An Analysis of Sampling Methods for Coarse Woody Debris in Australian Forest Ecosystems

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An Analysis of Sampling Methods for Coarse Woody Debris in Australian Forest Ecosystems

A Report for the National Greenhouse Strategy, Module 6.6 (Criteria and Indicators of Sustainable Forest Management).

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Executive summary

This study investigated efficient sampling methods for coarse woody debris (CWD, larger dead logs and branches on the forest floor) in Australian forests. CWD debris is an important component of forest ecosystems. It can contain a significant proportion (up to 20% and sometimes more) of the total forest biomass and is important habitat for native animals and invertebrates.

Data was collected in three forest types in different parts of Australia and analysed using a computer-based system to test alternative sampling approaches. The forest types surveyed were eucalypt-dominated woodlands in south central Queensland (Injune), eucalypt open forest (dry sclerophyll forest) in south coastal New South Wales (Kioloa) and tall open forest in southern Tasmania (Warra).

CWD is generally assessed using the 'line intersect' approach or by measuring logs and branches on fixed area plots. There have been varied recommendations in literature on the number of lines (transects) to use and their length and arrangement. Recommended plot size has also varied considerably.

Several one-hectare plots were established in each region. All CWD, stumps and standing dead trees above 10cm in the woodland, and 15 cm in the other forest types were measured and mapped. These data were used to analyse the effect on precision of estimates of the CWD volume using alternative approaches to the line intersect method and different sizes of fixed area plot.

Mean volume of CWD sampled on the plots was 26 m^3ha^{-1} at the woodland site, 117 m^3ha^{-1} at the open forest site, and 1351m^3ha^{-1} at the tall open forest site. Mean mass of CWD was 12 t ha^{-1} at the woodland site, 52 t ha^{-1} at the open forest site, and 500 t ha^{-1} at the tall open forest site. These were generally within the range from other studies in similar forest types of Australia. CWD at the Tasmanian site were some of the highest recorded in Australia and among the highest reported in the world.

Variability of CWD volume in forests is very high and achieving estimates with a precision (coefficient of variation) less than 50% of the mean will require a high sampling intensity.

In analysis of the line intersect method, precision of volume estimates decreased as total transect length increased. In denser forests, transects of at least 100 m are required to achieve a precision of less than 100% of the mean. One long transect resulted in a lower coefficient of variation than a number of short transects and is more cost effective. There was no improvement in precision by arranging the total transect length in a 'V', a triangle or a square.

In woodland vegetation (20-50% canopy cover) the amount of CWD is relatively low and variability is high. Very long lines (>200 m) would be required to achieve estimates with a precision below 100%.

In these situations fixed area plots are preferred. Using a larger fixed area plot improved precision of estimates. Plots 20 x 20 m can give estimates with precision less than 100% in forest structures but well over 200% in woodlands. Measuring all pieces on a 50 x 50 m plot in woodlands gave estimates with a precision of ±21-73% of the mean.

These results will be incorporated into future sampling for the National Forest Inventory and other studies of biomass and carbon stocks in Australian forest and woodlands.

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1. Introduction

1.1 Coarse woody debris in forests

Forests play a major role in the global carbon cycle. Of great interest to greenhouse science is the ability of forests to sequester and store carbon. This has been seen by some as a way to mitigate the affect of CO_2 discharged to the atmosphere by anthropogenic activities. Regardless of whether forests can effectively assist in the 'mop-up' of excess CO_2, Australia has an international obligation to report on greenhouse issues. Australia is a signatory to the Montréal Process and the United Nations Framework Convention on Climate Change, under which national carbon inventories are required.

Carbon pools in a forest ecosystem are generally partitioned into live trees, understorey vegetation, coarse woody debris, forest floor litter, and soil carbon. Coarse woody debris (CWD), which includes whole fallen trees, fallen branches, pieces of fragmented wood, and may or may not include stumps and standing dead trees (stags), is the least studied of the forest carbon pools (Harmon and Hua, 1991). CWD quantities can be substantial, particularly in old-growth forests on highly productive sites, as well as in harvested forests where large amounts of residue are left *in situ*. Although CWD is dead organic material that will eventually decompose, it can remain in a forest for hundreds of years. Such longevity has been observed in temperate forests with large trees where decomposition rates are low (eg. Foster and Lang, 1982). Dry environments and cold environments typically result in slow decomposition; decomposition of organic matter is enhanced by increased moisture and temperature (Houghton *et al*., 1983).

CWD also has a key role in many aspects of ecosystem functioning. Forest floor woody debris provides a nursery site for seedling establishment (Figure 1.1) (McGee and Birmingham, 1997; McKenny and Kirkpatrick, 1999; and Takahashi *et al*., 2000), as do stumps (Kennedy and Quinn, 2001). CWD also provides habitat for many invertebrates (Rieske and Buss, 2001), fungi (Figure 1.2) (Amaranthus *et al*., 1994; Goodman and Trofmow, 1998; and Allen *et al*., 2000), vertebrates (Williams and Faunt, 1997; Goodburn and Lorimer, 1998; and Loeb, 1999), aquatic species (Robison and Beschta, 1990; and Van Sickle and Gregory, 1990), and lichens, mosses and liverworts (Kruys *et al*., 1999; and Lindenmayer *et al*., 1999). CWD also has an influence on stream quality and morphology (Minore and Weatherly, 1994; Nakamura and Swanson, 1994; and Myers and Swanson, 1997), nutrient cycling (Means *et al*., 1992; Rice *et al*., 1997; and Laiho and Prescott, 1999), and the transportation of soil and sediments (Maser *et al*., 1979).

Figure 1.1 A rotting log in tall open forest, southern Tasmania, provides an ideal nursery site for rainforest trees, mosses and ferns.

Figure 1.2 Bracket fungi growing on decomposing wood, southern Tasmania

1.2 Coarse woody debris sampling methods

Sampling strategies for measuring CWD depend on the inventory objectives and what data and level of precision are required, eg. ecological study, residue assessment for a timber inventory, fire fuel loading, forest structural characteristics, etc. The objectives will determine what measurements are required – species, piece size distribution, volume, mass, decay classes, etc.

Generally two methods are used for sampling forest floor CWD (for more details on CWD sampling methods see Woldendorp *et al*., 2002). The most common is the line intersect method derived by Warren and Olsen (1964) and further developed by Van Wagner (1968). This method entails measuring the diameter at the point of intersection on each piece of wood intersected by a transect line of given length but no width. A similar method, called the planar intersect method developed by Brown (1971), incorporates height to eliminate errors due to tilt of pieces not lying horizontally. A formula utilising piece diameters and total line length gives an estimate of volume.

Many configurations of the line intersect method have been adopted, including an equilateral triangle (eg. Delisle *et al*., 1988), three transects radiating from a common point (eg. Waddell, 2002), a square, an 'L' shape, a single line (see Bell *et al*., 1996), and other variations on these themes. Most forest management agencies have developed recommended procedures for assessing logging slash using the line intersect method, but unfortunately there has been inadequate analysis done regarding sampling requirements for CWD in natural forests and managed stands (Parminter, 1998).

CWD is usually sampled to a minimum size limit (and sometimes to a maximum size limit) as determined by the inventory objectives (eg. fire fuel studies predominantly focus on small piece sizes, whereas some habitat studies may only be interested in large pieces of wood). Available literature indicates that minimum diameter thresholds have ranged between 1 and 25 cm for a variety of studies.

Alternatively, a full census of forest floor CWD can be made on a fixed-area plot where each piece is measured for length and diameter. The diameter measurements are dependent on the volume equation, or vice versa, as there are several commonly used equations that relate to form. The CWD sampling protocols by McKenzie *et al*. (2000) recommend this approach when there are ≤10 pieces on a 25 x 25 m plot. Standing dead trees and stumps can be measured on fixed area plots (eg. Spies *et al*., 1988), and standing dead trees can also be measured by a variable probability sampling approach such as angle count sampling (Harmon and Sexton, 1996) which is more commonly when an entire stand is measured (eg. Eyre *et al*., 2000).

To obtain mass of CWD, an estimation of wood density must be made. This is done by categorising wood pieces into decay classes according to the structural integrity of the wood. Three to five decay classes are typical (Harmon *et al*., 1986) but decay classification systems have ranged from two (eg. McKenzie *et al*., 2000) to eight classes (eg. McCullough, 1948, cited in Meggs, 1996). As initial wood density varies with species it is necessary to record the species of CWD samples. Wood samples from each decay class are generally collected to determine wood density by decay class in the laboratory (eg. Lambert *et al*., 1980; Graham and Cromack, 1982; McKenzie *et al*., 2000; and Grove, 2001).

1.3 Aims and objectives

Funding for this project was through the Australian Greenhouse Office with the primary focus of reviewing and testing CWD sampling methods in target forest types and regions. The project forms part of measure 6.6 of the National Greenhouse Strategy to improve capacity to report on 'criteria and indicators of sustainable forest management'. The amount and condition of CWD in forests is a component of one of these indicators. This report is the second and final from this project. The aims of this project were to:

1) Review estimates of CWD in Australian forests, source databases from which additional estimates could be derived, and review and describe the methodologies used to quantify CWD.

2) Investigate and report on alternative methods for quantifying CWD through a combination of field surveys and modelled sampling designs.

3) Provide information to increase our understanding of CWD sampling and data requirements for carbon accounting purposes, and later incorporate outcomes into a continental forest monitoring framework being developed through the National Forest Inventory. In addition, it is hoped that findings from this project may be useful for other areas of research, such as habitat and ecological studies, fuel loading, timber inventories, or other resource management activities.

The first aim was covered in the report by Woldendorp *et al*. (2002). The other aims are the focus of this report. The objectives of this report are to:

- Conduct comprehensive field measurements of CWD in key forest regions, which represent a broad range of native *Eucalyptus*-dominated forest types.

