimation of the leaf area of a tree.

In the case of a tree, the mass of the whole tree is estimated in the same manner as for a branch. The mass of the whole tree is estimated by the mass of the branches. The mass of the whole tree is estimated by the mass of the branches.

Destructive sampling of foliar units or whole branches are used to get tree estimates. In the sampling process, various methods are used to estimate the mass of a tree.

trees, DBH can vary greatly between trees due to the presence of buttresses. The addition of height in the regression is essential to help stabilize this variation, especially with old trees. On many tropical trees and *Eucalyptus*, this is not sufficient because the buttresses are too large and variable. One method is to measure above the buttresses with ladders (Condit et al. 1996). Another method is to develop a conversion from measured DBH to a functional DBH, which is calculated by taking the actual basal area and converting back to DBH. This requires using a survey laser and mapping the bases of a subset of trees. The trunk perimeter is mapped, and the area occupied by the fluted base is calculated with a digitizer. The set of diameter measurements is then used with the formula for a conic frustum to estimate the volume of the trunk. A frustum of a cone is simply a piece of a cone that has two parallel ends. The volume of a frustum is calculated as the average cross-sectional area of the two ends multiplied by the length of the frustum. For a trunk of a tree with multiple measured diameters, each section between two measurement points becomes a frustum, all of which are then summed for the total trunk volume. The volumes for branches, limb segments, and reiterations are calculated in the same way.

The size of each tree's crown must be calculated from the ground-based parameters. Simple conic shapes (e.g., cones and paraboloids) are useful for comparing relative crown sizes (Van Pelt and North 1996, Van Pelt and Franklin 2000). While an obvious oversimplification of eccentricities of individual trees, the measured parameters are surprisingly robust in estimating crown volume at the stand-level (Van Pelt and North 1999). The crown radii can be used to calculate a crown-projected area either through mapping individual radii and digitizing or through averaging. This radii is then combined with crown height and the chosen crown form to calculate crown volume.

Sample branches and foliar units are dissected in the laboratory. Components of each branch or foliar unit (leaves, twigs, branchlets, reproductive material, and epiphytes) are separated, oven-dried, and weighed. Component masses are then used as dependent variables, and branch dimensions (basal diameter, extension, and percent foliated) are used as independent variables in stepwise multiple regression analysis. The resulting species-specific equations are used to estimate component masses of all simple branches on each tree. For trees with complex branches, average values for the foliar units are used to estimate foliage biomass of all complex branches on each tree.

To estimate leaf areas, green, undried foliage of each species must be used. A subset of non-overlapping green leaves is counted and digitally scanned to obtain a one-sided estimate of leaf area. These leaves are then dried and weighed, and the specific leaf area ($\text{m}^2 \text{g}^{-1}$) is calculated. This allows the conversion of foliar biomass into leaf area for entire branches and trees.

In the case of thin-barked trees, the cambium may be an important part of the photosynthesis of the whole tree (Pflanz et al. 2000). The calculation of surface area proceeds in the same manner as for estimating volume. The surface area of a frustum is simply the average circumference of the two ends of the frustum multiplied by the length. In order to estimate the surface area on the smaller branches and twigs within the foliar units, these are separated into five categories: 3 to 4 cm, 2 to 3 cm, 1 to 2 cm, 0.5 to 1 cm, and < 0.5 cm, as well as leaves. The smaller branches within the foliar units are separated into five categories to aid in surface area estimations: 3 to 4 cm, 2 to 3 cm, 1 to 2 cm, 0.5 to 1 cm, and < 0.5 cm, as well as leaves. The total mass and linear length of each twig category is recorded for each foliar unit. These are converted to surface area per foliar unit and then combined with the trunk and branch measurements of surface area for a whole-tree surface area estimate.

Destructive samples of foliage biomass, leaf area, and leaf count, whether calculated from foliar units or whole branch estimates, must be applied to the entire trees to come up with whole-tree estimates. In the case of foliar units, because the entire tree was inventoried during the mapping process, values are simply multiplied for a whole-tree estimate. For trees in which entire

branches were measured in the field, regression must be used. Independent variables can include branch diameter, branch extension, branch height, and/or percent foliated. The predictive equation is applied to all of the branches within a tree that were not destructively sampled to derive a whole-tree estimate.

Once the tree-based estimates of branch and reiteration volume, foliage biomass, and leaf area are known for all of the mapped trees, we can estimate them for the remaining trees that were not climbed to derive stand-level estimates using multiple, stepwise regression. For each species, potential variables include DBH, height, crown depth, crown diameter, maximum crown radius, height to crown base, crown projection area, and crown volume.

Case Studies in Two Tall Forests

We selected two contrasting old-growth forest stands for detailed study, one in Victoria, Australia (Wallaby Creek), and one in Washington State, United States (Cedar Flats). These stands are similar in stature, but they differ greatly in composition and structure. We established 270 × 27 m plots at each site. Stem maps were made and double-checked prior to climbing any trees.

Site Descriptions

Wallaby Creek Located in Kinglake National Park, the Wallaby Creek forest straddles the Hume Plateau and helps supply the city of Melbourne with high-quality fresh water (see Table 3-1). There is strong interest in maintaining old-growth forest on the Plateau. Most of the old-growth *Eucalyptus* forests in Victoria have long been felled, but the unique situation of this site has allowed it to persist. It now stands as the tallest angiosperm-dominated forest in the world. The forest is 292 years old, having originated after a catastrophic fire (Ashton 2000), and is dominated by one tree species, *E. regnans* (see Figure 3-3). At least 26 trees over 85 m and at least two over 90 m tall occur here. A *Nothofagus/Atherosperma* rainforest mid-story, which is present in many of the Tasmanian *E. regnans* forests, is not present here. Instead, *Pomaderris aspera*, *Olearia agrophylla*, and tree-ferns (e.g., *Cyathea australis* and *Dicksonia antarctica*) form a dense understory along with occasional *Acacia* trees (*A. dealbata* and *A. melanoxylon*).

