

Calculation of Wood Volume and Stem Taper Using Terrestrial Single-Image Close-Range Photogrammetry and Contemporary Software Tools

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A method of estimating trunk and branch volumes of single trees is presented that uses a combination of elementary field measurements, terrestrial photography, image rectification and on-screen digitising using commercial software packages and automated volume calculation. The method is applicable to a variety of different sized trees in situations where the trunks are clearly visible. Results for taper measurement and wood volume calculation are presented for *Eucalyptus regnans* F. von Muell., *Sequoiadendron giganteum* (Lindley) Buchholz and *Quercus robur* L. Branch allometrics are provided for *E. regnans*. The largest errors arose from field observations. If the trees are asymmetrical in cross-section (e.g. due to irregular buttressing or forked stems), or if there is no vantage point perpendicular to the direction of lean, then photographs from more than one side are recommended. Accuracy and precision of geometric reproduction by the image rectification process, and the volume calculation, were tested using mathematically generated tree components. The errors in the branch volumes of the virtual tree showed complex trends due to interacting factors. Volumes were underestimated by an average 0.5% for stems and 4% for branches. Due to the area deficit resulting from non-circular cross-sections of the buttress, overestimation of stem volumes could be as high as 10% on average for mature trees. However, the area deficit was known for *E. regnans* and incorporated into the volume calculation. The underestimation of volumes would help counteract overestimation due to the area deficit. The application of this method to carbon accounting in forests and woodlands is explained.

Keywords terrestrial, photography, rectification, volume, taper, branches, biomass

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1 Introduction

Estimating the stem volume of standing trees usually entails measurements of tree diameters at several heights up the trunk, or for the more well studied species, integrating mathematical taper functions (Philip 1994, Robinson and Wood 1994). Hengl et al. (1998) calculated stem volume from stereo-photogrammetry of mature trees surrounded by a cubic array of survey points, photographed with a non-metric digital camera, and followed by edge detection analysis. From terrestrial photography of seedlings, Ter-Mikaelian and Parker (2000) developed a relationship between biomass, basal diameter and silhouette area. Gaffrey et al. (2001) obtained stem volume and taper curves of mature trees using single-image 35 mm photography, with a graduated pole for scaling, then retrieved measurements from the negatives using specially designed hardware. Terrestrial still and video cameras, in combination with laser range finders and magnetometers, have been used (Clark 2001) to measure segments of trees. The latest and most expedient method does not use a camera but a terrestrial scanning laser range finder that collects centimetre accuracy details of tree features in 3D and can produce stem volumes within a few minutes (e.g. Walden, Smart Forests, New Zealand, pers. comm., 2002). Presented here in detail is a method that uses single-image terrestrial photogrammetry to measure aboveground woody tree volume and biomass. A 35 mm single-lens reflex camera is used but a high-resolution digital camera would also be suitable. Some aspects of the field methods are related to those of Hengl et al. (1998) and others to Gaffrey et al. (2001) but the image analysis uses a finer spatial resolution by employing turnkey remote sensing and GIS software, followed by automated volume calculation. An outline and preliminary results of the method were given in Dean et al. (2003).

Our projects involve landscape-scale carbon sequestration forecasting and in the forests that we studied initially, the pre-dominant species was *Eucalyptus regnans* (F. von Muell.) (swamp gum/mountain ash). Fieldwork was undertaken because taper curves and biomass estimates were unavailable in the literature for the more mature *E. regnans* trees, i.e. with diameter at breast

height over bark (DBH) greater than 3 m. Only one even-aged, unlogged stand of such trees is known to exist on mainland Australia (the Big Trees Flora Reserve in the Otway Ranges) but several such stands exist in the island state of Tasmania. Experiments that might involve damage to such trees or their surroundings are best done during logging because the stands are cleared and burnt anyway. Consequently, most of the measurements on *E. regnans* were performed in clearfell logging coupes in Tasmania. The trunks often split when the trees were felled so we had to measure their taper while they were standing. For trees over about 30 metres a larger size of Spiegel relaskop is necessary to measure standing tree taper, alternatively a laser dendrometer can be used, but neither of these were available at the time. Soon after the understorey around the trees of interest in the logging coupes was cleared then the *E. regnans* themselves were felled, thus measurements had to be taken quickly. The quickest method available at the time for getting the measurements of large trees was to take photographs with the intention of taking measurements off the developed prints.

Computer software is available for correcting perspective distortion, rotational and some lens distortion (e.g. "Lensdoc", Andromeda 2002). Software used for correcting remotely sensed imagery goes one step further with the resultant image in metres. Remote sensing software is available in many resource management, geography or environmental science departments as it is often used in conjunction with GIS software. The software package Imagine (Erdas Inc. 2001) has a suitable geocorrection facility, that allows a camera model to be specified and adjusted by least squares refinement and the image rectified. The theory behind the rectification process in Imagine is explained in the "Photogrammetric Concepts" chapter of their "Field Guide" manual (Erdas Inc. 2001), in Wang (1990) and in Dowman and Tao (2002).

The method of stem measurement presented here uses photography of the whole tree, from which the stem is measured as a whole unit. This method inherently develops a taper curve of the stem and integrates the curve to get the volume of the tree. While the taper curve step is invisible to the operator, it can be written to a separate file

for reference. If several same species trees, with a range of sizes are measured and their volume determined, then a formula for DBH versus volume (for example) can be determined.

Little data was available on branch biomass of mature *E. regnans* but it is a necessary component of forest biomass calculations. Attiwill (1962) has shown that branch dry weight is related to branch girth for *Eucalyptus obliqua*, via a log-log equation. The point of measurement of the branch girth is just before it diverges into further branches. *E. regnans* has some similar properties to *E. obliqua* (e.g. they can hybridise, Ashton 1958) and so it was considered feasible that the branch biomass (and hence volume) would have a log-log relationship with branch girth (or diameter) for *E. regnans* also. Once such a relationship has been determined, it can be used to estimate total branch biomass for a tree.

The aim of the present study was to develop a method of measuring above-ground, woody volume, stem taper and biomass of mature trees, including those up to 100 m tall (e.g. *E. regnans*) without felling the tree and without causing indelible damage to the tree or nearby understorey. Examination of larger specimens allows derivation of allometrics, measurement of growth habits; and calibration of forecasting models for carbon sequestration. Non-destructive analysis in particular allows measured specimens to remain part of the sequestered carbon in the area of study. Other requirements were that the method developed must be reasonably fast and economical, require only the technical skills of a field technician and remote sensing or GIS analyst, and use turnkey software packages for image processing of 35 mm colour photography. In this study it was necessary to develop software for volume calculations from processed imagery but that software is now available for use in any further such analyses.

2 Materials and Methods

2.1 Study Location

The *Eucalyptus regnans* were studied mainly in clearfell logging coupes (compartments) in Tasmania: AR023B near Geeveston and SX004C in the Styx Valley. One was also measured in the Victorian Central Highlands. The *Sequoiadendron giganteum* (Lindley) Buchholz was measured in a grove of mixed species containing at least five *S. giganteum* at Killerton House gardens in Devon, England in June 2002. The *Q. robur* L was measured on Will Pratt's farm opposite the Parish Church, Buckerell, Devon, also in June 2002. Although other oaks in the same and nearby fields had similar trunk diameters the one measured had perhaps the least decayed crown and the most branch volume, it also contained a small hollow in the buttress of sufficient size for children to play in. All species measured were mature trees but were small in size compared with older specimens of the same species and in more specifically ideal locations.