- Use the field data collected from key forest regions to model alternative sampling approaches for forest floor CWD, and compare accuracy of the methodologies.

- Report on measurement costs and examine forest stand attributes in relation to amounts of CWD, and consider how these factors can influence the design of the sampling strategy.

2. Methodology

2.1 Sampling design

Three geographical locations were used for this study and covered a broad range of native forest types (and climates) found within Australia. These locations are woodland in south central Queensland (Injune), open forest in south coastal NSW (Kioloa), and tall open forest in Tasmania (Warra) (Figure 2.1). All sites consisted of forests dominated by *Eucalyptus* and other related genera, which is characteristic of approximately 80% of Australian native forests. The locations were chosen because it was considered that they broadly represented the range of *Eucalyptus* forest types across Australia. In addition, accessible data and sites for these regions were available through government agencies and institutions.

The plots selected had corresponding data including overstorey biomass and disturbance history. Time and resource limitations did not permit such attributes to be measured, but the data was considered important to relate to CWD quantities. These additional data were sourced from various inventory works, GIS and other studies. The principal sources of data and assistance with plot selection were from Forestry Tasmania – CFI plots and data at the Warra site, Tasmania; the Environment Protection Agency (EPA) Queensland and the Bureau of Rural Sciences (BRS), Canberra – plots and data from remote sensing work and ecological studies at Injune, Queensland; and Kimberly Van Niel (School of Resources, Environment, and Society, ANU, pers. comm.) and Austin (2000) – research plots and data in Kioloa State Forest through the Australian National University (ANU).

The method adopted involved a full survey of several small (one hectare) plots in each of the three different locations and forest types. Each of these plots represented a ‘population’ which was then sampled by modelling various methods to estimate the ‘population’ statistics. A one-hectare sample plot was chosen in order to compensate for the frequently large spatial variation in the amount of CWD within each stand, and is consistent with other CWD studies (eg. Graham and Cromack, 1982; and Siitonen *et al*., 2000). All CWD above a given diameter within each plot was measured and mapped to provide a graphical representation of the orientation, spatial distribution, density per unit area, and size of CWD pieces. This provided comprehensive data which were used as a basis for a computer simulation analysis of CWD sampling strategies to estimate the ‘population’ CWD. Mapping CWD has been used in other studies, particularly for plots where observations are made over a period of time (eg. Graham and Cromack, 1982; Agee and Huff, 1987; and McCarthy and Bailey, 1994).

The initial aim of the site selection at each locality was to sample five plots (encompassing pre-measured plots) covering a range of forest ages. This was more feasible in the tall open forests and open forests where a history of logging and fire has resulted in a broad spectrum of forest ages, but was less achievable in the woodlands where most of the disturbance (excluding cleared land) has been due to cattle grazing with only scattered timber removals. Five plots were measured in both the Queensland (Injune) and NSW (Kioloa) study areas, but only three sites could be measured within the timeframe in Tasmanian (Warra), where conditions (weather, terrain, vegetation, etc) and large amounts of CWD increased the measurement effort at each plot.

Each one-hectare plot (100 x 100 m) was over and, where possible, centred on a pre-measured vegetation plot so that other data relating to each plot could validly be used. If this placed part of the one-hectare CWD plot outside the forest condition to be sampled (i.e. into a different forest type or structure, into disturbed areas such as clearfelled forest, roads, woodpiles from road clearing, etc), it was moved the minimum distance that would keep the plot clear of the disturbance or different forest condition.

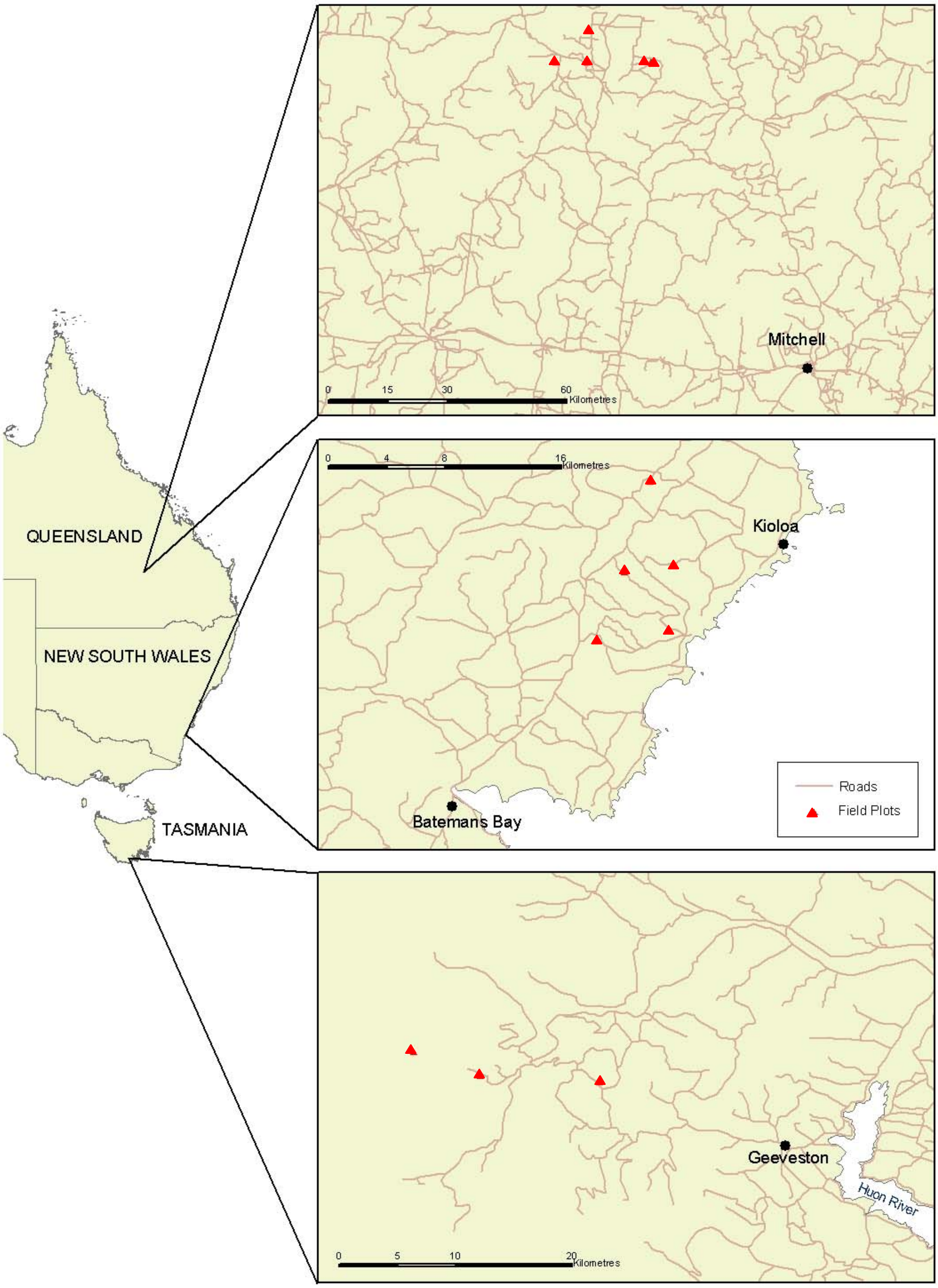


Figure 2.1 Study regions and plot locations in relation to road networks in south central Queensland (woodland), south coastal New South Wales (open forest), and southern Tasmania (tall open forest).

2.2 Study areas

2.2.1 Queensland

The Injune study area Injune is located in central Queensland, approximately 100 km north of Mitchell, and covers 222,085 hectares. Approximately 72% of this area is leasehold land, 24% is State Forest, and freehold land, roads, and reserves occupy 4% of the area. Five plots were sampled in the Injune study area, four within State Forest and one on leasehold land. The area lies within the Southern Brigalow Belt, a biogeographic region of Queensland, and is characterised by gently undulating terrain. The vegetation is dominated by *Callitris glaucophylla* (white cypress pine) woodlands on the sandy rises, and *Eucalyptus* and *Acacia* woodlands on the alluvial clays. Species common to the area include *Eucalyptus populnea* (poplar box), *E. melanaphloia* (silver-leaved ironbark), *E. crebra* (narrow-leaved ironbark), and *Acacia harpophylla* (brigalow).

The climate of the region is warm, temperate semi-arid, with hot, wet summers and cool, dryer winters. The mean annual rainfall at Injune is 642 mm with approximately 70% of this occurring in the summer months from October to March (Neldner, 1984). The hottest months are December and January with mean daily temperatures of about 26°C in Mitchell (mean maximum of 34°C), while the coldest month is July with a mean daily temperature of 11°C (mean minimum of 3°C). Water availability is the dominant factor affecting plant growth in the semi-arid climate of South Central Queensland, but frosts and floods may occur in the region and also impact upon plant growth.

The study area occurs within the Great Artesian Basin which has internal drainage and is mainly filled with Mesozoic sediments (Dawson, 1974, cited in Neldner, 1984). The soils of the study region are derived from Lower Jurassic sediments and Middle to Upper Jurassic sediments (Neldner, 1984). The Lower Jurassic sediments consist of the Precipice Sandstone, Evergreen Formation and the Hutton Sandstone, all predominantly of quartzose. The Middle to Upper Jurassic sediments are of the Injune Creek Group and include the Birkhead Formation composed of sandstone, some siltstone and minor coal seams, the Adori Sandstone which was derived from the north and deposited as river flats, and the Westbourne Formation of siltstone, mudstone and sandstone. There is a strong relationship between soil type, landform, geology and vegetation communities in the region (Neldner, 1984).