We climbed and mapped nine trees at Wallaby Creek. The selected trees represented the full array of sizes and crown structures, which allowed us to extrapolate to the entire stand. The extremely dense understory forced us to alter our standard protocol. Rather than uniformly sample the entire plot, a 20 percent sub-plot (270 × 5.4 m) was used for the *Pomaderris* and *Olearia* component. A complete inventory was made of tree ferns over the entire plot. *Eucalyptus regnans* has an easy-to-recognize foliar unit due to its fast growth and short leaf life (18 months; D. Ashton, personal comm.). Similar foliar units were used for the *Pomaderris* and *Olearia* shrub-trees;

Table 3-1 Summary of Site Characteristics*

Site	Latitude Longitude	Elevation (m)	Age	Slope (% aspect)	Precipitation (cm)			Temp (°C) Annual (Ave)
					Ann.	Summer	Snowfall	
Wallaby Creek	37° 26' S 145° 11' E	680	292	0.5% S	145	27 (18.6%)	~38	5.0-17.5 (8.9)
Cedar Flats	46° 07' N 122° 01' W	411	~650	0%	317	20 (6.3%)	77	5.0-14.4 (9.7)

*Both sites are on the margin of a Mediterranean climate with warm, dry summers and mild winters. The Cedar Flats stand is on swampy ground, thus reducing a need for summer precipitation. Precipitation data does not include condensation from fog, which can add 10-30% at both sites.



Figure 3-3 Photos of dense understory. No

these were counted 133 individuals v

We also quarantined *regnans* allows light through the bark, which protects the tree understory from fire. The height of this tra



Figure 3-3 Photo of the Wallaby Creek site. Photos are difficult to take once one leaves the roads due to the extremely dense understory. Note that the height of bark exfoliation roughly corresponds to the height of the understory.

these were counted from the ground. For tree ferns, we counted all live fronds on each of the 133 individuals within the plot.

We also quantified whole-tree surface area. The annual exfoliation of bark of *Eucalyptus regnans* allows light to penetrate through the very thin bark to the photosynthetically active bark, which presumably supplements foliar photosynthesis. Near its base, the main trunk retains thick bark, which protects it from low-level fires. This thick bark extends only to the level of the shrub-tree understory before giving way to the thin, smooth bark of the upper tree. We measured the height of this transition on each tree.

Cedar Flats Located in the Gifford Pinchot National Forest, the Cedar Flats Research Natural Area contains one of the finest *Pseudotsuga menziesii*-dominated forests remaining in the Cascade Mountains (see Table 3-1). The site was originally protected for its representation of *Thuja plicata* swamps, but magnificent 600- to 650-year-old *P. menziesii*/*Tsuga heterophylla* forests surround the swamps. These are among the largest and tallest known forests in the Pacific Northwest of North America, with individual *Pseudotsuga* up to 90 m tall and 360 cm in diameter (see Figure 3-4). *Thuja plicata* is a common associate, and there is a rich shrub/fern/herb/moss understory topped by *Acer circinatum*. Crowns of the large conifers support lush epiphyte communities dominated by lichens and bryophytes.

We climbed and mapped 17 trees of all three dominant tree species (10 *Pseudotsuga*, 4 *Tsuga*, and 3 *Thuja*). The foliar unit in *P. menziesii* was a 3- to 4-cm diameter branchlet, whose shape varied along the vertical gradient. Foliar units in the upper crown were more compact and dense than those in the lower crown. Because nearly all *Thuja plicata* and *Tsuga heterophylla* branches had simple architecture, basic branch measurements were adequate for foliage estimation in these trees.

Results

Basic Stand Comparisons Basic stand-level information was summarized for all of the tree species present on the plots, followed by summaries of the dominant species, *E. regnans* and *P. menziesii* (see Table 3-2). Although the density and basal area of *P. menziesii* were only about half as high as *E. regnans*, the mean diameters, heights, and their respective standard deviations were similar. The main structural difference between the two forests was attributable to the absence of tree crowns in the mid-story canopy at Wallaby Creek. The abundance of the small shrub-trees at Wallaby Creek reduces the mean DBH to a value 15 cm smaller than the mean DBH at Cedar Flats, while increasing its standard deviation (see Table 3-2). A similar phenomenon occurred with tree height, although the presence of a tall mid-story provided a more even distribution of tree heights at Cedar Flats, where the standard deviation of height was less than the mean.

These differences in stem number, basal area, and the presence or absence of a mid-story canopy were clearly evident in the trunk diameter distributions of the two forests (see Figure 3-5). The presence of a dominant *Tsuga heterophylla* component at the Cedar Flats site fills the mid-story whereas the large diameter *Thuja plicata* somewhat compensated for the difference in density of the large trees.

Mapped Tree Comparisons While on ropes, a total of 51,371 measurements were taken on 4,541 branches, 194 limb segments, and 125 reiterated trunks on the 26 mapped trees in this study (see Table 3-3). All tree heights were measured from the ground, but the final number reported is that obtained by direct climbing and measuring. Due to the techniques used to measure tree height and the additional advantage of having lasers, the difference between the ground-based estimates and actual tree heights was small (1.2 percent error).

Clipped foliar units were used to derive the whole-tree foliage biomass estimates for *E. regnans* and *P. menziesii*. Foliage biomass on the foliar units of *E. regnans* averaged 874 g (sd = 263 g, n = 9) while the foliar units of *P. menziesii* averaged 297 g (sd = 66 g, n = 38). The crowns on some of the *P. menziesii* trees at Cedar Flats are among the largest known for that species. A value of over 500 kg of foliage biomass on a single tree is nearly twice that previously reported (Pike et al. 1977). Six of the ten trees climbed had values over 300 kg (see Table 3-3).

The foliar biomass of *Tsuga heterophylla* and *Thuja plicata* were estimated from whole branch samples. The number of collected branches on these two species was too small to develop branch-based estimates of foliage biomass, so data from branches we collected were supplemented with previously published data and equations from felled trees (Brown 1976, 1978; Snell and Anholt 1981; Snell and Max 1985; Means et al. 1994).