2.2 Apparatus and Data Acquisition Procedure

The camera used was an Olympus-IS 300 SLR, auto-focus, with a large diameter, aspherical glass lens, a 52 mm filter diameter and a UV filter. The film used was Kodak Max colour print film with an ASA of 400. Photographs were taken on a tripod and with the focal lengths set at 28 mm and 110 mm. The distance of the camera from the trees was the same as that used for clinometer measurements, i.e. about tree height distance away from the trees. The distance was measured with a tape to within ± 0.5 m. That error (recording accuracy) may appear large but the trees were about 50 m tall on average, which makes that error in distance only 2%. The error usually decreased for smaller trees because there was less undergrowth and less uneven ground to traverse. In addition, the camera-to-tree distance was usually refined during image rectification. Examples of positioning of the trees within the field of view for a few different species in different environ-



Fig. 1. Scanned negatives before rectification, focal length = 28 mm. Details for specimen numbers are given in Table 2: (left) logging coupe, #1; (centre) gardens, #4; and (right) farm, #5.

ments are shown in Fig. 1.

“Geo-control points” (GCPs) are necessary for the rectification of remotely sensed imagery and consequently they were necessary in our terrestrial work. In essence, they are conspicuous points in the photograph for which their relative location is known in a particular axes system, such as latitude and longitude or Australian Map Grid. In the remote sensing context, GCPs might be the intersection of roads, a shed or a large rock, all of which have been measured using differential GPS or conventional surveying. When photographing standing trees different GCP markers were employed in different situations at measured locations on the buttresses and at measured distances from the buttress (e.g. a 1.1 metre quadrat, flagging tape, stakes and fluoro-paint). For GCPs higher up the tree a Suunto clinometer was used to measure tree heights and positions of conspicuous points along the length of the trunk, such as where branches met the trunk, shedding bark, small dead branches or holes in the trunk. When possible, two or more bands of flagging tape were tied around the buttress so that clinometer measurements could be based on more than one known height measurement so as to reduce measurement error. Hengl and Križan (1997) showed that measurement error of tree dimensions decreased with increasing number of GCPs and that advice was inherently followed in the present work by using as many GCPs along the length of the

trunk and across the buttress, as could be identified in the field. Colour photography was found to be imperative for identification of the GCPs in the scanned imagery, mainly for locating the quadrat and stakes but also for identifying GCPs on the trunk, e.g. differentiating between moss, leaves and strips of bark, and between silvery bark and background sky. In contrast Gaffrey et al. (2001) used black and white photography but recommended taking several photographs with different exposure settings.

The axes used when photographing standing trees had the origin at the centre of the base of the tree, with the x-axis going to the right hand side and the y-axis vertical. Therefore the z-axis extended from the centre of the base of the tree towards the viewer but at right angles to x and y. The plane containing the x- and y-axes and passing through the origin was called the “z = 0” plane or “object plane”, it corresponds to flat ground in the normal remote sensing case (but in our work it was usually at right angles to the ground). The GCPs were usually placed in the object plane because this made measuring their location simpler and hence less error prone. Only on parts of the buttress, where a diameter tape could be used, were GCPs placed in front of the object plane.

The 28 mm shots captured the entire above ground portion of the tree. The 110 mm shots were taken in order to locate extra GCPs near



Fig. 2. Some of the methods used in placing horizontal geo-control points. (above) quadrat and out-stretched arms at known heights. (below) tapes to stakes at known heights and distances from the centre of the trunk.

the base of the tree for later use in rectifying the 28 mm image. For example in Fig. 2. (above) the person's right arm is below the diameter tape, which is at 1.3 m so technically the origin of the x-axis can not be accurately overlaid with the origin of the y-axis. However, when using a 110 mm focal length, over small distances near the centre of the photograph, the horizontal and vertical scales are very similar. In Fig. 2. (above) this allows the horizontal position of the finger tips on the right hand, near the centre of the photo, to be raised up to the level of the diameter tape, without introducing any additional error, and thereby facilitate relation of the horizontal and vertical measurements to the same origin. Once the 110 mm images had been rectified then points measured on them, on screen, could be used as additional GCPs for rectification of the 28 mm images.

2.2.1 Scanner Calibration

The image correction procedure in Imagine relies on the relationship between the size of the objects in the image and their real size. In early photographic remote sensing procedures this relation was determined by comparison with the accurately known positions of fiducial marks on the negatives. For this reason Imagine requires the locations of some fiducial marks to be provided by the user. In the majority of cameras today there are no fiducial marks present like those in the large format aerial cameras. We developed a scale system to scale between the width and height in pixels of the scanned image and its real width and height in millimetres. I.e. the corners of scanned images were the fiducial marks. Franke and Montgomery (1999) undertook close-range photogrammetry using a 35 mm camera and scanned negatives, similarly measuring the position of the corners of the frames and using them as fiducial marks. Although Gaffrey et al. (2001) used a specially designed apparatus to measure

their negatives they still had to measure the position of the exposed frame on each negative, in order to determine the principal point. Although our use of Imagine does not require knowledge of the coordinates of the principal point, the size of the image, in mm, is still needed for scaling purposes. Instead of measuring each negative, which was a tedious and error prone step, and included difficulties scanning the full area of exposure (Thomas et al. 1995), it was decided to make use of the preset scanning resolution of the scanners. This preset scaling may have not been of analytical precision so we calibrated the scanners.

Two scanners were used: a Polaroid SprintScan 35 and a Nikon Super Coolscan 4000, both were negative (or slide) scanners, on Macintosh computers running Photoshop 4.0 (Adobe Systems Inc. 1996). (A flatbed scanner with a negative attachment was tested but it gave a much coarser image than the dedicated negative scanners.) Both scanners were set at a scanning resolution of 2700 dots per inch (dpi) (68 580 dots per mm). The dimensions of the exposed area of a single 35 mm negative were measured using a digital calliper to an accuracy of 0.01 mm. The ideal size of the exposed area for the IS-300 camera is 24 × 36 mm (Olympus Optical Co., Ltd., pers. comm., 2002). From five measurements on each side of the sample negative, the measured dimensions were: 23.82(6) × 35.73(9) mm (with the numbers in brackets being the standard deviations in the last significant digit).

The negative was scanned at a setting of 2700 dpi. The measured dimensions in millimetres were compared with the number of pixels in scanned images of that negative to obtain a conversion factor from pixels to mm. The corresponding number of pixels on the scanned images were, for the Polaroid scanner: 2556(4) × 3831(4), and for the Nikon scanner: 2545(4) × 3807(4). These distances correspond to scanning resolutions of 2725.33 dpi for the Polaroid scanner and 2709.63 for the Nikon scanner. These scanning resolutions represent a deviation from the preset 2700 dpi of 0.94% and 0.36% respectively for the two scanners. Inverting the measured scanning resolutions gave: a width of one pixel on the scanned negative corresponds to 0.009312 mm when using the Polaroid scanner and 0.009374 mm when using

the Nikon scanner. Those conversion factors were used to calculate the coordinates of the corners of scanned images in millimetres, these being the fiducial marks used in the rectification process.

2.2.2 Rectification of Imagery

The particular method of geocorrection selected in Imagine was the “camera model” so that camera characteristics could be entered. The projection selected was “Orthographic” with units of metres so as to provide orthogonal axes of equal length. Data entered for the camera location were: the horizontal distance of the camera to the centre of the tree (z-axis), the height of the camera derived from clinometer data at the same position (y-axis) and its sideways displacement (usually less than 1 metre) from the centre of the tree (x-axis). In most instances they were set as “estimated” rather than as “fixed”. Both the orientation and location of the camera were adjusted during least-squares refinement. In some cases the terrain was more even and there was little undergrowth to traverse, in which case part of the camera’s location was more accurately known, in these instances it was set as “fixed” and not refined. A correction for radial lens distortion was not applied to the camera model. At exposure time the focal length may have changed a little due to the auto focus mechanism. Consequently, during image rectification, the focal length was refined along with the other parameters. The resultant focal length was always within 1.5 mm of that selected in the field (either 28 or 110 mm).