The present vegetation of the study area is a reflection of site potential as determined by climate, soil and land form, and also by land use and disturbance (Neldner, 1984). Most of the study region has been modified to varying degrees by anthropogenic activities such as burning, grazing, clearing and cultivation. Clearing has occurred in south central Queensland since the settlement of European graziers between the mid 1840s and the early 1860s (Smith *et al*., 1994). Clearing ranges from complete removal of the natural vegetation in cultivation areas, to selective removal of trees and shrubs to encourage pasture development or to feed stock during drought (Neldner, 1984). The natural frequency of fire in the area is low and irregular due to lack of sufficient fuel, although fire is often used after clearing operations, to remove woody debris or unpalatable grasses, and to control the regeneration of trees and shrubs (Neldner, 1984). Selective grazing by sheep and cattle has affected the composition of ground layers of plant communities in south central Queensland. Sites selected for this study had not been dramatically modified but some selective logging and grazing had occurred at some sites.

The EPA Queensland and the BRS in Canberra originally measured plots at Injune for a collaborative remote sensing work, and were also used for the Forest Condition and Habitat Assessment (FCHA) conducted by the Queensland Department of Natural Resources (QDNR). Plots used for the present study were selected from these plots. As part of the remote sensing work, a field assessment of biomass was conducted at 35 plots, each 50 x 50 m, for groundtruthing the remotely sensed data. Data from this work, as well as some data from the habitat assessment, were used for the CWD project.

2.2.2 New South Wales

The study area is in the south coastal region of New South Wales, located between 14 and 24 km north of Bateman's Bay. Five plots were sampled – four in Murramarang National Park and one in South Brooman State Forest. Topography has a large influence on the vegetation of south coastal NSW and Murramarang National Park. Along the coast from Bawley Point in the north to Durras in the south, the steep forested slopes of the Murramarang Range rise to a maximum height of 285 m (Durras Mountain). The undulating terrain west of this range are contiguous with the Great Dividing Range. The mean monthly rainfall is approximately 100 mm with a fairly uniform distribution throughout the year. Mean daily temperatures range from 9 to 16°C in July and 17 to 23°C in January (Ash and Helman, 1990). Temperatures in the region are closely related to elevation, distance from the coast, latitude, and local topography (Kalma and McAlpine, 1978)

The vegetation is open, dry sclerophyll forest with patches of wet sclerophyll forest and temperate rainforest. The tall open forests on the coastal slopes are usually of mixed *Eucalyptus* composition, although some are dominated by *E. maculata* (spotted gum) or *E. sieberi* (silvertop ash) (Costermans, 1993). Other species common in these forests include *E. pilularis* (blackbutt), *E. gummifera* (red bloodwood), *E. paniculata* (grey ironbark), and *E. globoidea* (white stringybark). Closed wet forests occur in sheltered gullies and typical species include *Acmena smithii* (lilly-pilly), *Acacia melanoxylon* (blackwood), *Livistonia australis* (cabbage fan-palm), *Elaeocarpus reticulatus* (blue olive-berry), and *Doryphora sassafras* (NSW sassafras).

Close to the coast soils in the area are derived from predominantly Permian – Triassic sediments mainly of the Sydney Basin (Costermans, 1993). These sediments make up the Conjola Subgroup of which there are three formations overlaying each other: the Wasp Head Formation consisting mainly of sandstone, conglomerate and sedimentary breccia beds; the Pebbly Beach Formation of siltstone, claystone, some sandstone and minor conglomerate; and the Snapper Point Formation of sandstone with some siltstone and conglomerate (Gostin and Herbert, 1973). Distinct belts of vegetation with differing dominant eucalypt species seem to correspond to the different soils formed on these three formations of the Conjola Subgroup (Galloway, 1978). Ordovician sediments are associated with the steep hilly and mountainous terrain occurring further inland and consist of greywacke, shale, sandstone, argillite and phyllite (Galloway, 1978).

The plots in Murramarang National Park occur in what was Kioloa State Forest until 2001, when Murramarang National Park was extended from a narrow coastal region to include Kioloa State Forest. The study area has been selectively logged since the 1830s (Donaldson, 1983, cited in Davey, 1989). From their study of the Butlers Creek catchment area just outside the Kioloa SF, Ash and Helman (1990) found old tree stumps that indicated the forest once contained many large trees, of which few living examples remain. They stated that timber had been taken from the catchment since the 1880s, most intensively between 1910 and 1926. Logging, together with the settlement of Europeans in the area in the early 1800s, have modified the landscape significantly (Davey, 1989). Some CFI plots were measured in Kioloa State Forest around the 1960s and 70s, but prior to this there is very little detailed information on the logging history (Ian Barnes, State Forests NSW, pers. comm.).

Plot selection and supplementary data for this project were from Austin (2000) and current PhD work by Kimberly Van Niel (ANU). Both these studies utilised plots originally established and measured in Davey (1989).

2.2.3 Tasmania

Three plots were sampled in Tasmania, approximately 60 km west south-west of Hobart in the vicinity of the Warra Long Term Ecological Research (LTER). The Warra LTER site covers 15,900 hectares and is near the junction of the Huon and Weld Rivers (http://www.warra.com). One plot was located within the Warra LTER site, one in the Picton Valley just outside the south-eastern boundary of Warra, and one in the Arve Valley also near Warra's south-eastern side. The Warra LTER site was designated in 1995 to foster long-term ecological research and monitoring in Tasmanian forests, and to facilitate the development and demonstration of sustainable forest management practices. The western part of Warra is part of the Tasmanian Wilderness World Heritage Area and is managed primarily for conservation values. The eastern part (including the area outside Warra where two CWD plots are located) is State forest managed by Forestry Tasmania for multiple purposes including wood production (http://www.warra.com).

The biome of the study region is principally cool temperate wet forest (tall open forest), with some areas of button-grass moorland, alpine moors, temperate rainforest, riparian forests, conifer forests, and scrub. The tall open forest, which consists mainly of *Eucalyptus obliqua*, is the most widespread forest community in Tasmania, and was of particular interest to this study. The *E. obliqua* forest occurs in a full range of successional stages from young regrowth forests to old-growth mixed forests (Hickey *et al*., 1999). Other eucalypt species found in the tall forests include *E. delegatensis, E. regnans, E. johnstonii* and *E. nitida* (Corbett, 1997, cited in Hickey *et al*., 1999).

Elevation at the Warra site ranges from 37 to 1260 m above sea level. Dominant soils are derived from Jurassic dolerite and derived Quaternary slope deposits that together cover about two-thirds of the area (Laffan, 2001). In the western part of Warra, soils are predominantly based on Precambrian quartzite, dolomite, slate and phyllite, in association with Permo-Carboniferous sedimentary rocks of the Parmeener Supergroup (Laffan, 2001). Mean annual precipitation is 1477 mm, with a fairly uniform distribution throughout the year. There are 1969 mean hours of sunshine per year. Mean annual temperature is 7.9°C, while the mean monthly temperatures range from 3.5°C to 12.8°C (http://www.warra.com).

Selective logging occurred in the region in the 1950's. Modern logging practices (clearfelling) in the Arve Valley began in the 1960s. The Warra LTER site and the Picton Valley were first logged in the early 1970s after the construction of a bridge over the Huon River (John Hickey, Forestry Tasmania, pers. comm.). Coupes were clearfelled, the slash was burnt at high intensity to create a receptive seedbed, and then reseeded. Between 1972 and 1993 approximately 40 ha per year of commercial forest was harvested and subsequently regenerated in the Warra LTER site (Hickey *et al*., 1999). Major wildfires occurred at the Warra LTER site and surrounds in 1898 and 1934.

Plots sampled for the CWD project were located around suitable continuous forest inventory (CFI) plots that are monitored by Forestry Tasmania. In general, CFI plots have been established in the area since the late 1960s and early 1970s, and are measured at establishment, at five years, ten years, and at ten-yearly intervals to determine forest productivity. For CFI there are two sizes of plots – 0.1 hectare (20 x 50 m) and 0.2 hectare (20 x 100 m) – the size established dependant on the substrata characteristics (Edgley, 1985). Aboveground tree data used for this study was supplied by Forestry Tasmania from their CFI plots. CFI plots are established on a random basis in selected strata determined by air photo interpretation.

2.3 Field measurements

The field survey was designed to capture the orientation, density per unit area and spatial distribution of CWD pieces as well as stag and stump density per unit area and spatial distribution. This was achieved through approximate measurements and mapping to obtain a diagrammatic representation of each piece of CWD within each plot. To facilitate mapping of logs, stags and stumps, each hectare plot was subdivided into a 10 x 10 m grid, with each intersection point marked with coloured tape (Figure 2.2). This was done using a compass and tape, starting from the centre of the plot and working out to the middle of the sides, then turning 90° toward each corner to create the plot boundary. The internal grid points were located by working from the centre line out to the sides. Field datasheets for mapping CWD corresponded to the grid layout, with four 10 x 10 m grids per page numbered for identification (Appendix 1).