Figure 3-4 Photograph of *Thuja plicata*. Note the ab

Research Site	S
Wallaby Creek	5
Cedar Flats	2

*The first column alone—*Eucalyptus* or *P.* and the standard deviation is in m².



Figure 3-4 Photo of the Cedar Flats site. The two rough-barked trees are *Pandanus menziesii*, the others *Tsuga heterophylla*. Note the abundant bryophytes on trunks, branches, and the forest floor.

Table 3-2 Stand Characteristics for Each Site*

Research Site	Stem Count		Mean DBH		σ DBH		Mean Height		σ Height		Basal Area	
	Stand	Dom	Stand	Dom	Stand	Dom	Stand	Dom	Stand	Dom	Stand	Dom
Wallaby Creek	515	51	43.0	205.1	71.6	45.8	18.7	76.6	25.1	6.1	186.6	176.0
Cedar Flats	232	29	58.4	210.8	67.8	50.3	27.4	77.3	23.2	8.2	133.2	86.4

*The first column in each of the six categories listed are shown for all trees, followed by that for the dominant (Dom) tree alone: *Eucalyptus* or *Pandanus*. Stem count and basal area are per hectare values, and includes all trees >5 cm dbh. Mean diameter and the standard deviation of diameter are in centimeters, mean height and standard deviation of height are in meters and basal area is in m^2 .

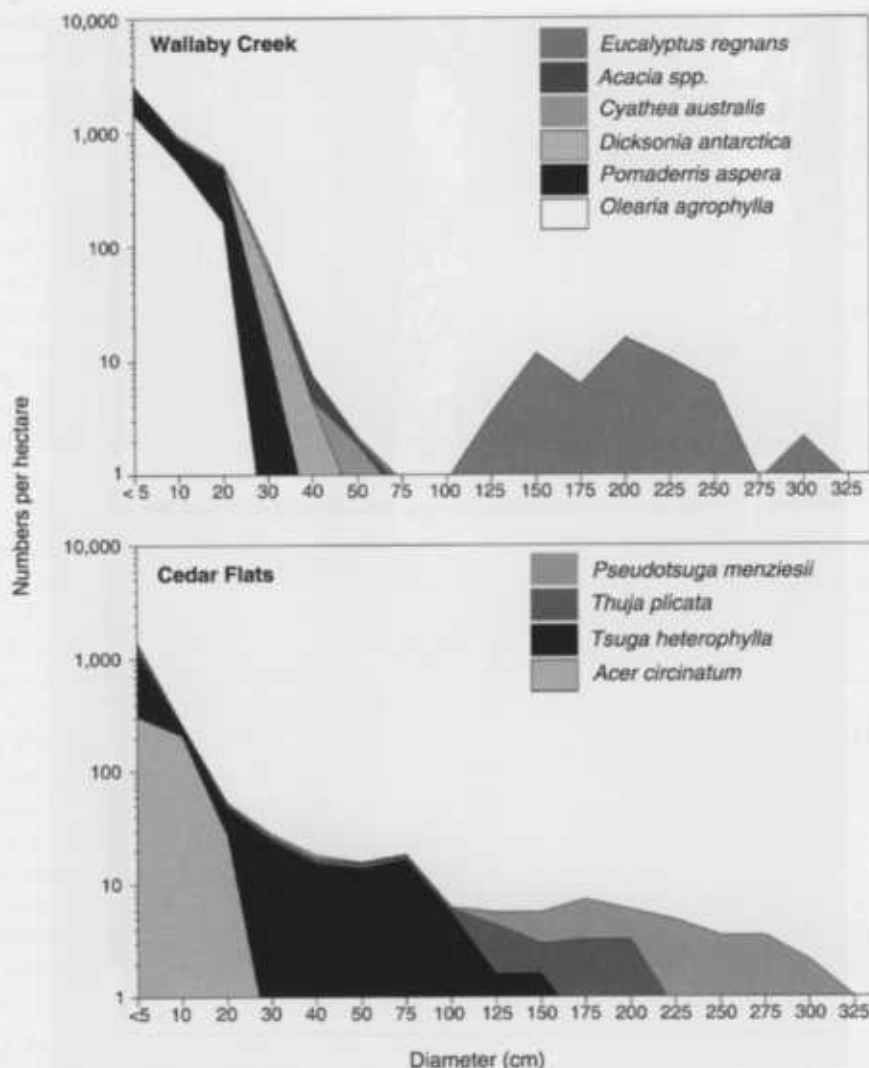


Figure 3-5 Diameter distribution of trees at the two sites. The Y-axis is logarithmic. Note the lack of medium-sized trees at Wallaby Creek.

To determine whole-tree surface area on *E. regnans*, component areas were calculated on all of the trunks, limbs, and branches. The lower portion of the main trunk covered with thick bark was excluded from these calculations. The surface area per foliar unit was multiplied by the total foliar unit count and then added to the remainder of the tree to come up with whole-tree estimates of surface area (see Table 3-3).

Visualizations Every measurement taken within the crowns was done in a spatial context so 3-D visualizations were possible. Two perpendicular views of the largest *Eucalyptus* and *Pseudotsuga* within this study were prepared using all of the height, diameter, and extension data for trunks, reiterated trunks, limbs, branch segments, and branches to show these capabilities (see Figure 3-6).