2.2.3 Volume Calculation from Digitised Stems and Branches

The application of the Smalian method of volume calculation, when using diameters measured with a Spiegel relaskop, usually assumes that the cross sections are circular (Philip 1994). Calculation of stem volumes from taper equations also assumes circular cross-sections (Tarp-Johansen et al. 1997). Similarly in this work, the width of stems and branches was considered to correspond to the diameters of circular cross-sections, except in some special instances where the deviation from

circularity was notable, as will be discussed later. Outlines of the stems and branches were obtained by digitising on the rectified images. The stem of a tree can be divided into thin cross-sections, each of which approximates a conic section. However, as the width of any cross-section approaches zero the shape of each cross-section approaches that of a cylinder. The volumes of each very thin cross-section can be tallied to give the total volume. This method was employed to calculate the volume in the present work. The thickness of the cross-sections used was less than that for which a difference in diameter of the two ends of the cross-section could practically be measured, namely 1 mm. This method avoids any assumptions about the curvature of the stem as in Smalian's, Huber's or Newton's formulae (Philip 1994) and corresponds more to measurement of the stem diameter using a tape.

Digitising of the stem (and branches) was performed on the rectified imagery, on-screen, using ArcMap (ESRI Inc. 2001). The topology of the outlines was automatically placed in ESRI 2D-shapefile format. Each shapefile was examined by software written as part of this study, to calculate the volume of the corresponding part of the tree. The methods of the volume calculation described in this section were coded in C++ in a program called "shptovol" and run from the MS-DOS window or from a Unix window on a Microsoft PC.

The fundamental component of the volume calculation (applied to each shapefile) was to divide the shapefile into 0.001 m deep cross-sections along a line perpendicular to the mid-line of the stem. The width of each of these 0.001 m deep cross-sections was assumed to be the approximate diameter of the stem, at that particular height up the stem (or position along the branch, for branches). Thereby all detail recorded during the digitising process, was transferred in the form of a sequence of 0.001 m deep cross-sections, to the taper and volume calculations.

The widths (stem diameter) of each 0.001 m deep cross-section were calculated by intersecting a wide (200 m) and thin (0.001 m) rectangle with the shapefile. Rather than write new code for this intersection calculation, we adapted routines from the shapefile library "Shapelib", of Warmerdam (2002). Shapelib provided the area of intersection

between each 0.001×200 m rectangle and the stem outline. The diameter of the corresponding cylinder is that of the area of intersection divided by the height of the cylinder (0.001 m). That diameter is the width of the stem. The volume of the cylinder is the volume of a 0.001 m deep cross-section of the stem.

The mid-line of the stem can change direction along its length corresponding to curvature of the stem. This means that the direction of the cross-section should also vary. The direction of the cross-section makes a difference to the volume calculation when assuming circular cross-sections. Consequently an automated direction calculation was implemented and compared with the effect of a specifically pre-selected direction. The direction of slicing used in the automated procedure was simply that of the vector between the two most distant points in each digitised shape.

Stem (and branch) curvature was taken into account as follows. A segment of a gently curving stem approximates a cylinder tilted to one side. If one were to measure the horizontal distance between the sides of such a tilted cylinder, it would be greater than the cylinder's diameter. If one used this larger distance to calculate the volume of the cylinder then it would also be too large. To gauge the amount of curvature of the stem the midlines of the stem were calculated before the volumes of each 0.001 m thick cross-section were calculated. The angular change in the midline between successive cross-sections was used to adjust the volume of each cross-section. A fast method of midline calculation was adopted with the only negative aspect being that the stem (or branch) curvature could not be 90° or greater.

As a result of stem curvature, the adjusted diameter is the original diameter multiplied by the cosine of the angle of tilt. The adjusted height is the original height (0.001 m) divided by that same cosine. Consequently the adjusted volume is simply the original volume multiplied by the cosine of the angle of tilt:

$$v = \pi/4 \times \cos(\alpha) \times h \times d^2 \quad (1)$$

where

v is the volume of a cross-section after correction for tilt (in m^3)

α is the angle of tilt of the cross-section
 h is the depth of the cross-section (0.001 m)
 d is the diameter of the cross-section (in m), (the area of cross-section divided by 0.001 m).

The tilt angle between neighbouring 0.001 m steps along the midline was calculated and the corresponding volume for each 0.001 m step was adjusted for stem curvature using Eq. 1. Addition of the individual volumes after adjustment for curvature, along the length of the stem, gives the total external volume of the stem, assuming it has circular cross-section.

2.4 Error Analysis

Detailed error analyses of some components of the methods employed in the present work have been reported elsewhere and will not be repeated here. For example: Hengl and Krizan (1997) reported the relationship between the number of GCPs and photogrammetric measurements of trees and accuracy of digitization; and Gaffrey et al. (2001) reported at length the errors in measuring the exposed areas of negatives, the resolution of the film versus digital cameras, and the errors in photographing trees of different sizes. The error analyses reported here are related to the specific experimental and analysis methods used or developed as part of this work and not reported elsewhere, e.g. the method of volume calculation.

2.4.1 Errors in Field Photography of Trunks and Branches

Errors involved in measuring stem or branch diameters, using both contact and optical dendrometers, have been reviewed by Clark et al. (2000). An error arises because tangents, extended from the camera to meet the outside of the stem, are not parallel. Therefore they measure a closer, thinner part of the stem than when using a pair of callipers. However, as the camera gets further away from the stem (or as one photographs a thinner stem, or branch) the two tangents become more parallel, the error decreases, and the measurement more closely approximates a pair of

callipers. Simple geometry shows that the error in the measurement of stem (or branch) diameter, due to dendrometer characteristics of the camera, can be expressed as:

$$\delta d = d \times (1 - \cos(\alpha \sin(d/2c))) \quad (2)$$

where

δd is the error in the diameter measurement (in m)

d is the true diameter (in m)

c is the distance from the camera to the centre of the stem (or branch), (in m)

As the buttress of the tree is the widest part and usually the closest part of the tree to the camera, then that is where δd is likely to be largest. In the form of example: the widest tree we photographed (specimen # 1) had a DBH of 4.95 m, a diameter at ground level of 8.9 m, and the camera was 51 m from the centre of the tree. Therefore using Eq. 2: δd for the DBH was -0.5% (-0.04 m), at ground level -1.5% (-0.28 m), and negligible for the crown. For the smaller trees it was possible to position the camera further from the tree (relative to its height and diameter) therefore the errors were smaller. For example, the oak (specimen # 5) had a DBH of 2.01 m, a diameter at ground level of 2.94 m, and the camera was 30 m from the centre of the tree. Therefore using Eq. 2: δd for the DBH was -0.22% (-0.01 m), at ground level -0.5% (-0.03 m), and again negligible for the crown. Consequently, the errors due to the optical dendrometer aspects of using a camera, were relatively insignificant (compared with errors resulting from clinometer measurements) and were not corrected for in the volume calculations.

Measurements other than stem taper, such as some branch diameters or changes in bark type, could easily be extracted off the rectified imagery but branches that were not in a plane perpendicular to the camera-to-tree vector were incorrectly adjusted during the rectification process. Most notably branches in the crown that extended towards the viewer were overly long after rectification. This is because the geocorrection method assumes everything is in the object plane (unless informed otherwise by specifying a non-zero z -coordinate for a GCP, or by providing an elevation image.)