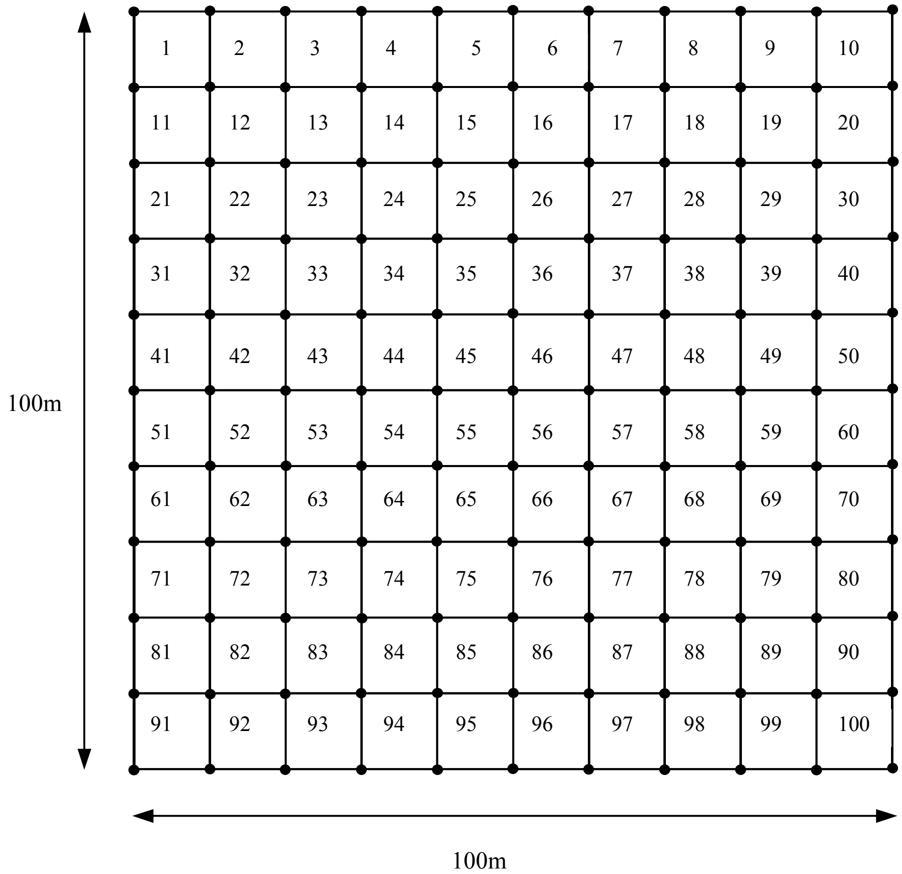


Figure 2.2 One-hectare plot layout. Black dots mark the 10 x 10m grid. Grid squares are numbered for mapping reference.

All downed woody debris, standing dead trees and stumps ≥15 cm in diameter and ≥50 cm in length/height were measured at sites in NSW and Tasmanian, and all CWD ≥10 cm in diameter (and ≥50 cm in length/height) was measured in Queensland due to smaller-sized trees. Because sampling CWD ≥10 cm at all sites would have increased the sampling effort significantly, it was felt that the additional time required to measure pieces between 10 and 15 cm in diameter at the NSW and Tasmania sites could not be justified in terms of any additional contributions to the CWD pool. More importantly, small piece sizes are more abundant than large pieces, and as the frequency of large wood is lower (Harmon and Sexton, 1996), the development of a methodology that is appropriate for capturing a representative number of pieces in the large diameter classes will consequently capture more than an adequate number of pieces in the small diameter classes.

Each piece of downed wood that was above the size threshold was measured for length and diameter at both ends (Figures 2.3 and 2.4). When a log was asymmetrical about the central axis, the maximum and minimum diameters were averaged (USDA Forest Service, 2001). When applicable, lengths and diameters were taken at the point where the log extended beyond the plot boundary or tapered to less than the minimum diameter threshold. All branching segments (within the size limit) of a single fallen tree or branch were recorded as separate pieces, and pieces that were bent significantly were measured as separate, roughly linear sections.

Figure 2.3 Using callipers to measure the diameter of forest floor CWD.

Figure 2.4 Measuring log length in southern Tasmania.

Stags were measured for height with a vertex hypsometer (Haglöf, Sweden) and for diameter at breast height (DBH). Stumps were measured for height and top diameter. Stumps included broken stag remnants <1.3 m in height and all cut stumps regardless of height. All measured logs, stags and stumps were numbered and their size and orientation recorded onto datasheets.

Each piece of CWD was assigned to a species of tree when this could be determined. However, when the species for a piece of wood could not be identified (often the case with highly decayed wood) it was either identified as a broad class (eg. rainforest sp., *Acacia* sp., *Eucalyptus* sp., etc), or deemed unknown. Logs and stumps were categorised into five decay classes (Table 2.1) based on Sollins *et al*. (1987), Pyle and Brown (1999), Spetich *et al*. (1999), and USDA Forest Service (2001), and stags categorised into four classes (Table 2.2, and see Figure 2.5) based on Spetich *et al*. (1999). Wood characteristics from termite damage were added to reflect Australian conditions.

Table 2.1 Characteristics of wood in five decay classes used for determining state of decay of forest floor CWD and stumps (based on Sollins *et al*., 1987, Pyle and Brown, 1999, Spetich *et al*., 1999, and USDA Forest Service, 2001).

Decay class	**Characteristics**
I	Most of the bark is present Branches retain twigs Solid wood Fresh wood Original colour
II	Some bark may be present Twigs absent Decay beginning to occur but wood still solid Invading roots are absent
III	Bark is generally absent Log still supports own weight More extensive decay throughout but structurally sound Moss, herbs, fungal bodies, may be present Some invading roots may be present Some termite damage (in warm climates)
IV	Log can't support own weight, all of log on ground Kicked log will cleave into pieces or can be crushed May be partially solid or some large chunks (sometimes quite hard) still remain Bark absent Small soft blocky pieces Branch stubs rotted down, can be removed by hand Moss, herbs, fungal bodies may be present Invading roots (when present) are throughout More extensive termite damage, producing hollows (in warm climates)
V	Soft and powdery (when dry), often just a mound Log does not support own weight Does not hold original shape, flattened and spread out on ground Moss, herbs, fungal bodies may be present Invading roots (when present) are throughout Hollow log from termite damage may have collapsed or be a thin shell (in warm climates)

Table 2.2 Characteristics of wood in four decay classes used for determining state of decay of standing dead trees (based on Spetich *et al*., 1999).

Decay class	**Characteristics**
I	Recently dead Branches and twigs present Bark intact and tight on bole
II	Bark loose and/or partly absent Large branches present, much of crown broken Bole still standing and firm
III	Large branch stubs may be present Top may have broken Bark generally absent Bole still standing but decayed Some termite damage
IV	Branches and crown absent Bark absent Broken top Wood is heavily decayed or hollow Extensive termite damage producing hollows

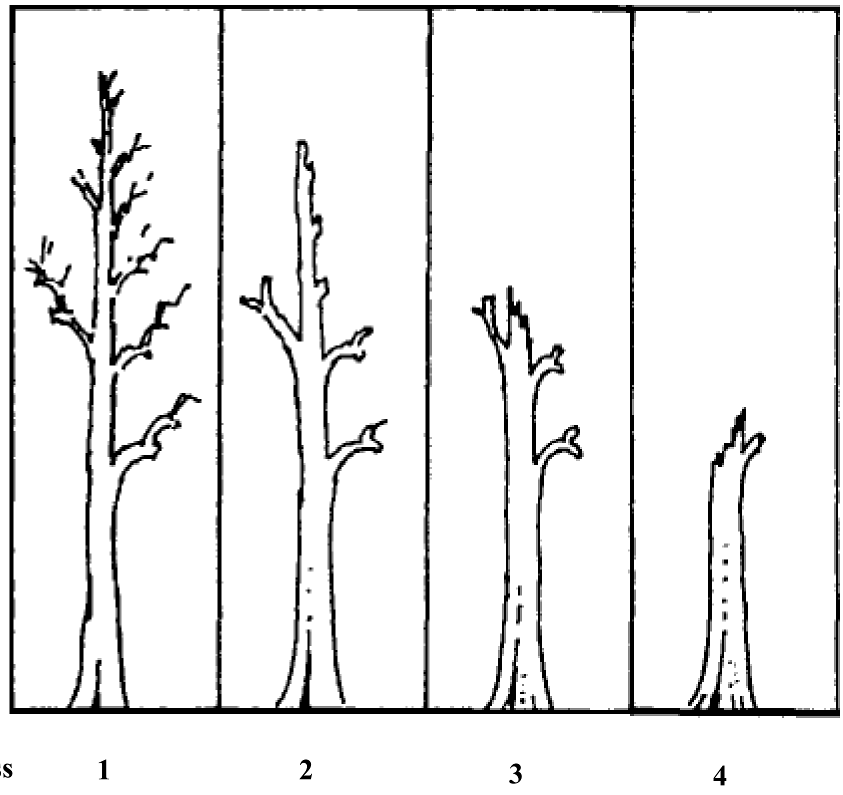


Figure 2.5 Guideline for form of stags in each of four decay classes (modified from Smith and Lindenmayer, 1988)

A piece was assigned to a decay class that best represented the greatest proportion of the wood. CWD did not necessarily exhibit all characteristics in a decay class, but characteristics listed in each decay class are typical for that class. Most of the decay class characteristics were derived from various US studies. Therefore some characteristics are not typical of decomposing wood in the dryer forests of Australia. Structural damage from termites as a decay characteristic was included (Figure 2.6). Stags do not occur in decay class V because this class would indicate total collapse. Also, the form of a tree is not always as a result of decay status, such as a bole broken by lightening strike.