Table 3-3 Summary Statistics of the Mapped Trees from the Two Old-growth Sites*

DBH	Height	Crown Depth	Crown Spread	# of Branches	# of Limb Segments	Branch Vol	# of Reits	Reit Vol	Main trunk Vol	Total Vol	Foliage Biomass	Bark Surface Area
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Table 3-3 Summary Statistics of the Mapped Trees from the Two Old-growth Sites*

	DBH	Height	Crown Depth	Crown Spread	# of Branches	# of Limb Segments	Branch Vol	# of Reits	Reit Vol	Main trunk Vol	Total Vol	Foliage Biomass	Bark Surface Area
Wallaby Creek													
<i>Eucalyptus regnans</i>													
	316	85.5	30.2	21.4	112	33	14.8	2	0.5	134.5	149.7	353 (45)	1,274
	247	91.6	23.6	13.3	49	13	7.1	1	1.2	98.0	106.3	155 (20)	664
	240	79.2	21.2	14.3	63	11	7.2	0	0.0	86.1	93.3	139 (20)	649
	227	79.3	20.7	18.5	54	6	7.1	2	0.2	74.7	82.0	162 (20)	680
	226	85.2	24.2	14.0	34	16	6.7	1	0.1	74.7	81.5	240 (30)	831
	208	82.1	21.1	14.8	73	17	7.2	3	2.7	64.6	74.5	170 (21)	693
	203	75.6	19.3	13.2	36	9	4.5	0	0.0	59.1	63.6	119 (15)	482
	196	78.8	23.7	12.2	24	3	2.1	0	0.0	46.5	48.6	87 (11)	385
	133	73.9	24.4	9.7	23	0	1.9	0	0.0	37.7	39.6	59 (7)	277
Cedar Flats													
<i>Parishliranga menziesii</i>													
	308	86.5	52.0	15.2	426	16	12.2	22	2.1	140.5	154.8	381 (57)	
	281	84.5	30.5	17.8	133	6	9.5	6	0.1	138.0	147.5	206 (30)	
	249	78.1	63.6	14.8	317	3	13.0	6	0.4	130.2	143.7	514 (80)	
	263	79.4	46.9	15.1	225	14	10.3	19	0.6	124.4	135.3	364 (54)	
	266	83.8	60.8	15.4	343	6	11.6	12	1.1	113.2	125.9	397 (60)	
	226	84.5	64.0	16.3	248	6	9.1	8	0.3	108.5	117.9	366 (57)	
	219	83.4	55.6	14.6	330	11	7.5	13	0.3	101.0	108.8	319 (49)	
	231	80.7	44.1	12.7	107	6	3.1	6	0.1	94.8	97.9	245 (75)	
	209	77.7	48.2	10.1	171	2	1.2	2	0.0	37.8	59.0	215 (32)	
	176	70.4	40.0	11.4	72	2	0.7	3	0.0	44.5	45.3	136 (21)	
	222	51.1	35.7	11.0	356	10	1.7	13	0.5	32.6	34.9	309 (58)	
<i>Thuja sibirica</i>	204	60.7	46.3	11.6	369	0	1.3	0	0.0	32.0	33.2	288 (57)	
	177	56.0	43.4	12.8	231	4	2.4	6	0.2	25.1	27.6	239 (68)	
<i>Tungus heterophylla</i>	119	52.8	37.4	11.6	197	0	2.8	0	0.0	17.6	20.4	200 (35)	
	77	48.4	42.0	11.0	139	0	0.7	0	0.0	7.5	8.2	130 (26)	
	82	46.2	40.1	12.0	205	0	0.7	0	0.0	6.8	7.5	149 (24)	
	61	43.0	31.1	10.4	184	0	0.5	0	0.0	3.9	4.4	89 (17)	

*Trees are listed by species in descending order of total volume. DBH is in cm and represents the functional diameter (actual basal area converted into a diameter). Height and crown dimensions are in m. Reit refers only to reiterated trunks. Volumes are in m³, foliage biomass (g) in parentheses) in kg, and surface area in m². See text for discussion of specific variables.

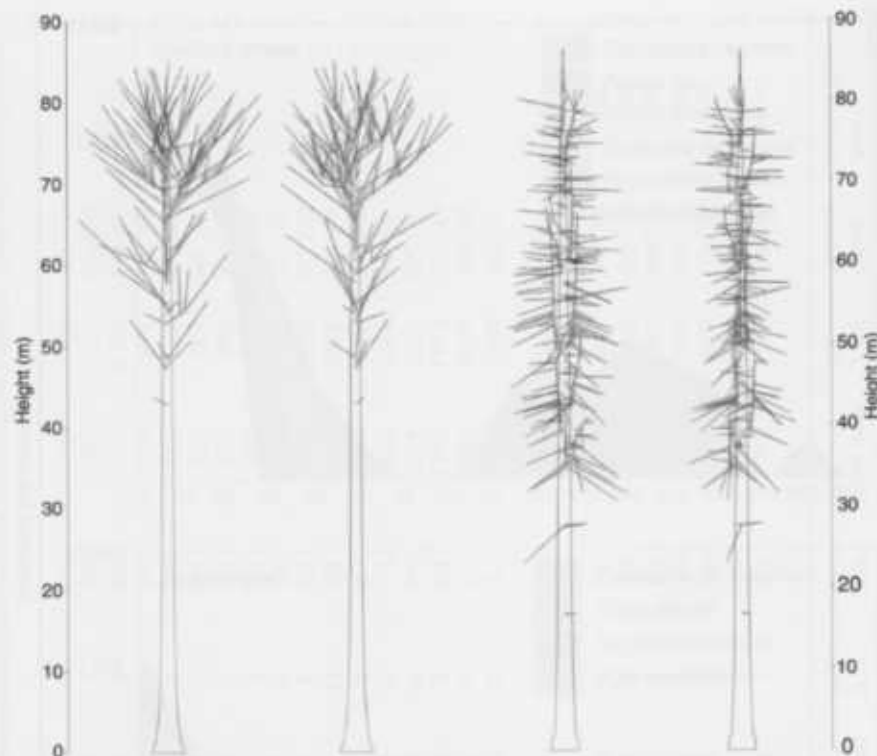


Figure 3-6 Two perpendicular views of the largest tree at each site. The main trunk, all reiterated trunks, limbs, branch segments, and branches are shown.

The 3-D tree maps were used to help prepare a stand profile drawing for each site. These were combined with location data from the stem map, all of the ground-based tree measurements, and detailed sketches and photos made on site (see Figure 3-7). The width of the transect was partly chosen for its usefulness in stand profile visualizations, allowing reasonable illustrations of stem density, tree height, and form. Using the stem map data, we constructed comparative maps including crown projections for the two sites (see Figure 3-7).