2.4.2 Errors in Rectification

To gauge the accuracy of rectification and its effect on volume calculation a virtual, 3-dimensional tree was created mathematically, imaged onto virtual 35 mm film, rectified and digitised (Fig. 4). The tree was 55 m tall with DBH = 2.99 m. The trunk and each branch were cones. The tree had four sets of five horizontal branches and within each horizontal set the branches were equally spaced around the trunk. These were at each of 25.6667, 33, 40.3333 and 47.6667 m up the trunk. Each horizontal branch had one vertical branch starting halfway along its length. Virtual stakes in the ground near the tree and flagging tape were added to simulate GCPs used in field-work. The virtual camera, with a focal length of 28 mm, was positioned at 50 m from the tree, 1.35 m above the ground and pointing nearly halfway up the tree at 22 m.

The coordinates of points on the surface of the cones, the stakes and flagging tape were projected onto virtual 35 mm film using transformation matrices and vector algebra for axes transformations adapted from Dean (1985). The corners of the film were added to the virtual image for use as fiducial marks. The projection matrices were for a lens of pinhole size and did not include simulation of any optical aberrations such as radial lens distortion. The projected image consisting of the virtual tree plus virtual field markers, on virtual 35 mm film, was formatted as a TIFF image. The TIFF image was rectified using the same procedure as for real trees. Seven points on the tree plus one from each of two stakes were used as GCPs.

2.4.3 Errors in Volume Calculation

Errors resulting from the method of 3D volume calculation used in the present work were examined using 2D projections of 3D geometric shapes. The 2D projections of 3D shapes were performed on a quarter and on an eighth of a torus (a toroid in 2D), on a cylinder (a rectangle in 2D) and on different sized cones with different 3D orientations. The cylinder was tilted at three different angles to the vertical: 0°, 25° and 45°, in order to test the automated slice direction algorithm. The

torus and cylinders were drawn using ArcInfo and the cones were drawn using a specifically written C++ program.

2.4.4 Image Distortion

The types of distortion commonly observed in non-metric 35 mm cameras used for photogrammetric work have been reviewed by Fryer et al. (1990). The primary distortion is radial lens distortion (Wolf 1974) or termed “barrel distortion” by photographers. The Olympus IS-300 is designed to have a low amount of this type of distortion due to its thick aspherical lens. The distortion due to film unflatness is a lesser effect and entails a more complex correction, depending on whether or not the film is held flat in the camera or during the measuring process (Fryer et al. 1990). An additional distortion can occur due to lens distortion in the scanner, which is also a form of “barrelling” (Thomas et al. 1995). The resultant amount of radial distortion observed in our imagery from the IS-300 (using its 28 mm lens) plus the scanning process (i.e. from all three causes mentioned above) was measured by photographing a grid in the form of an array of windows in a multi-story building. An example of the resultant distortion is shown in Fig. 3. The dashed lines in Fig. 3 are straight lines but the corners of the building beside the dashed lines, appear to bend slightly. The distortion has caused the outer parts of the image, centred on the horizontal and vertical axes, to be spread further from the centre.

The root mean square error (RMSE) for the rectification of the building photograph was 24.21 pixels using 20 GCPs. The maximum horizontal and vertical, radial distortion was equivalent to an increase of 3% in the length of a line passing through the centre of the photo and approaching each side (either horizontally or vertically). This amount of distortion is similar to the radial distortion of 2.5% measured by Gaffrey et al. (2001) for their CANON AE1 reflex camera with a 28 mm lens.

Most trees were photographed so that their branches and trunk were contained within about the middle three quarters of the photograph. The stem was near the centre of the photographs,



Fig. 3. Photo of a building showing the degree of radial lens distortion. (left) before rectification and (right) after rectification with straight dashed lines beside aberrantly curved lines.

consequently the image distortion acting on the width of the stem was negligible. Conceivably the height of the stem could have been increased by the radial distortion. However that possible increase in height would have been counteracted during the image rectification process by the use of GCPs at both the top and bottom of the stem. Consequently it was considered unnecessary to reduce the length of the stem due to image distortion. Thus, the image rectification process in Imagine does not specifically correct the image distortions observed in our camera imagery but fortuitously compensates for them to some extent, as explained below.

Ramifications on the accuracy of measured trunk volume are complex but remain much smaller than the errors in field measurements taken with the clinometer. Points near both the bottom and top of the trees were used in the rectification process and consequently rather than the final tree height being too large the middle of the tree would have been slightly, vertically compressed during rectification. The middle of the tree is wider than the apex so its measured volume would have been slightly reduced; the stretching of the base and apex may have counteracted this slightly. No correction for radial lens distortion of stem measurements was made, other than that

inherent in the rectification process.

Branches do not extend over the length of the photograph, therefore the effect on them of radial lens distortion and rectification must be considered separately. The branch volume of the crown may have been slightly increased due to lengthening of upward pointing branches resulting from radial lens distortion. For example, if a vertical branch in the crown increases in length by 2.5% then because branches can have an approximately conical shape (with volume proportional to height) the volume of the branch also increases by 2.5%. However, the crown branches start from near the top of the tree and consequently both their starting point and finishing point would be extended, therefore the branch lengthening due to radial lens distortion would be considerably less than 2.5%. Consequently, no correction for radial lens distortion (other than that inherent in rectification) was applied to branch measurements.

2.5 Wood Volume of Trunks

The wood volume in each cross-section can be found by subtracting the outer cylinder of bark volume. This requires knowledge of bark thickness at different heights up the tree. Bark thickness

for *E. regnans*, as a function of DBH and height up the tree was determined in a related project by the current authors and was also reported by Galbraith (1937) and Helms (1945).

Bark thickness for the *S. giganteum* and *Q. robur* specimens was not measured in the field because non-destructive measurement was a prerequisite and using a bark gauge between such different locations could have spread disease. Instead, rough estimates of bark thickness were used. This is a simplification but for the purposes of this study is satisfactory. If more details are learned about the change in bark thickness with height or branch diameter then the automated volume calculation can simply be re-run.

The bark thickness for the *S. giganteum* specimen was estimated to be an average of 3 cm over the whole tree. Bark thickness for the *Q. robur* has been shown to vary with age (Troddenbrodt, 1994), continually increasing under the age of 33 yrs to about 1 cm. The particular *Q. robur* tree photographed was 250(±50) years old. That age was estimated from the growth curves of Mitchell (1974) for a tree with mean to moderately rapid growth. Data for variation of bark thickness with trunk or branch width for a tree of that age was unavailable. Therefore, as an approximation over the whole tree, a constant value of 1.5 cm was assumed in this study.

Precisely circular cross-sections of trunks rarely occur in nature and the deviations from a circle reduce the cross sectional area because a circle is the two-dimensional shape with the highest area-to-perimeter ratio. The reductions in cross-sectional area are mostly due to: 1) flutes in between the spurs on the buttress; and 2) outer polygonal perimeters (as measured by standard diameter tapes) not being circular even though isoperimetric (of equal perimeter). This area deficit leads to a corresponding volume deficit, after multiplying by the thickness of the cross-section. There has been a little work published on cross-sectional area deficit in eucalypts (e.g. Ash and Helman 1990, Waterworth 1999) but very little work on the effects for large DBH or large buttresses. The volume deficit in *E. regnans* buttresses can be considerable. Deviations of stems from circularity can be taken into account by adjustment of each cross-section's volume as it is calculated. This deficit adjustment is species

specific. We calculated the deficit as a function of DBH for *E. regnans* and incorporated it into the stem volume calculation in *shptovol*. The summary of our volume deficit work in Dean et al. (2003) showed that the stem volume deficit can reach a maximum of about 20% in *E. regnans* of moderate size (e.g. DBH = 5 m). The other species photographed were not of sufficient maturity to develop significant flutes, and although they were of course not exactly circular in cross-section (and therefore will have less volume than if they were), their cross-sections were taken as circular for the purposes of this study.