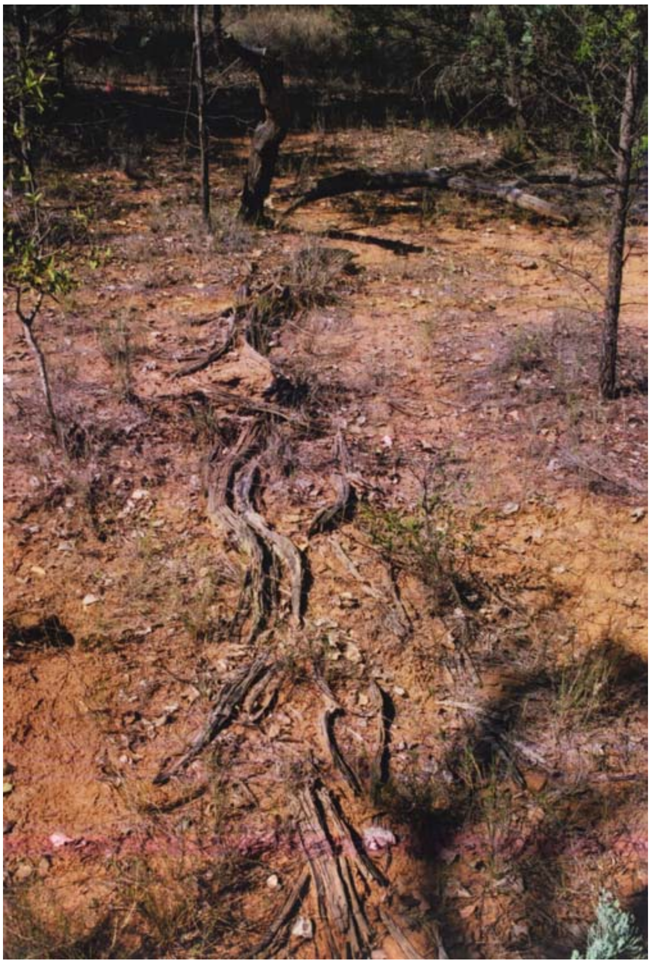


Figure 2.6 A highly decayed log, predominantly due to termite attack, in woodland, south central Queensland.

Hollows in logs were generally not taken into consideration when measuring logs for volume but they were considered as part of the structural integrity of the wood when allocated to a decay class. Volume, therefore, may be overestimated whereas mass estimates are likely to be more accurate. This was mainly due to limitations of time and because hollows were difficult to measure, as dimensions were usually irregular and could often not be seen or accessed to measure. For example, hollows caused by termites were, for the most part, irregular in shape. This is because the termites create galleries, runways, and pipes. Pipes occur when the centre of a trunk is completely eaten away, which is common in eucalypts where heartwood is prone to termite attack. The pipe walls may be regular or have galleries penetrating into the surrounding wood (Ratcliffe *et al*., 1952). These features are commonly filled or constructed with termite excreta which, according to the species of termite, is of either cemented soil or “carton” – predominantly semi-digested wood and organic matter, sometimes incorporating soil particles (Ratcliffe *et al*., 1952). The geographical distribution of termites is limited by temperature, generally occurring between 48º north and south (http://www.labyrinth.net.au/~dewart/). Some families of termite feed on sound dead wood, others feed on decaying wood, and many species feed only on wood that is in an advanced state of decomposition (Lee and Wood, 1971).

Site-based biophysical attributes were also recorded, including situation and slope position, slope angle, aspect, elevation, percentage canopy cover, percentage ground cover, main overstorey and understorey species, and disturbance (disturbance history was sourced from records or informants).

2.3 Analysis

2.3.1 Total plot volume

2.3.1.1 Logs

Volume of forest floor CWD pieces was estimated using Smalian's formula. It estimates the volume of a log as the mean of the cross-sectional areas at both ends multiplied by length:

$$V = L\ (A_b + A_s)/2 \qquad (1)$$

where V = volume (m^3)

L = piece length (m)

A_b = cross-sectional area at the large end of the piece (m^2)

A_s = cross-sectional area at the large end of the piece (m^2)

Smalian's formula assumes that the shape of the section being measured is a second-degree paraboloid (Cris Brack, Dept. of Forestry, Australian National University, pers. comm.).

Piece volumes were summed for each decay class and for each one-hectare plot to give volume per hectare.

2.3.1.2 Stags and stumps

The volume of stags and stumps determined from field measurements were included to provide a complete picture detrital biomass. Volume calculations varied for each region due to species and data availability.

<u>Tasmania</u>

The volume of stags and stumps from the tall open forest plots in Tasmania was estimated using the Farm Forestry Toolbox (FFT) version 3.5, a program developed by Private Forests Tasmania. The FFT enables calculations of volume to be made for individual trees by using diameter at breast height over bark (DBHOB), height and species. For broken stags and stumps, the original top height of the tree was estimated from DBHOB/height relationships for species of live trees measured previously on the plots (CFI measurements). *Eucalyptus regnans* and *E. obliqua* were combined for this analysis as it was usually difficult to identify decomposing stags and stumps by species. However, only one site had both species (the other sites were dominated by *E. obliqua*) and therefore it was reasonable to use *E. obliqua* as the tree form for estimating stag and stump volume with the FFT. DBHOB/height relationships were examined for other dominant non-eucalypt species at the sites– *Acacia* spp. (grouped) and *Nothofagus cunninghamii* (Myrtle). Using data of live trees >10 cm DBH from the CFI plots for each site, height was plotted against DBH for the three groups – *Eucalyptus* spp., *Acacia* spp., and *N.*

cunninghamii. Log linear curves were then fitted to the data to enable original height of broken stags to be estimated from DBH:

Eucalyptus spp. →	$h = 15.268 \ln(dbh) - 23.721$	$R^2 = 0.9316$	n = 441	(2)
N. cunninghamii →	$h = 10.441 \ln(dbh) - 12.24$	$R^2 = 0.9755$	n = 26	(3)
Acacia spp. →	$h = 9.5402 \ln(dbh) - 13.459$	$R^2 = 0.7942$	n = 25	(4)

where h = height (m)

dbh = diameter at breast height (cm)

The estimated height for an individual stag or stump was used in the FFT to calculate the original tree volume. The FFT then allows for a portion of each tree's volume to be calculated, in this case from ground level to the height of the broken stag or stump. The diameter of stumps <1.3 m in height (height at DBH) were found by adjusting the estimated DBH in the FFT program.

<u>New South Wales</u>

Stag volumes in the open forest plots in New South Wales were calculated using allometric equations from Bi and Hamilton (1998) and volume ratio equations from Bi (1999). These equations are species specific, so the mean of estimates was used when several species occurred in a plot (and when several species equations were available). The volume of each whole stag was calculated solely by allometric equations but broken stags required further analysis. This involved estimation of the original tree height of each broken stag from a DBHOB/height relationship for live trees on the plots. This was done by plot rather than by species as stags could usually be identified to Genus only, and site characteristics (topography, soils, productivity, etc) commonly determined top tree height at a site. From pre-measured plot data, DBH and height for all live trees were plotted and the following equations obtained:

Plot NSW1 →	$h = 8.8352 \ln(dbh) - 11.988$	$R^2 = 5983$	n = 52	(5)
Plot NSW2 →	$h = 14.779 \ln(dbh) - 26.907$	$R^2 = 0.8669$	n = 64	(6)
Plot NSW4 →	$h = 14.059 \ln(dbh) - 30.62$	$R^2 = 0.5602$	n = 71	(7)

where h = height (m)

dbh = diameter at breast height (cm)

Estimated top height of trees from plots NSW3 and NSW5 were calculated using equation 6 derived from plot NSW2 data. This was because there was not sufficient data on live tree heights and diameters from plot NSW3 as it had been recently harvested and burned. Data were from regrowth and sapling trees which was not suitable for estimating the height of stags and stumps with larger diameters. For plot NSW5, there were no tree height data available as measurements had not been taken from previous sampling efforts. Forest type and species composition were similar for plots NSW2, NSW3 and NSW5, therefore use of tree height data from plot NSW2 appeared to be justified.

Original tree volume was calculated with allometric equations using DBHOB and estimated top height for each stag. Then a simple ratio of top height/stag height was used in species specific equations from Bi (1999) to calculate a volume ratio for each stag. The volume ratio was used to calculate actual stag volume, based on original tree volume. Volume of cut stumps >1.3 m in height were also calculated by this method.

Queensland

A similar method for estimating volume and mass of stags was used for the woodland plots in Queensland. Many biomass and allometric regression equations that exist for species in Queensland woodlands use a diameter or circumference at 30 cm from the ground rather than diameter at 1.3 m (DBH). As DBHOB measurements were taken for stags at all sites, diameter at 30 cm was extrapolated from DBHOB measurements of stags. Data from previous measurements at each plot included height, DBH, and diameter at 30 cm for live trees >10 cm in diameter, allowing relationships of these parameters to be interpreted from DBH alone. Thus diameter at 30 cm could be estimated.

To calculate the original top height of stags, DBH and height for live trees previously measured at the plots were plotted. As topography in the study region did not change significantly between plots, data were grouped into two sets – *Callitris* spp and *Eucalyptus/Angophora* spp. Logarithmic curves were then fitted to the data (several curves were tested but a natural log curve gave the best fit) to give the following equations:

Callitris spp. → $h = 5.203 \ln(dbh) - 3.352$ $R^2 = 0.4615$ n = 126 (8)

Euc./Ang. spp. → $h = 6.1342 \ln(dbh) - 6.4629$ $R^2 = 0.509$ n = 106 (9)

where h = height (m)

dbh = diameter at breast height (cm)

To estimate the diameter at 30 cm for stags, the rate of change of diameter over a 100 cm height (the difference between diameter at 30 cm and diameter at 130 cm) was initially calculated from the live tree data by:

$$r = (D - dbh)/10 \qquad (10)$$

where r = the rate of change for every 10 cm in height (cm)

dbh = diameter at breast height (cm)

D = diameter at 30 cm height (cm)

The rate of change was calculated for each live tree, separated into the two groups (*Callitris* spp. and *Eucalyptus/Angophora* spp.) and plotted against DBH. Linear equations were fitted to the data so that rate of change in diameter for stags and stumps could be estimated:

Callitris spp. → $r = 0.0064\ dbh + 0.1127$ $R^2 = 0.1153$ n = 126 (11)

Euc./Ang. spp.→ $r = 0.0106\ dbh + 0.1179$ $R^2 = 0.3751$ n = 106 (12)

where r = rate of change for every 10cm in height (cm)

dbh = diameter at breast height (cm)

Diameter at 30 cm height was then estimated by rearranging equation 10 as:

$$D = r * 10 + dbh \qquad (13)$$

where r = the rate of change for every 10cm in height (cm)

dbh = diameter at breast height (cm)

D = diameter at 30cm height (cm)

A volume ratio for stags at the woodland sites was calculated in the same way as for the NSW sites - stag height as a percentage of estimated original tree height - using an equation for mixed *Eucalyptus* spp. from Bi (1999). Allometric equations for woodland trees in Queensland were sourced from Burrows *et al.* (2000), Eamus *et al*. (2000), and Burrows *et al*. (2001). Existing allometric equations estimated biomass by species. Above-ground biomass was estimated by species for the whole tree and converted to volume using the basic wood densities for species from Ilic *et al.* (2000). This gave volume for whole tree, which was multiplied by the volume ratio calculated for each stag to give stag volumes. For *Eucalyptus/Angophora* species having no unique allometric equation for total biomass, a mixed *Eucalyptus* spp. equation for intact woodlands was used (Eamus *et al*., 2000).