Scaling Up to Stand Level Once whole-tree estimates of branch and reiteration volume, foliage biomass, and leaf area were calculated, we were then able to estimate (via regression) these quantities for the remaining trees that were not climbed to derive stand totals (see Table 3-4). Mapped tree bases for *Eucalyptus* provided the data needed to calculate functional DBH from measured DBH ($r^2 = 0.953$, $n = 14$). The volume of the main trunk, branches, and limbs were then estimated from the results ($r^2 = 0.978$, $n = 14$; $r^2 = 0.822$, $n = 9$). Bark surface area (that portion above the thick-barked base) was also estimated at the stand-level. The thin-bark portion of *Eucalyptus* in the forest was nearly one-quarter the surface area of the leaves. The values for total wood volume and foliage biomass for the *E. regnans* forest are the highest recorded for Australia and are only known to be exceeded by some *P. menziesii* and *Abies procera* forests in the Pacific Northwest of North America, as well as many *Sequoia sempervirens* forests in coastal California (Van Pelt and Franklin 2000; Sawyer et al. 2000).

At Cedar Flats, the wood volume for unmapped trees was predicted from regression equations based on height and diameter (*P. menziesii* $r^2 = 0.949$, $n = 42$; *T. plicata* $r^2 = 0.956$, $n = 23$; *T. heterophylla* $r^2 = 0.987$, $n = 58$). Foliage biomass estimates were regressed on crown volume,

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"CANOPY TREKKING": A GROUND-INDEPENDENT, ROPE-BASED METHOD FOR HORIZONTAL MOVEMENT THROUGH FOREST CANOPIES

Roman Dial, Stephen C. Sillett, and Jim C. Spickler

Who among us, having climbed into the canopy, has not wanted to move "just over there" maybe a few meters, maybe into another tree, or maybe even across the entire forest canopy? The canopy raft (Hallé 1990), "web" (Perry and Williams 1981), cranes (Shaw, this volume), booms (Ashton 1995), walkways (see Chapter 23), and zip-lines (Chapter 25) are all realizations of this wish for horizontal freedom within forest canopies. Unfortunately, all of these techniques are expensive with regard to both time and money, are sometimes cumbersome and elaborate, and are potentially harmful to the canopy we wish to study. What many of us really want is the individual freedom to go where we want and to leave little trace of our passage.

The first hint of rope-based horizontal movement came with exposure to arborist techniques for moving within crowns and between trees (Dial and Tobin 1994; Jepson 2000).



Figure 1

Continued

"CANOPY TREKKING"—cont'd

Because these techniques use a moving rope rather than single rope technique (reviewed by Moffett and Lowman 1995; Lowman and Wittman 1996), climbers can move through the canopy pulling their ropes along with them, moving for hours or even days in any direction they can situate their ropes.

The principal objective in rope-based horizontal movement through a canopy is to place a climbing rope from one limb across the top of a second limb and to retrieve the rope from under the second limb and back to the climber at the first limb. Then the rope can be anchored, allowing the climber to move horizontally from the first to the second limb. The process of actually moving between limbs is straightforward, and several techniques can be used (Dial and Tobin 1994; Smith and Padgett 1996). What is more problematic is how to (1) get the climbing line over the second limb and (2) retrieve it from under the second limb.

Sillett and his students at Humboldt State University working with inventor Tom Ness came up with a fist-sized mini-grapnel attached to fly-fishing line for retrieving throw bags tossed over distant limbs. This technique described by Ellyson and Sillett (2003) is suitable for distances less than 10 m. For distances greater than 10 m, we employ something called the "magic missile" (see Figure 1). The magic missile is a fiberglass arrow tipped with re-curved tines and a backward pointing barb fired from a 150-pound pull crossbow. The missile is tied to fishing line fed from a crossbow-mounted spinning reel. This setup can be used to retrieve a throw bag line up to 40 m away. We have applied the technique for greater than 500 m horizontal movement through tall canopies in California conifers and hardwood forests in Borneo and Australia (Weintraub 2003).

While orangutans, gibbons, and spider monkeys still mock our technique, it does bring canopy access and movement closer to the ideal of total freedom of movement that is low in weight, cost, and impact to the forest environment.

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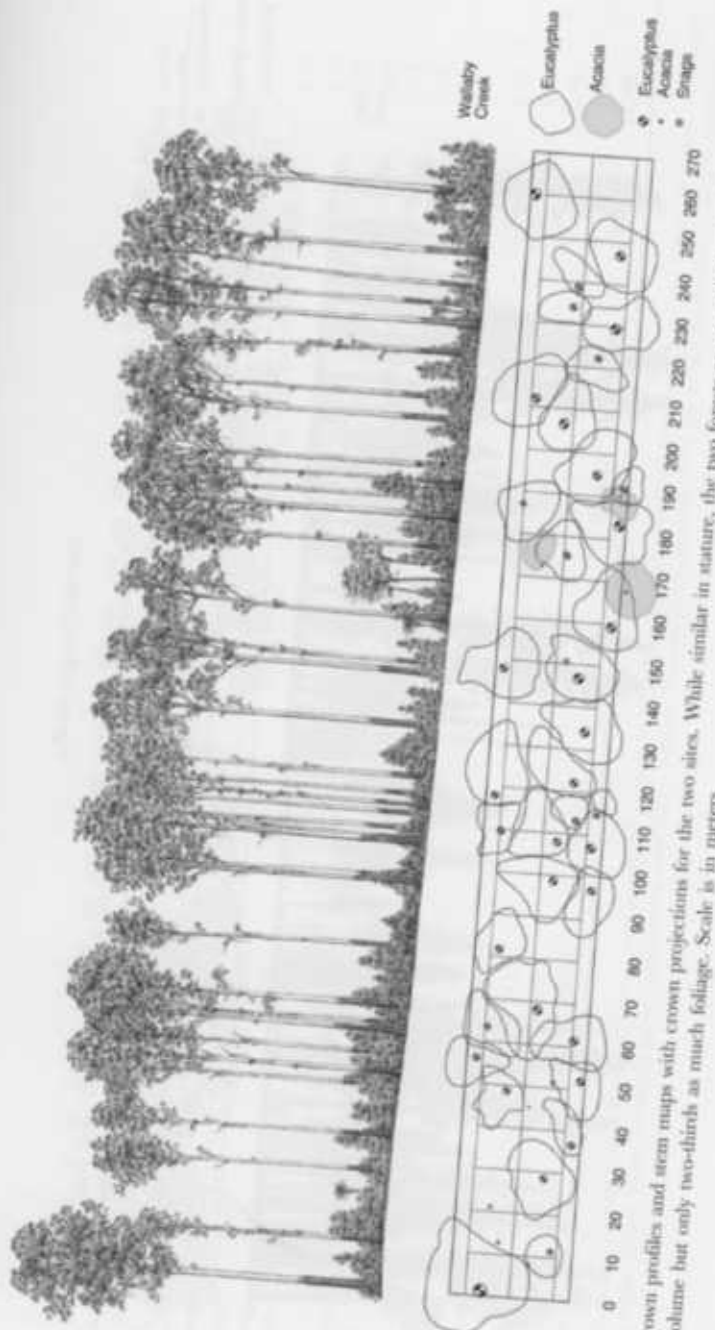