2.6 Wood Volume of Branches

A total of 193 branches were measured from the rectified images of *E. regnans*. Of these, 31 were digitised as shapefiles and their volumes determined using *shptovol*; 160 were too small to warrant the precision of digitising and were approximated as cones and their diameters (minus bark thickness) and lengths measured to yield wood volume; and 2 were short, thin broken branches approximated as cylinders. The digitised branches had diameters ranging from 0.04 m to 0.84 m. Broken branches (except those obviously broken by the felling of neighbouring trees) were included to give natural variability to the derived relationship. The cones had (basal) diameters ranging from 0.02 m to 0.42 m. Large branches were subdivided into many smaller ones. All the smaller ones were tallied to yield the total branch volume for the larger, parent branch, as in Attiwill (1962).

The volumes of all visible major branches were measured from the rectified images of *E. regnans* trees using the derived equation. For some trees not all the major branches were clearly visible in the one or two views photographed, some were on the far side of the trees and partly obscured by either the trunk or foliage. For such trees, the proportion of branches not observed was approximated and added to the observed branches to yield an estimate of the total branch volume. The error in the step of estimating the proportion of unobserved branches is estimated to be about ±15%.

Branches on the *S. giganteum* were not measured (although they were clearly visible) because

Table 1. Volumes calculated for different 3D shapes by different methods of cross-sectioning their 2D projections and compared with correct (formula) volume. In the second column of each calculation-method pair, the column “diff.” is the difference between the calculated volume and the correct volume.

3D shape	Correct volume	Uncorrected for curvature, manual slice direction		Corrected for curvature, manual slice direction		Corrected for curvature, automated slice direction	
	m ³	m ³	diff. (%)	m ³	diff. (%)	m ³	diff. (%)
1/4 Torus	12.9539	11.8154	-8.79	12.8940	-0.46	12.8937	-0.46
1/8 Torus	6.4769	6.3222	-2.39	6.5535	+1.18	6.3179	-2.45
Cylinder at 0°, 25° & 45° tilts	15.7080	15.7080	0	15.7080	0	15.6726	-0.23

they appeared to contribute no more than about 4% to the total volume of the tree. The *Q. robur* had obviously developed in an open space and thus had a comparatively large branch volume, typical of many large trees on pastoral properties. Some of its major branches were measured to provide an estimate of the total branch volume. The smaller branches (less than 0.3 metres in diameter) diverging off these main branches were not measured as the aim was not to develop an allometric equation for *Q. robur*. (This could have easily been done however, using the same process as for *E. regnans*).

3 Results

3.1 Errors in Measurements of the Geometric Shapes

Tests of the volume calculation from 2D projections of the 3D geometric objects and the automated slice direction calculations are shown in Table 1. The average percentage error in the volume calculation from digitising the 40 different sized cones with different orientations was -3.9%, i.e. a small under-estimation of volume. This was found to be mainly due to sub-optimal slice directions by the automated slice direction algorithm. The errors enter the volume calculation near the base of the cone. When measuring branches, the branch base is rarely flat and so the magnitude of the error due to automated slice direction finding would be less significant. When the direction of the slices was chosen manually (as it is for trunks, the automatic procedure was used

for branches) then the average error in volume calculation of digitised cones was -0.5%.

The reason for coding an automated slice direction was so that volumes of branches could be calculated without the user having to specify a starting and finishing point. Similarly, the direction for stems is nearly always vertical but if the stem was leaning due to wind stresses or competition from neighbours, or not oriented precisely by the photographer then the user would have to specify a slice direction. The results show that the errors resulting from automated slice direction are not too severe and would usually slightly underestimate the volume. The error is larger in magnitude for the one eighth of a torus probably because of its higher relative width to length ratio compared with the one-quarter torus (the errors due to non-circularity near the corners in the projected shape have a greater influence). But such a large curvature within a short distance was observed in branches only infrequently (perhaps once per tree) on the trees we measured and never observed in the stem.

3.2 Errors in Measurements of the Virtual Tree

The RMSE for the rectification of the virtual tree (Fig. 4 left) was 1.6 pixels (0.0131 mm). This is low compared with the RMSE in rectifying real trees. This low value is probably due to no error in locating the corners of the film, no image distortion, and no errors from field measurements with a clinometer. The output cell size selected for the rectified image was 0.01 m. The trunk and branches in the rectified image were digitised,

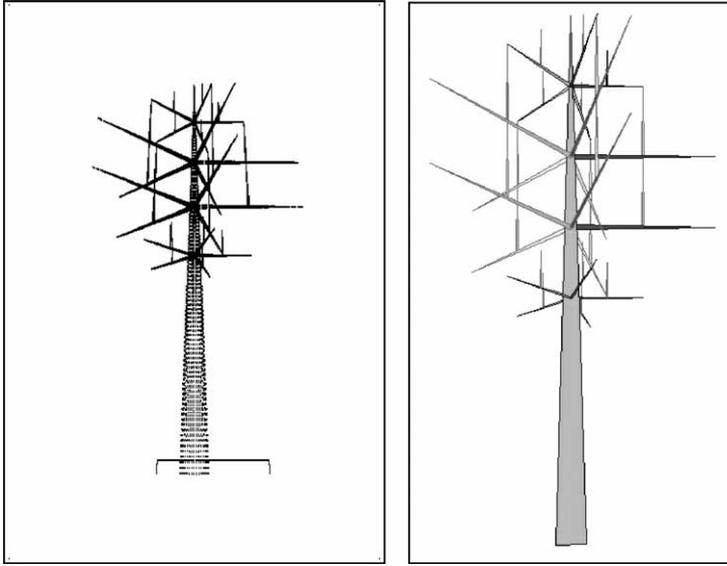


Fig. 4. (left) Projection of virtual tree onto virtual 35 mm film and (right) after image rectification showing the digitised Shapefiles for the trunk and branches.

converted to shapefiles (Fig. 4 right) and their volumes calculated, again using the same process as for trees studied in fieldwork.

The correct volumes of the trunk and each branch were known precisely because each cone was derived from predetermined radii and heights. Thus, the errors in the volume calculations from the rectified image could be determined. The correct volume of the trunk cone was 138.37 m³ and the volume measured from the rectified image was 137.70 m³ (an error of -0.48%). The total volume of the branch cones was 9.330 m³ and the total branch volume measured from the rectified image was 9.408 m³ (an error of -0.84%). The average percentage error in the individual branch volume measurements from the rectified image was 0.46%. Dividing this between the horizontal and vertical branches, the average errors were 8.57% and -7.65% respectively. However, there was a wide range of volume errors across the different branches, e.g. 0.23% for a vertical branch near the top of the tree and 2.2 m towards the camera, and 83% for a horizontal branch also near the top of the tree and in the object plane). These individual errors in measured branch volume were plotted against a range of characteristics

for each branch in order to determine the main contributing factors; the more informative graphs are shown in Fig. 5.

3.3 Measurement of Specimen Trees

3.3.1 Taper and Stem Volumes

The RMSE was usually in the order of a few pixels. Measurements of the trunk taken off the resultant rectified images were within about 2% of the measurements taken in the field.