For stumps <130 cm in height at the woodland plots the rate of change of diameter by height was extrapolated to the base of the stump so that a basal diameter could be estimated in a similar way to equation 13:

$$d_b = r*(h/10) + d_t \tag{14}$$

where d_b = diameter at base (cm)

r = the rate of change for every 10cm in height (cm)

h = height of stump (cm)

d_t = top diameter of stump (cm)

From top diameter, estimated basal diameter and height, the volume of each stump was estimated using Smalian's formula (equation 1). The method of estimating the basal diameter of stumps used here possibly underestimates the true basal diameter, as taper from 30 cm to base is generally more than taper from 130 cm to 30 cm of a tree. However, it was felt that this method was adequate for the purposes. This method was also used for estimating stump volume for the open forest plots in NSW. The rate of change of taper determined from Eucalypts at the woodland plots was used for estimating diameter at base of stumps measured at the open forest plots, as it was the best available data on hand.

2.3.2 Total mass

To determine mass of logs, stags and stumps, the volume of each piece of wood was multiplied by the basic wood density (kg m^{-3}) for that species, and included a percentage reduction for each decay class. Decay class one is characterised by fresh solid wood and it is fair to assume that CWD in this class has the basic density of wood for that species. For decay classes 2, 3, 4 and 5, mass was calculated as 84%, 69%, 46% and 36% of the basic density, respectively, by species. The loss of mass for each decay class was determined according to Woldendorp *et al*. (2002) using estimates of wood densities for five CWD decay classes from published literature and calculating each decay class as a proportion of decay class one. Basic wood densities for each species were taken from Ilic *et al*. (2000). When species of a CWD piece could only be identified to genus, the mean was taken of the basic densities for species (of that genus) occurring on the plot. If species or genus of a wood piece was unknown, the average basic density for all dominant overstorey species was used. The mass of all CWD pieces was summed for each decay class in each one-hectare plot to give mass per hectare by decay class.

2.3.3 Modelled sampling designs

Maps of CWD generated in the field were scanned and digitised using MapInfo. A computer program was developed to simulate the line intersect method for sampling forest floor CWD. Shapefiles were created from the mapped data, and used for the simulations. The program simulated the sampling process by allowing arbitrary (user defined) transects or quadrats to be randomly orientated and located within the sampling area. A transect or quadrat was nulled if it intersected the plot boundary. This may cause some bias toward the centre of the plot, particularly for longer transect lengths where the constraints of the sampling area has a greater effect. Once the transect(s) were located the statistics of interest for the particular sampling method were calculated based on the digitised log data. The program allowed this process to be replicated so that the sampling distribution of the estimates could be approximated to arbitrary levels of accuracy. The program is written in visual C++ and uses ESRI shapefiles as input.

The program enabled sampling of forest floor CWD using different lengths, number, and layouts of line transects. Random transect of 10, 20, 40, 60, and 80 m length were generated for each plot. An 80 m transect was considered to be the longest practicable transect for use in a one-hectare plot although some bias may occur at the centre of the sampling area due to the constraints of plot size. The number of transect elements for a given length was tested using a total length of 20 m divided into 1 x 20 m, 2 x 10 m 3 x 6.67 m, and 4 x 5 m sections, and a total length of 60 m was divided into 1 x 60 m, 2 x 30 m, 3 x 20 m, and 4 x 15 m sections. These elements were also placed randomly within each plot. Different transect orientation and layout were evaluated using transects of 20 m and 60 m as a single transect, as three segments of equal length located randomly, as an equilateral triangle, and as a square. Alternative approaches were compared using 10,000 random replications. This provided results on the frequencies and range of different estimated values.

Resulting from the findings using the simulations mentioned above, an additional test was performed at the woodland site in Queensland. Using the longest transect tested indicated that it was still too short to account for the high spatial variability of wood pieces at this site. Therefore, a larger landscape was created with a mosaic of plots QLD1, 2, 3, and 5, to give a plot of four hectares. Plot QLD4 was excluded as the other plots were more similar in structure and species composition. An equilateral triangle with 100 m sides was tested on the mosaic of woodland plots, using 10,000 replicates.

Volume of forest floor woody debris was also sampled by simulating quadrats of 10 x 10 m, 20 x 20 m, and 50 x 50 m. In these cases all pieces of forest floor CWD were measured within a quadrat and a volume calculated from length and diameter at both ends of a piece, assuming the shape of a truncated cone. For logs extending outside the quadrat, the modelled sampling includes only that portion of the log contained within the quadrat, and uses an estimated diameter measurement at the point where the log exits the quadrat.

For analysis, the coefficient of variation (CV) is used to show the variation in volume estimates for individual plots in each region. The CV is calculated as the standard deviation divided by the mean, expressed as a percentage. It is a useful measure for comparing the variability of different population estimates because it removes the effect of different scalar values – in this case different densities of forest floor CWD – i.e. it is independent of the unit of measurement. Nevertheless, care is required in interpreting the results because all of the Queensland plots included pieces of wood between 10 and 15 cm in diameter which were excluded from the plots in Tasmania and New South Wales.

As 10,000 replicates were used for each test, it was expected that mean volume estimates would be similar regardless of transect length or plot size. This was generally the case on most plots with all sampling methods. However, there was a tendency at plots QLD1, NSW2, and NSW5 for the mean volumes to be lowest for the largest transects and quadrats. The computer-simulated sampling may bias the centre of the plot because any transect intersecting the plot boundary is nulled. This would be exacerbated with increasing transect length and quadrat size as the placement of larger transects/quadrats within the plot becomes increasingly limited. From a cursory examination of the pattern of CWD distribution at these plots (QLD1, NSW2 and NSW5), there was a substantial proportion of downed CWD near the perimeter of the plot. Therefore, it was speculated that larger transects/quadrats are not sampling as much material close to the plot perimeter compared with smaller ones. This may explain the lower mean volume estimates for the longest transects and largest quadrats at these plots.

To demonstrate the range and frequency of estimates obtained from simulating the line intersect method and associated variables, histograms were constructed from data derived from one of the woodland plots (QLD1 which had 97 measured pieces of downed CWD), open forest plots (NSW1 which had 253 measured pieces of downed CWD), and tall open forest plots (TAS1 which had 439 measured pieces of downed CWD). These plots were chosen because they represent the lowest, mid-range, and highest volumes and number of CWD pieces of all the plots sampled.

The aggregation of CWD pieces to a maximum of 50m was examined at plots QLD1, NSW2 and TAS2 using the spatial library routines from Venables and Ripley (1994). The available methods are applicable to points and the CWD pieces have, for this analysis, been represented by the coordinates of their larger end. Ripley's K function can be used to specify the second moment for the distribution of n points which have a spatial intensity of λ (the expected number of points per unit area).

The expected number of points within a distance t from a point is given by $\lambda K(t)$. For the Poisson process, $K(t) = \pi t^2$, Venables and Ripley's procedures produce a plot of $L(t) = \sqrt{(K(t)/\pi)}$ against t. One hundred simulations from a binomial process are used to provide an approximate 95% confidence envelope to assess the observed $K(t)$. For complete spatial randomness the plot of $L(t)$ against t should be a straight line. Values significantly above this line indicate clustering and values significantly below this line indicate regularity.

3. Results

This section presents and discusses the results from this project under two main sections: stand attributes which are the results of the plot measurements in the three forest types, both from the CWD field survey and from the available data for each plot; and modelled sampling designs that compares the accuracy of the selected CWD sampling strategies.

3.1 Stand attributes

Within each of the three forest types, stand characteristics at each plot varied, predominantly in terms of stand age and disturbance, and to a lesser extent, position in the landscape and species composition. Plot descriptions and stand attributes for each plot are given in Appendix 2. Briefly, all Injune plots were on flat terrain at similar elevations, and vegetation type was grassy woodland at all but plot QLD4, which was in open forest. Disturbance at the Injune plots was minimal but evidence of grazing, selective logging, and/or vehicular tracks could be seen at some plots.

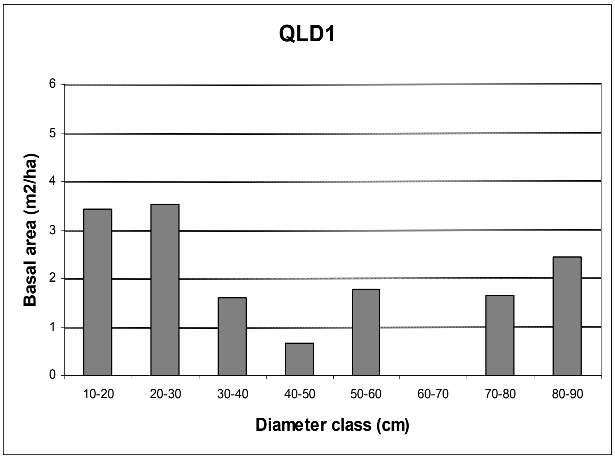
The Kioloa plots were in forest that was previously managed for wood production, so were multi-aged, and evidence of timber removals could be seen at all plots except NSW4. Plot NSW3 had been harvested more recently and most of the trees on the plot were young regrowth (about five years old). Kioloa plots were on undulating terrain, generally situated mid-slope, and with a range of aspects.