Figure 3-7 Crown profiles and stem maps with crown projections for the two sites. While similar in stature, the two forests are very different architecturally. Wallaby Creek has a higher wood volume but only two-thirds as much foliage. Scale is in meters.

Continued

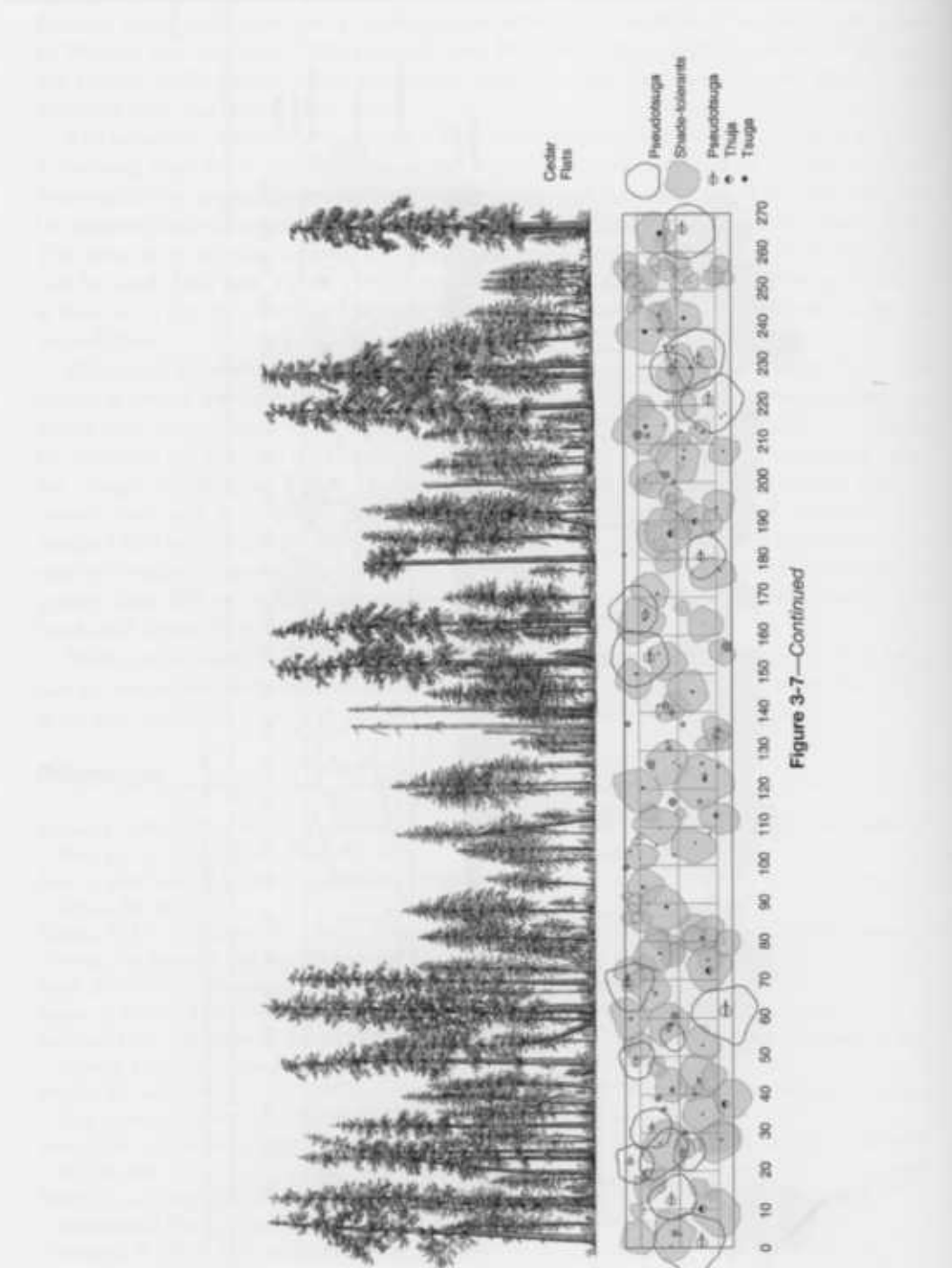


Figure 3-7—Continued

Table 3-4 Summary of Total Stem Numbers, Basal Area, Wood Volume, and Foliage Components at the Two Sites*