The taper measurements for *E. regnans* are shown in Fig. 6. Taper curves from the published literature and other sources are added for comparison. All data are presented as under bark diameters in order to allow comparison with the earliest records. The curves of Galbraith (1937), Helms (1945) and Goodwin (pers. comm., 2002) all represent smoothed data. In the current work all trees were measured by image rectification except the tree "SX004C, 2.98", which was measured by tape only after felling but the stem split at 32 metres so its full taper curve could not be measured. The other two trees in SX004C split

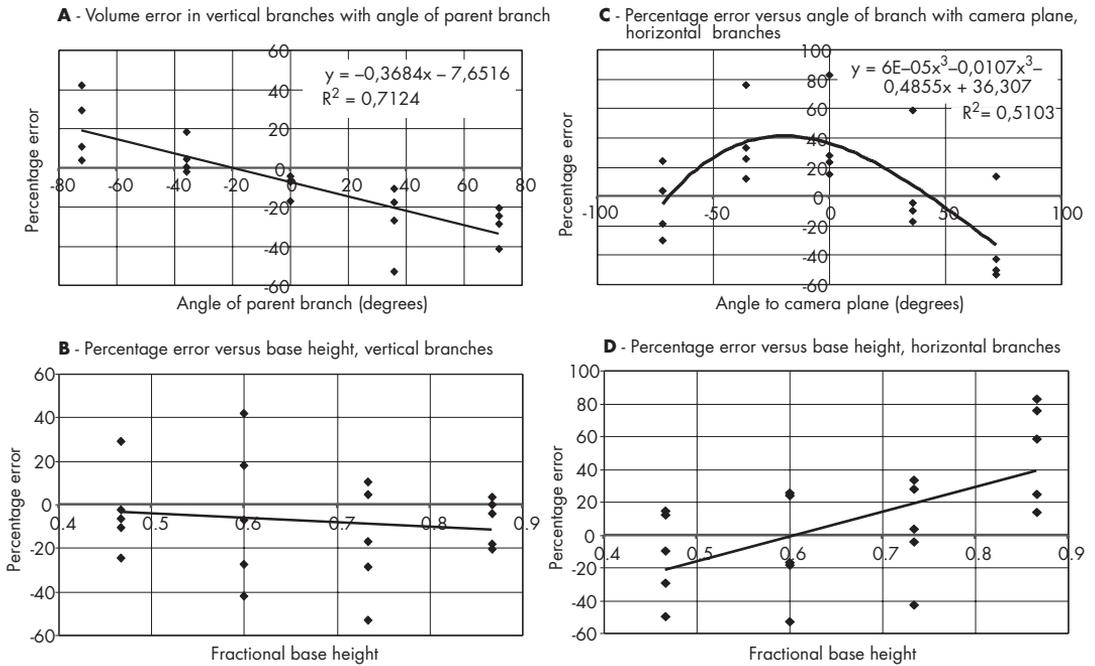


Fig. 5. Percentage errors in volume calculation as a function of different characteristics, with lines of best fit. Values were calculated from the rectified image of the virtual tree projected using the pinhole lens camera. A positive angle means the branches are behind the tree and a negative angle means they are on the in front of the tree; a larger magnitude of angle means they are further from the $z = 0$ plane (object plane).

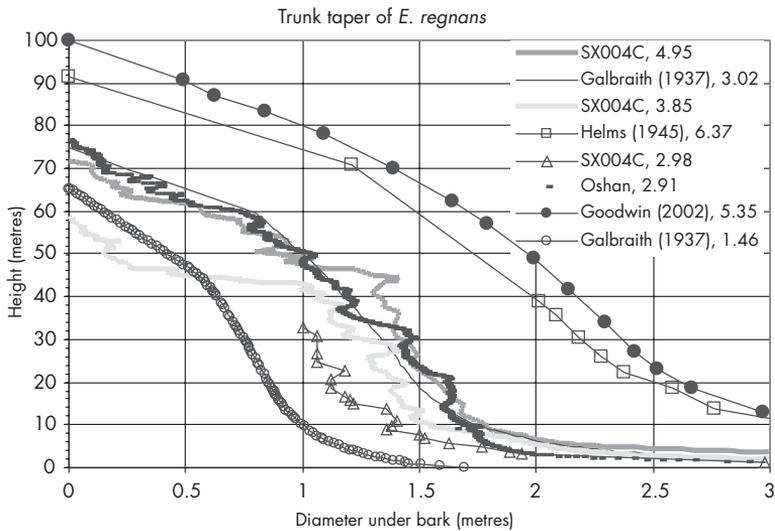


Fig. 6. Taper curves for several *E. regnans* specimens.

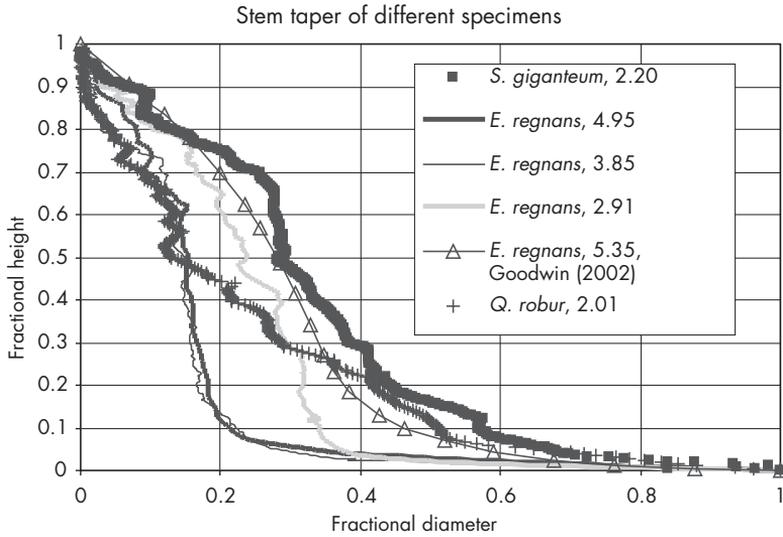


Fig. 7. Relative taper of different specimens, drawn for comparison. DBH is given to allow comparison with Fig. 6.

Table 2. Stem volumes for several of the trees studied. Only for the *E. regnans* trees, was the volume deficit in the buttress taken into account.

Specimen#	Species	Age in 2002 (yrs)	DBH (m)	Height (m)	Number of GCPs	RMSE (pixels)
1	<i>E. regnans</i>	320(±5)	4.95	72	9	22.1
2	<i>E. regnans</i>	320(±5)	3.85	59	8	3.61
3	<i>E. regnans</i>	220(±5)	2.91	77	12	21.5
4	<i>S. giganteum</i>	148	2.20	37	6	10.3
5	<i>Q. robur</i>	250(±50)	2.01	25	6	3.42

Specimen#	Volume over bark (m ³)	Circular volume over bark (m ³)	Volume of bark (m ³)	Volume under bark (m ³)
1	159.00	191.18	3.4672	155.53
2	93.97	118.26	2.5379	91.43
3	104.72	111.32	2.4684	102.25
4	41.59	41.59	3.51	38.07
5	17.13	17.13	0.8090	16.32

after felling and therefore could not be re-measured by tape for verification. Tree “Oshan, 2.91” (specimen # 3) was in a water catchment reserve and therefore not felled. It was asymmetrical with more branches on one side so it was photographed from two sides and its taper curve (Fig. 6 and Fig. 7) was derived from averaging the taper from the two views.