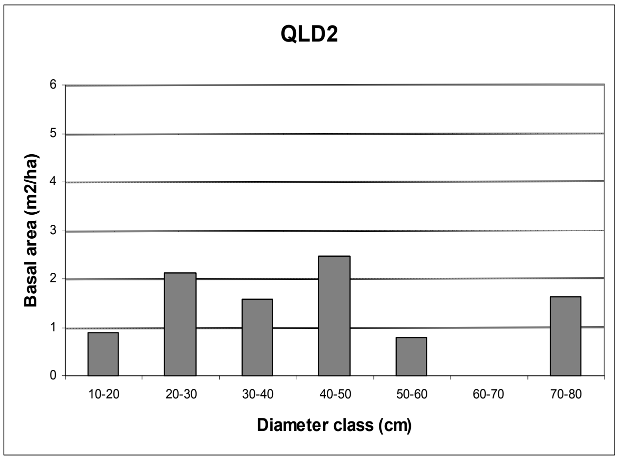
Two of the Warra plots were in forest that had not been logged whereas plot TAS1 was in relatively young, regrowth forest approximately 35 years old. All Warra plots were on hilly terrain, at various positions on the slope, and with a range of aspects.

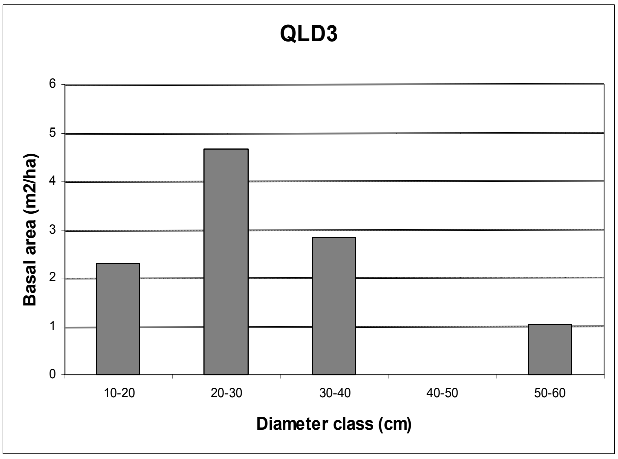
3.1.1 Basal area

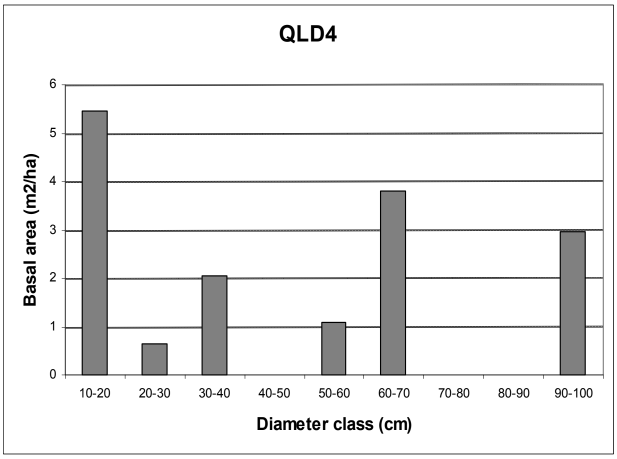
Basal area for live aboveground trees >10 cm DBH are shown for each plot in Injune, Kioloa, and Warra (Figures 3.1, 3.2, and 3.3). Total basal area of live trees ≥10 cm DBH was compared to basal area of stags and stumps measured, and results are given in Table 3.1 for each plot, including number of stems. Live tree basal area at plot NSW3 is for ≥20 cm DBH due to available data. Generally, basal area of live trees increases from Injune, to Kioloa, to Warra.

At Injune, plot QLD4 had the largest trees, with diameters up to 100 cm (Figure 3.1) and is later shown to reflect the high quantity of CWD at that plot (section 3.1.3). The forest type at this plot was considered to be open forest with *Angophora leiocarpa* dominating. This is a larger tree species than those found in the woodland typical of the Injune study area. There is also considerable regrowth at this plot, as indicated by the high basal area of live trees in the 10 – 20 cm diameter class. The regrowth at plots NSW3 (Figure 3.2) and TAS1 (Figure 3.3) is evident by the live trees in only small diameter classes compared to other plots in the same location. Also, total basal area of live trees for these plots is much lower than at other the plots (Table 3.1).









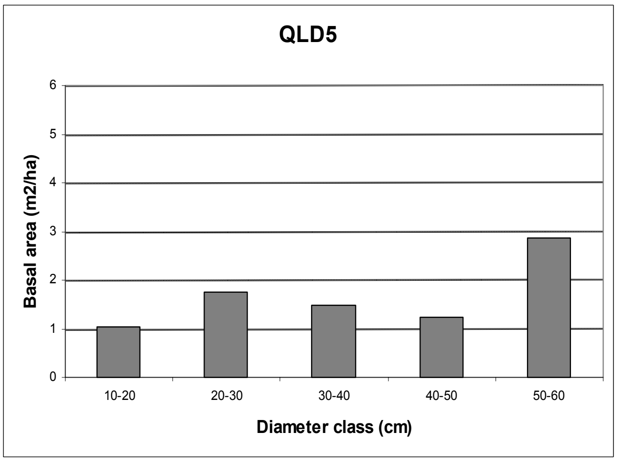


Figure 3.1 Basal area of live trees by diameter class at the Injune woodland plots, south central Queensland.

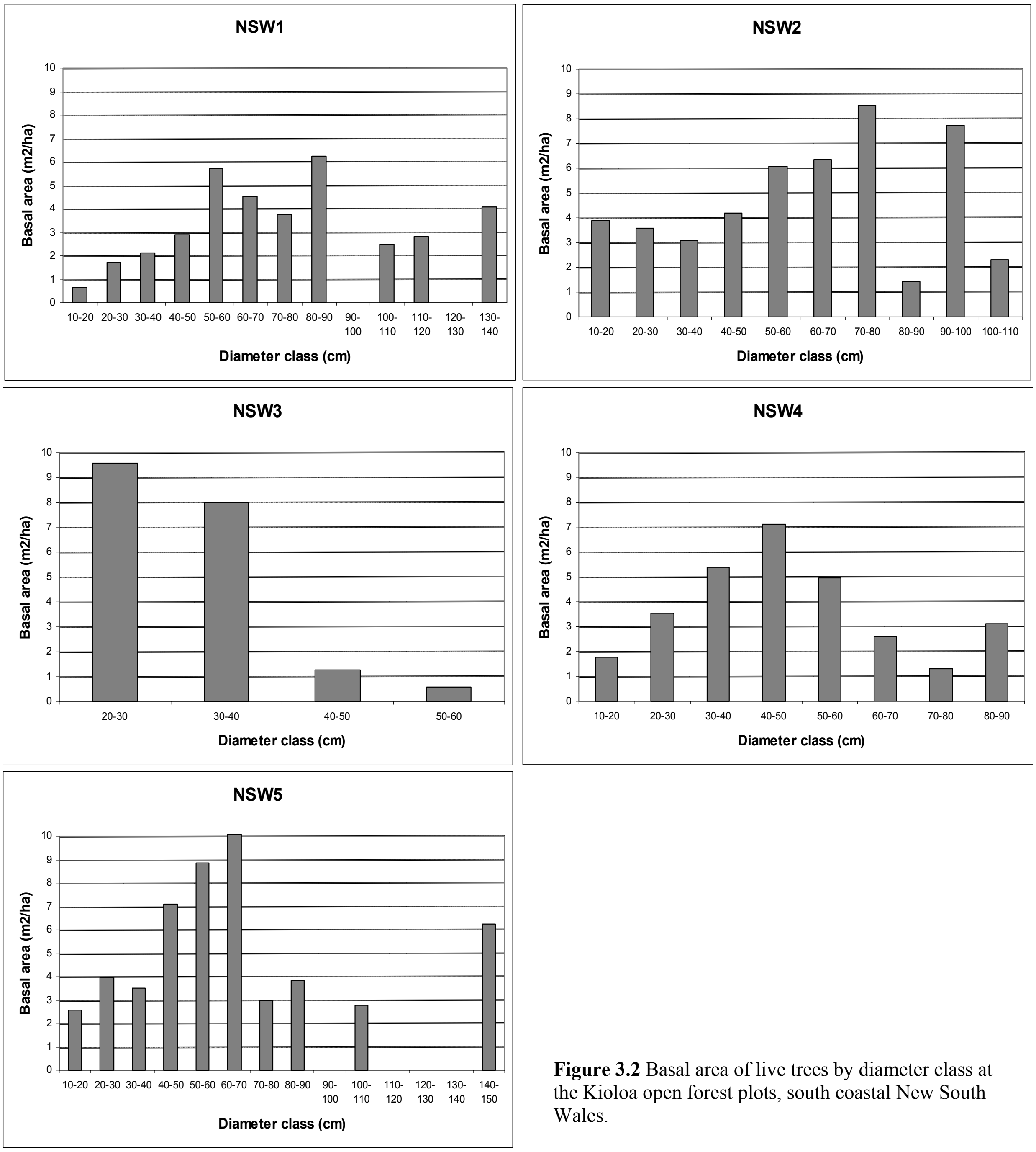


Figure 3.2 Basal area of live trees by diameter class at the Kioloa open forest plots, south coastal New South Wales.