Species	Stem Count	Basal Area	Main trunk Volume	Branch Volume	Reiteration Volume	Total Volume	Crown Volume	Foliage Biomass	LAI	SSA
Wallaby Creek										
<i>Eucalyptus regnans</i>	51	176.0	2,902.8	234.3	9.7	3,146.8	101,310	5,931	4.59	24,018
<i>Pinusideris aspera</i>	133	2.6	50.6	34.0	—	84.6	19,510	2,832	4.10	—
<i>Olusia apophylla</i>	145	1.9	16.3	17.9	—	34.2	8,720	610	0.75	—
<i>Acacia</i> spp.	4	0.4	2.9	1.1	—	4.0	1,378	124	0.03	—
<i>Dicksonia antipodica</i>	155	4.1	—	—	—	—	3,350	991	0.48	—
<i>Gynerium australe</i>	27	1.6	—	—	—	—	620	172	0.08	—
Total	515	186.6	2,972.6	287.3	9.7	3,269.6	135,088	10,660	10.03	
Cedar Flats										
<i>Paratocoge macgregoriae</i>	29	86.4	1,904.7	116.9	8.7	2,030.3	101,500	6,082	4.26	—
<i>Tinnea heterophylla</i>	155	23.4	206.0	18.9	0.7	225.5	76,960	6,949	4.20	—
<i>Thuja pluvialis</i>	23	20.9	273.7	17.3	7.3	298.3	19,100	2,772	2.07	—
<i>Acer circinnatum</i>	25	2.5	0.9	0.3	—	1.2	3,790	302	0.96	—
Total	232	133.2	2,385.3	153.4	16.6	2,555.3	203,350	16,005	11.49	

*Listed are the total stem numbers of each species per hectare, basal area (in m² per hectare) by each species, the various wood components (in m³ per hectare) by species, crown volume (in m³ per hectare) by species, foliage biomass (kg per hectare) by species, and leaf area index (LAI - Unitless). The total stem surface area (SSA) per hectare is calculated for only the escarpment and excludes the portions of the lower trunks covered by thick bark.

crown height, DBH, height, wood volume, branch volume, and reiteration volume to find the best-fit predictors. For *P. menziesii*, the best predictor was crown volume and the ratio of branch plus reiteration volume to trunk volume. For *T. plicata*, it was DBH, height, and crown height. For *T. heterophylla*, it was DBH and the ratio of crown height to tree height.

Using the ground-based measurements of the crown location of individual trees, the known foliage distribution of the climbed trees, and the foliage biomass estimates for all of the trees, we estimated the vertical distribution of foliage biomass by tree species for the two sites on a per hectare basis (see Figure 3-8). This was accomplished by calculating how much of the crown of each tree will be present at a given height for each 2 m height interval. Based on the crown shape chosen for a given tree (e.g., paraboloid and cone), the proportion of its crown volume was separated into 2-m segments, based on the total crown height, then summed and converted into per-hectare totals.

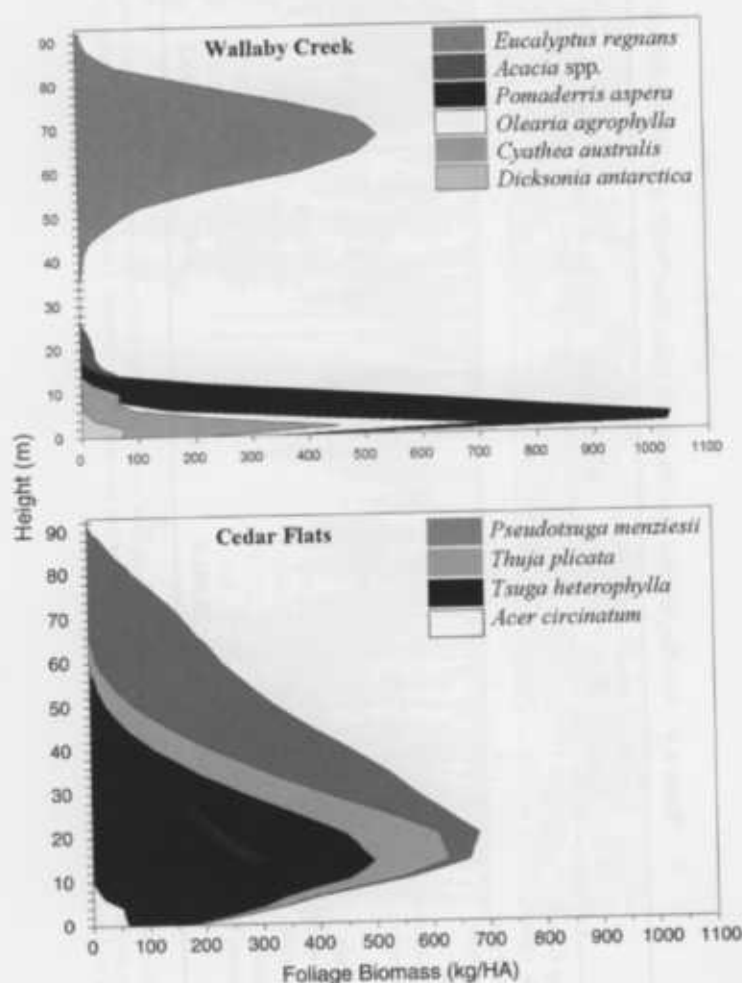


Figure 3-8 Vertical canopy distribution at the two sites. While both forests have foliage distributed for 90 m, it is astounding that the two distributions are nearly the inverse of each other.

Accuracy is one of the main concerns. Trees have been mapped but this is limited to diameters cannot be used for example, it may be useful for each ground-based map.

Biomass estimates from debris to estimate Logan 1977; Snell and damage to the Within-tree mapping. Apart from some technique useful in nature reserves).

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Discussion

Accuracy is one obvious strength of direct within-tree mapping over ground-based methods. Trees have been mapped from the ground (Sumida et al. 2001; Nychka and Nadkarni 2003), but this is limited to relatively small trees. Also, only the branching nodes can be mapped; branch diameters cannot be accurately measured from the ground. The resulting stick-figure representation may be useful for some applications but not for others. In the two stands used in this study, for example, it was a challenge to get accurate estimates of tree height, let alone the 3-D coordinates for each node within the crown. Evergreen trees further complicate the problem for ground-based mapping techniques by hiding much of the needed information with foliage.