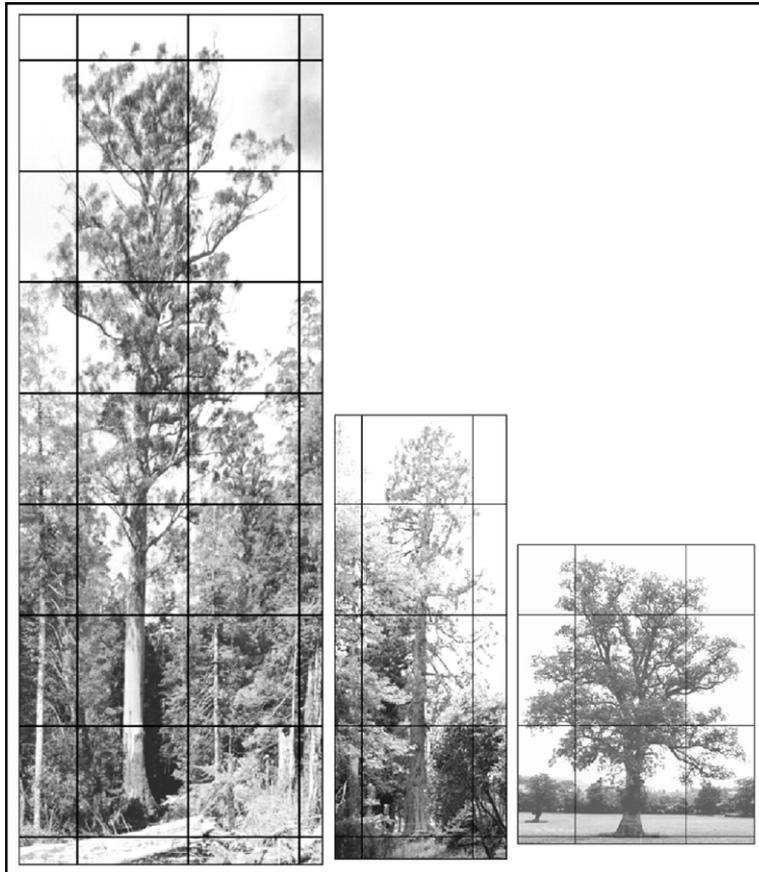


Fig. 8. Rectified images drawn at the same scale, grid size is 10 metres. Details of specimens are given in Table 3. From left to right: specimens: #1, #4 and #5.

3.3.2 Branch Volumes

The data for branch volumes of *E. regnans* are shown in Fig. 9 and the derived equation for branch allometrics is:

$$\ln(v_b) = p_1 \times \ln(d_b) + p_2 \tag{3}$$

where

v_b is the volume of a branch (in m^3)

d_b is the diameter of the branch (in m), just before it subdivides into smaller branches

p_1 is a regression parameter: 2.7835 with standard error 0.0555

p_2 is a regression parameter: 1.9460 with standard error 0.1482

$R^2 = 0.929$, $N = 193$ and Variance = 0.3455.

From the three *E. regnans* trees measured, the average amount of branch wood as a percentage of stem wood, was 8.5%. Volumes for the larger branches of the *Q. robur* that were measured (shown as solid, white polygons in Fig. 10 (right)) are given in Table 4. The total branch volume measured (under bark) for the *Q. robur* specimen was 4.6 m^3 , which corresponds to 28.3% of the stem volume. The sub-branches, leading off the branches outlined in Fig. 10 (right) were not measured. Therefore, that figure of 4.6 m^3 , corresponds to only a portion of the total branch volume on *Q. robur*. The total branch volume for the *Q. robur* specimen is estimated to be approximately, 6.5 m^3 , i.e. 40(±10)% of the stem volume, bringing the total wood volume (stem plus branches) to 22.9 m^3 .

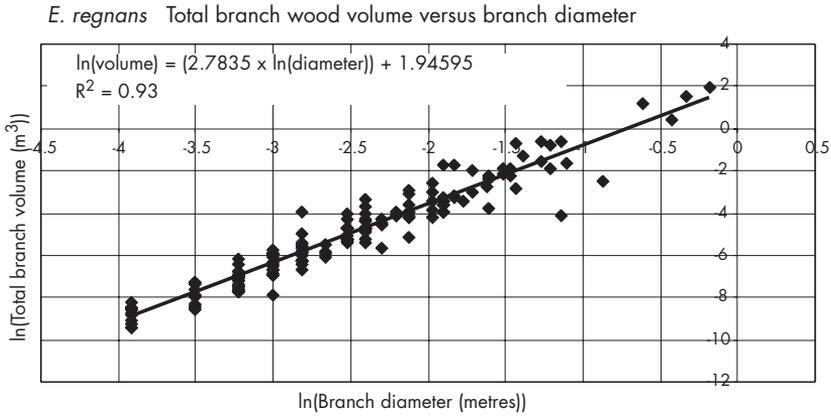


Fig. 9. Plot of Branch volume versus branch diameter for *E. regnans*, natural log scale.



Fig. 10. Examples of branches digitised and measured for specimens: (left) #3 and (right) #5.

Table 3. Branch volumes for three *E. regnans*. Specimen numbers refer to the same trees as in Table 2.

Specimen#	DBH (m)	Stem vol. under bark (m ³)	Number of branches measured	Fraction observed (%)	Total branch volume (m ³)	Branch vol. as % of stem vol.	Total above ground wood vol. (m ³)
1	4.95	155.53	18	50	10.26	6.6	165.8
2	3.85	91.43	26	75	10.34	11.3	101.8
3	2.91	102.25	10	50	7.70	7.5	110.0

4 Discussion

4.1 Error Analysis

When using terrestrial photography, the errors in the measurement of tree wood volume and stem taper have a range of origins and magnitudes and the impacts of these are discussed below.

The largest error in fieldwork was from the clinometer measurements with about a ± 1 metre error on larger trees. If these errors are non-systematic and if sufficiently numerous GCP points are measured (with the clinometer) then the overall inaccuracy from clinometer measurements is less than the individual error, due to the least-squares refinement process. The positioning of the flagging tape in the buttress region had errors of about ± 5 cm thereby contributing to an error in the placement of the origin. Location of a correct ground level is important for volume comparisons between trees but not within an individual tree. The error in the scanner's preset resolution was small, with the scanner calibration step indicating that the maximum scaling error was near 1%.

The errors in the branch volumes of the virtual tree showed complex trends due to interacting factors. The image rectification process assumes that all points in the image lay in the object plane unless specified otherwise, i.e. in the plane containing the centre line of the trunk and facing the camera. No equivalent of a digital elevation model is available for trees to indicate the distances that branches deviate from this plane. Standard perspective effects cause branches further from the camera to appear smaller. This explains the smaller magnitude of error for vertical branches in the plane of the tree (Fig. 5A) and explains the reduction in error with increasing height up the tree of the vertical branches (Fig. 5B). Branches that do not lay in the object plane

Table 4. Branch volumes for the branches with diameter >0.33 m on the *Q. robur* specimen (shaded as white, solid polygons in Fig. 10 (right)). Volumes of sub-branches not included.

Branch diameter (m)	Branch vol. under bark (m ³)	Bark vol. (m ³)	Branch vol. over bark (m ³)	Branch vol. as % of stem vol.
0.76 (fork)	2.626	0.3213	2.947	16.1
0.57	1.311	0.1858	1.497	8.0
0.52	0.4942	0.1011	0.5954	3.0
0.37	0.1835	0.0546	0.2381	1.1

are rectified incorrectly: those pointing either towards or away from the camera become foreshortened. But there is a height effect too, with branches pointing towards the camera, while also being overhead, becoming lengthened. This difference in apparent length leads to the asymmetry between the volume errors for horizontal branches behind and in front of the tree (Fig. 5C).

The higher percentage error for the horizontal branches in the object plane was due to the unexpected effect of the radius appearing larger than it really is, for these branches. This was due to the use of flat film (in the camera), the effect would not be observed with a relaskop. When observed at an angle and projected onto flat film the top-front of the branch and the bottom-rear of the branch, are further apart than the diameter of the branch. This effect increases with the view angle (i.e. the angle between the horizontal ground and the line between the camera and the branch), the increase is proportional to the inverse of the cosine of the view angle. For example, for a horizontal branch in the object plane near the top of the tree where the view angle is 45° , the apparent increase in the branch diameter is 41.4%, which causes an increase in the volume (assuming the branch is conical) of 100%. This distortion of the branch diameter is the reason for the increase in error

with height for the horizontal branches (Fig. 5D). This increase in diameter effect does not occur for the trunk because it is in the centreline of the photo. Vertical branches towards the edge of the photo will however show this effect because their diameter is being observed at an angle and being projected onto a flat plane.