Biomass estimates have often been obtained by felling trees and then sorting through the debris to estimate such aspects as branch size, wood volume, and foliage biomass (Grier and Logan 1977; Snell and Anholt 1981; D. Ashton, personal communication). The amount of debris and damage to the crowns of large trees after they have fallen reduces the usefulness of the data. Within-tree mapping techniques permit the acquisition of these data with minimal disturbance. Apart from some clipped branches, there is virtually no impact on the forest. This makes the technique useful in many situations where little or no felling is allowed (e.g., national parks and nature reserves).

The use of transects to establish stand maps prior to canopy access enabled us to extrapolate our results from individual trees to the whole stand. Previous studies using within-tree measurements (e.g., Pike et al. 1977; Clement and Shaw 1999; Ishii et al. 2000; Ishii and Wilson 2001) focused on individual trees and were unable to extrapolate to entire stands.

Quantifying the surface area of tree bark, which is easily accomplished using the methods presented here, facilitates studies of photosynthesis and epiphytes. The bark of many trees contains chloroplasts, and bark photosynthesis can substantially contribute to carbon gain at the whole-tree level (Pflanz et al. 2000). Knowing the linear distances between branch nodes is not adequate for such estimations. Only by mapping the diameters of the trunks, limbs, and branches can these estimates be made with a high degree of accuracy. Bark surface area is also useful when attempting to estimate epiphyte biomass on a whole-tree basis. Such estimations require random sampling a known proportion of a tree's surface area and then extrapolating to the whole tree by dividing epiphyte masses by the sampling intensity (Pike et al. 1977; Nadkarni 1984; Rhoades 1981; Hofstede et al. 1993; Ellyson and Sillett 2003). Accurate quantification of bark surface areas on whole trees would greatly improve these estimations.

Quantifying the biomass of foliage in forests has become a high priority for models of ecosystem productivity, stand respiration, and carbon budgets (Chen et al. 2002). Leaf Area Index (LAI), a concept developed in agricultural research for estimating productivity, has often been used as a surrogate for foliar biomass. Its use in forested ecosystems has always been uncertain (Parker 1995; Parker and Brown 2000; Turner et al. 2000; Van Pelt and Franklin 2000). In some simple, plantation forests, LAI is not difficult to obtain. For tall-stature forests, however, these data are nearly impossible to collect from the ground. Optical methods, which are based on the amount of light passing through the canopy, are useless since in complex canopies there is a low correlation between the amount of foliage and the amount of light transmitted by a canopy (Van Pelt and Franklin 2000). Vertical foliar arrangement in forests determines how much light will penetrate much more than the total amount. Direct methods such as line intercept sampling can be accurate but are extremely time-consuming in tall forests (Thomas and Winner 2000). Remote techniques have promise but are most useful for landscape-level assessments (Leřky et al. 1999).

The techniques presented here provide a simple, universal protocol for mapping the 3-D structure of forest trees. Since the methods are rope-based, they are not limited to areas that already

have a canopy crane, walkway, or other expensive, permanent structure. The nondestructive nature of the protocol allows trees at virtually any location to be considered. The resulting datasets yield information on the 3-D structure of a forest, including foliage biomass, leaf area, bark surface area, and wood volume. They allow quantification of vertical and horizontal distributions of these variables at whole-tree and stand levels.

There are, however, a few disadvantages to our protocol. Chief among them is the need for tree climbers experienced in the use of nondestructive, arborist-style rope techniques. The initial rigging of study trees is particularly difficult for novices. Thus, research budgets must include funds for experienced climbers to rig the trees and train others in safe rope technique. Without proper care, foot traffic and moving ropes involved in tree climbing also have a negative impact on tree surfaces, especially delicate epiphytes. This damage can be minimized by the use of soft-soled shoes and cambium savers (see Jepson 2000).

Another disadvantage of our protocol is a bias toward trees that are safe to climb. Dying and excessively leaning trees are too dangerous and can only be accessed from traverse ropes suspended between sturdy surrounding trees. Thus, our protocol should not be used to study declining forests containing many hazardous trees.

Not only do the methods presented here give an accurate assessment of the amount of foliage of individual trees, but they also yield stand totals. These can be converted into total leaf number or leaf surface area, which are useful for analyzing canopy-atmosphere interactions (Baldocchi et al. 2000), as well as nutrient and gas exchange estimations (Martin et al. 2001).

The strength of our mapping protocol for large trees lies in its simplicity. In this case study, we effectively mapped two tall forests with widely differing architectures. The key is quantification of each major structural component of tree crowns—including the main trunk, reiterated trunks, limbs, branches, and foliar units—and cataloguing these components in a 3-D framework. From this perspective, the differences between the architecture of conifers and angiosperms become trivial; even a banyan (e.g., *Ficus bengalensis*) is mappable using these techniques.

Acknowledgments

This research was supported by the National Science Foundation (BIR 96-30316 and BIR 99-975510) and the Global Forest Society (GF-18-1999-51, GF-2001-18-201, and GF-2001-18-202). Trees were rigged by lead climbers Steve Sillett, Jim Spickler, and Billy Ellyson. Assistant climbers were Marie Antoine, Yoav Bar-ness, Dan Barshis, Matt Dunlap, Kelly Gleason, Tom Greenwood, Mariah Gregori, Karl Gillick, Rich Gvozdz, Brenden Kelley, Steve Rentmeester, Abraham Svoboda, Gary Tryon, Greg Urata, and Robert Van Pelt. Thanks to Peter Frenzen for helping set up accommodations near Cedar Flats in Washington. Thanks also to Ion Maher for providing accommodations and access to facilities at Kinglake National Park in Australia. We thank David Ashton for valuable ecological insights about *Eucalyptus regnans* forests. Judith Cushing and Erik Ordway gave valuable database input to the project. We thank the Computer Applications Laboratory at the Evergreen State College for technical support. We also thank Roman Dial and National Geographic for their assistance.

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