The causes for errors in volume measurements from the virtual tree indicate ways to minimise errors in volume calculation of branches on real trees. When developing allometrics, accuracy can be increased by selecting for measurement only those branches that are more vertical and lay in the object plane. When measuring branches that are more horizontal it is best to measure those that are near the same level as the camera. Fortuitously this corresponds to the usual situation for closed canopy, forest eucalypts as their lower branches are the more horizontal ones (seeking light sideways from the crown) and their crown branches are the more vertical ones (seeking light above their neighbours). Although branches growing at 45° to the horizontal were not synthesised in the virtual tree it seems reasonable to presume that measured volumes of such branches will show a combination of the effects for horizontal and vertical branches.

The area deficit (resulting from non-circular cross-sections) would be a systematic error depending on species, environment and size of the tree; it would be in the form of an overestimation of volume. A previously modelled area deficit for *E. regnans* was used in the volume calculation in the present work so their volumes reported here would not be overestimated. The error in stem volume measurement of real trees could be as high as +10%, on average, due to the area deficit. The “Arve Tree”, for which data was supplied by Goodwin (pers. comm., 2002), shown in Fig. 6, can be used to illustrate the difference in volume between a tree of circular cross-section and one with an area deficit. The Smalian volume (Goodwin, pers. comm., 2002) was 404.27 m³, and the volumes calculated in the present work were: assuming circular cross-section – 398.69 m³ and taking into account likely fluting in the buttress etc – 371.19 m³.

Tests on geometric shapes showed that the present volume calculation method (using shp-tovol) underestimated stem volume on average

by –0.5% for stems (when specifying the slice direction) and so the overestimation of stem volume resulting from non-circularity would be slightly reduced during volume calculation. For branches the underestimation of the volume of cone shaped branches was –1% on average, but combined with the errors of image rectification it was –4%. Short curved branches (the toruses and cylinders) had total errors of between –0.5 and –2.5%. These underestimates should help to counteract the overestimates due to area deficit for real branches. This would be best tested by photographic analysis in a logging coupe followed by destructive analysis in a logging coupe or demolition site.

4.2 Taper Curves

Overall, the taper curves for *E. regnans*, derived from rectified images, agree well with the previously published work of Galbraith (1937). The exception appears to be tree “SX004C, 3.85” above 40 metres; this is due to a multiply divergent crown at that point. The larger deviations along the taper curves (e.g. at 45 metres height on “SX004C, 4.95”) are where the trunk swells below large branches. Forks (or double leaders) in the trunk present a special case for reporting the trunk volume and taper measurements. The question arises as to whether or not forks should be added to the stem volume or treated as branches. Similarly with taper curves, the taper could follow one of the forks only or include the sum of diameters of both forks. The question was not answered here: only one fork was followed and the values for the stem and fork (interpreted as a branch) were both reported. Trees with significant forking of the trunk or other major asymmetry should be photographed from more than one direction.

Comparisons of the relative taper of different trees and different species (Fig. 7) showed interesting effects. The *E. regnans* specimens exhibit both slow and fast taper with the most mature specimen exhibiting less buttressing but the smallest *E. regnans* exhibiting moderate buttressing. This may be an environmental effect as buttressing in *E. regnans* has been shown to be a response to strains of trunk and crown move-

ment (Ashton 1975). The *Q. robur* has a steady decrease in stem diameter corresponding to the many large branches that diverge from it over its length. The *S. giganteum* had the least taper over its length which could correspond to the minimal branch weight observed.

4.3 Branch Volumes

The amount of branch wood for *E. regnans* as a function of stem wood determined in the present work (8.5%) agrees quite well with the figure of 7.1% determined by Feller (1980) for 44 year old *E. regnans*. The error in the step of estimating the proportion of unobserved branches is estimated to be about $\pm 15\%$ and is therefore greater than the error resulting from the standard deviation in the parameters of the regression equation (Eq. 3) for branch volume as a function of branch diameter.

Attiwill (1962) developed regression equations for branch wood mass as a function of branch diameter. The wood biomass of the branches can be estimated from their volumes. If \log_{10} is used in place of natural logarithm, girth (in inches) used in place of diameter, and weight (in grammes) used in place of volume (assuming density = $0.5124 \text{ tonnes.metre}^{-3}$, Dean et al. (2003)) then the slope of the regression equation (Eq. 3) remains the same but the intercept changes to 0.73076:

The slope and intercept for this latter equation are in fair agreement with those of Attiwill (1962) for *Eucalyptus obliqua* branches with diameters greater than 0.0127 m. Their slope was 2.2158 (0.0980), and intercept was 1.0454 for smooth barked and 3.5300 (0.3591), 0.0360 (respectively) for rough barked.

4.4 Potential Applications

For many tree species, allometrics based on data that included larger specimens are fairly rare, for a variety of reasons, one of which is the current scarcity of the larger specimens due to previous resource usage. The photographic method shown here allows one to measure such larger trees with minimal damage to them and thereby conserving

them for whatever needs might be found in the future. Allometrics based on such information can be used to forecast potential carbon sequestration by the trees that are currently less mature. This is the sort of work currently being undertaken by our group.

The stem and branch measurement of deciduous trees could be further automated by bypassing the digitising stage. A photograph taken during winter should allow classification of image pixels (after rectification) into tree and non-tree. Multiple fine, horizontal slices of the image would yield a series of line segments (on each horizontal slice) representing woody components. These segments could be then re-constituted into branches (assuming circular cross-section). This method of measuring tree mass by repeated transects is used in a much less intensive and more manual way for coarse woody debris data collection (McKenzie et al. 2000).

Rectified terrestrial photographs also allow comparison of lidar data with terrestrial field observations. The program used for projecting the virtual tree onto 35 mm film was initially designed, and used successfully, to project lidar data collected from a helicopter, onto virtual film for comparison with ground based photography.

Usage of the method presented here might be more widespread if it was simplified further, e.g. by the use of a digital camera rather than 35 mm film, as in the work of Hengl et al. (1998). This would negate the need for the scanner calibration process described above with its calibration error and the additional image distortion from the scanner (Thomas et al. 1995). The scanner calibration stage is then replaced by knowledge of the lateral dimensions of a pixel in the CCD or of the CCD itself plus the number of marginal, discarded pixels (e.g. Dean et al. 2000). However few digital cameras can match the spatial resolution of 35 mm film in SLR cameras (Mason et al. 1997, Gaffrey et al. 2001) so some details such as small GCP markers or thinner branches would have been lost. Preliminary tests of our method using a 2.3 Mpixel digital camera indicated that the CCD resolution was sufficient for trees under about 25 m tall but insufficient for locating some GCPs on trees taller than about 40 m (where the camera is 40 m or more from the buttress). Also, blooming of pixels, neighbour-

ing those representing fluorescent flagging tape, decreased the precision of GCP location. A higher resolution digital camera could provide sufficient resolution for GCP location on the taller trees; consequently tests using a 5 Mpixel SLR camera will be undertaken.

The terrestrial photography presented here relies on a fairly clear view of the tree and is therefore not suitable to undisturbed, dense forest. However it has been successfully applied in logging coupes, water catchment reserves, woodland, pastoral land, parks and gardens. Apart from the species detailed here, it has also been successfully applied to measurement of *Angophora costata* subs. *leiocarpa* L. Johnson (Qld. smoothed-barked apple), *Eucalyptus pilularis* Sm. (black butt) and *Eucalyptus melanophloia* F. von Muell. (silver-leaved ironbark). The use of remote sensing software was found to be very productive and adaptable to objects other than standing trees. For example, it was also used to measure cross-sections of stumps and it could be used to rectify images of artwork for online historical records or incorporation into animations as in Criminisi et al. (2000).

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