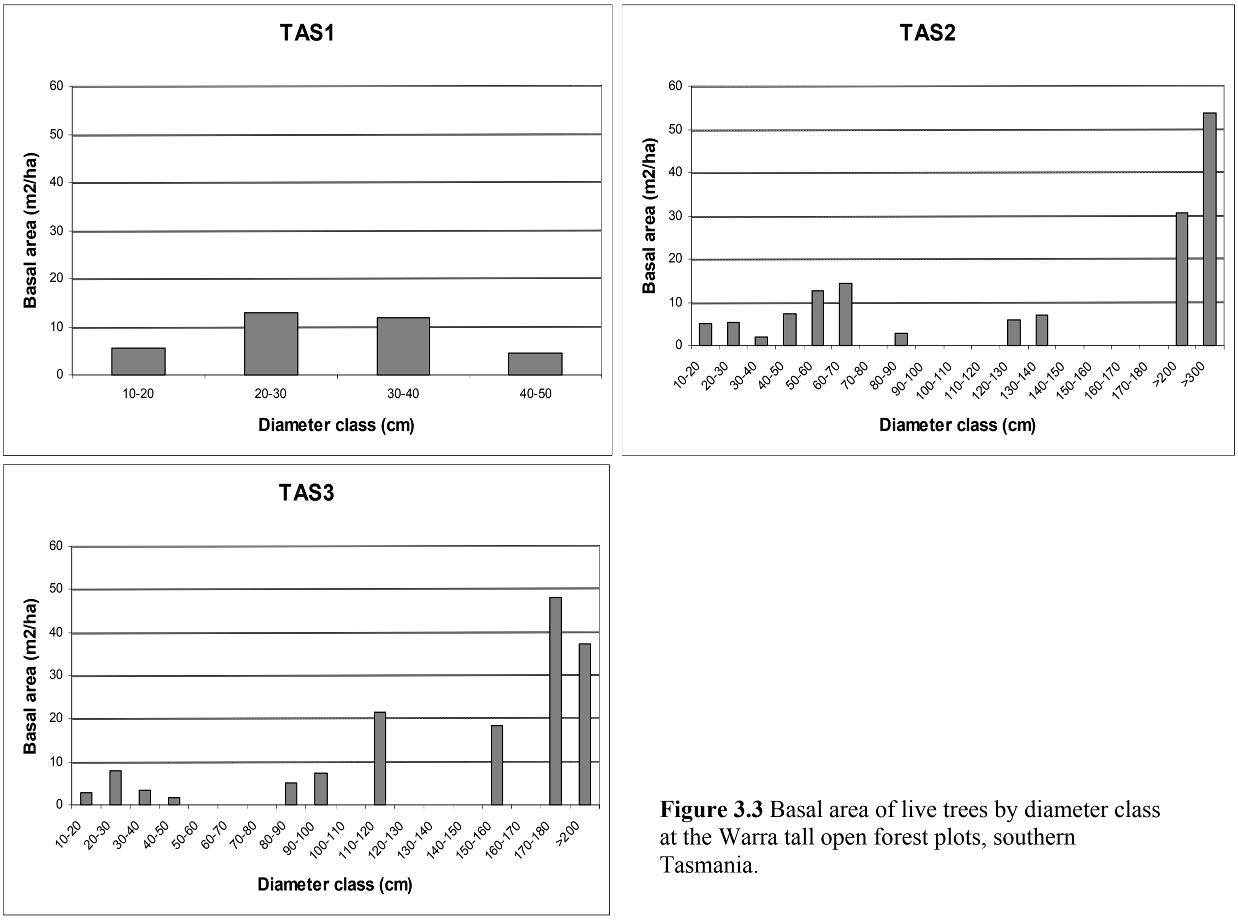


Figure 3.3 Basal area of live trees by diameter class at the Warra tall open forest plots, southern Tasmania.

Total basal area of live trees ranged from approximately 8 – 16 m^2 ha^{-1} at Injune, 19 – 47 m^2 ha^{-1} at Kioloa, and 35 – 154 m^2 ha^{-1} at Warra. High basal area of stumps, together with a high number of live trees with low basal area at plots NSW3 and TAS1 (Table 3.1), once again reflect extensive and recent timber harvesting. Note that live tree basal area at NSW3 also may be low as trees 10 – 20 cm DBH were not included. Across all plots, stags made up from 1 – 13% of all standing trees. This type of range occurred at each of the three sites.

Table 3.1 Basal area in m^2ha^{-1} for live trees ≥10 cm DBH at all plots (except NSW3 where BA ≥20 cm), and stags and stumps ≥10 cm in diameter at Queensland plots and ≥15 cm at Tasmania and NSW plots. Number of stems in parenthesis.

Plot no.	Live tree BA (m^2ha^{-1})	Stag BA (m^2ha^{-1})	Stump BA (m^2ha^{-1})
QLD1	15.12 (308)	1.50 (11)	0.56 (5)
QLD2	9.49 (152)	0.81 (20)	0.24 (5)
QLD3	10.83 (256)	1.47 (37)	0.69 (6)
QLD4	16.03 (388)	1.24 (13)	0.74 (5)
QLD5	8.39 (140)	0.69 (14)	0.26 (3)
NSW1	37.10 (183)	4.20 (24)	2.80 (18)
NSW2	47.13 (449)	2.33 (9)	6.34 (17)
NSW3	19.31 (297)	0.14 (3)	13.72 (80)
NSW4	29.82 (326)	1.67 (21)	0.67 (14)
NSW5	35.51 (414)	2.19 (13)	5.66 (15)
TAS1	34.99 (770)	10.77 (8)	61.79 (21)
TAS2	146.90 (600)	24.79 (84)	9.98 (30)
TAS3	153.54 (450)	19.29 (13)	2.35 (9)

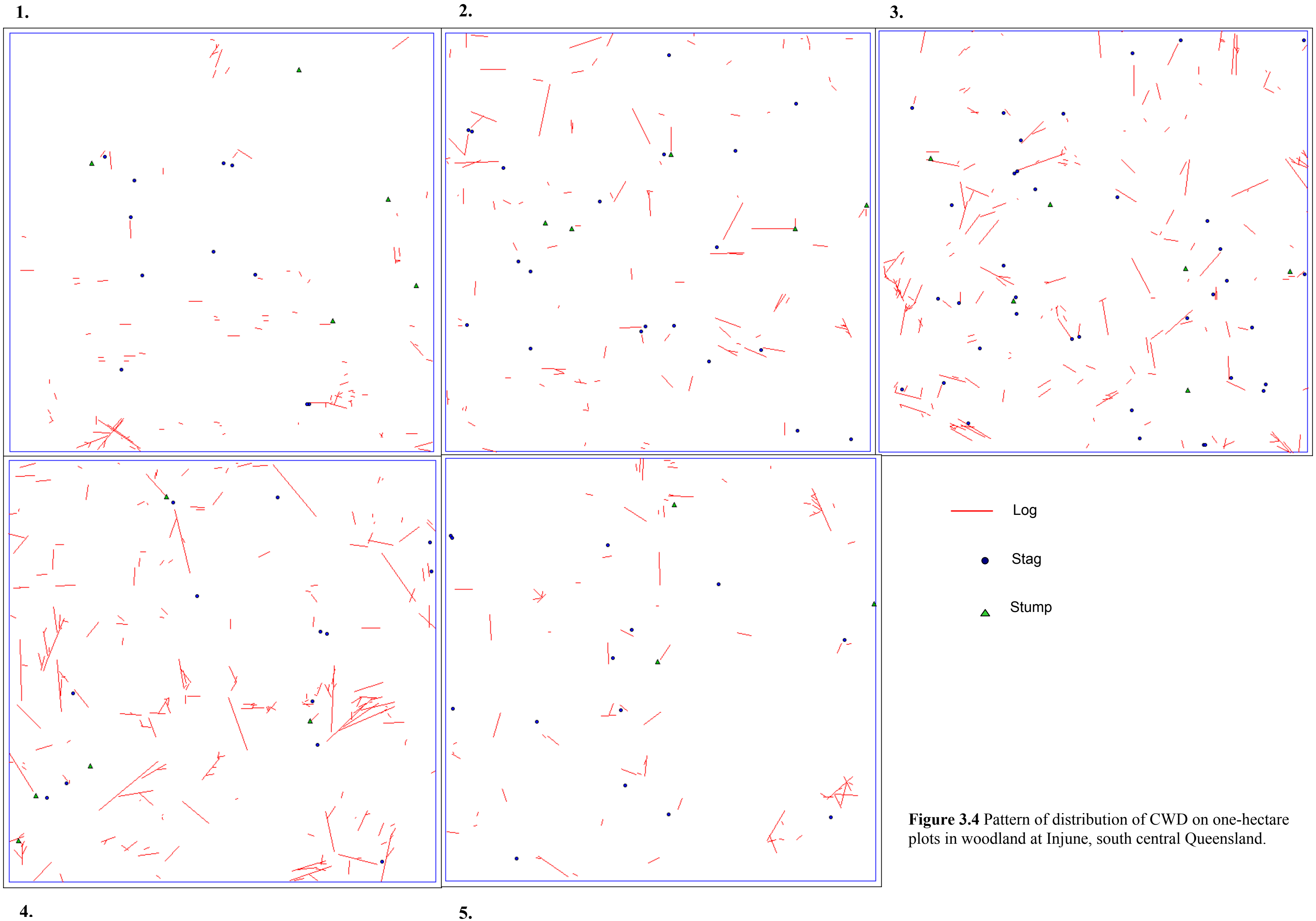


Figure 3.4 Pattern of distribution of CWD on one-hectare plots in woodland at Injune, south central Queensland.

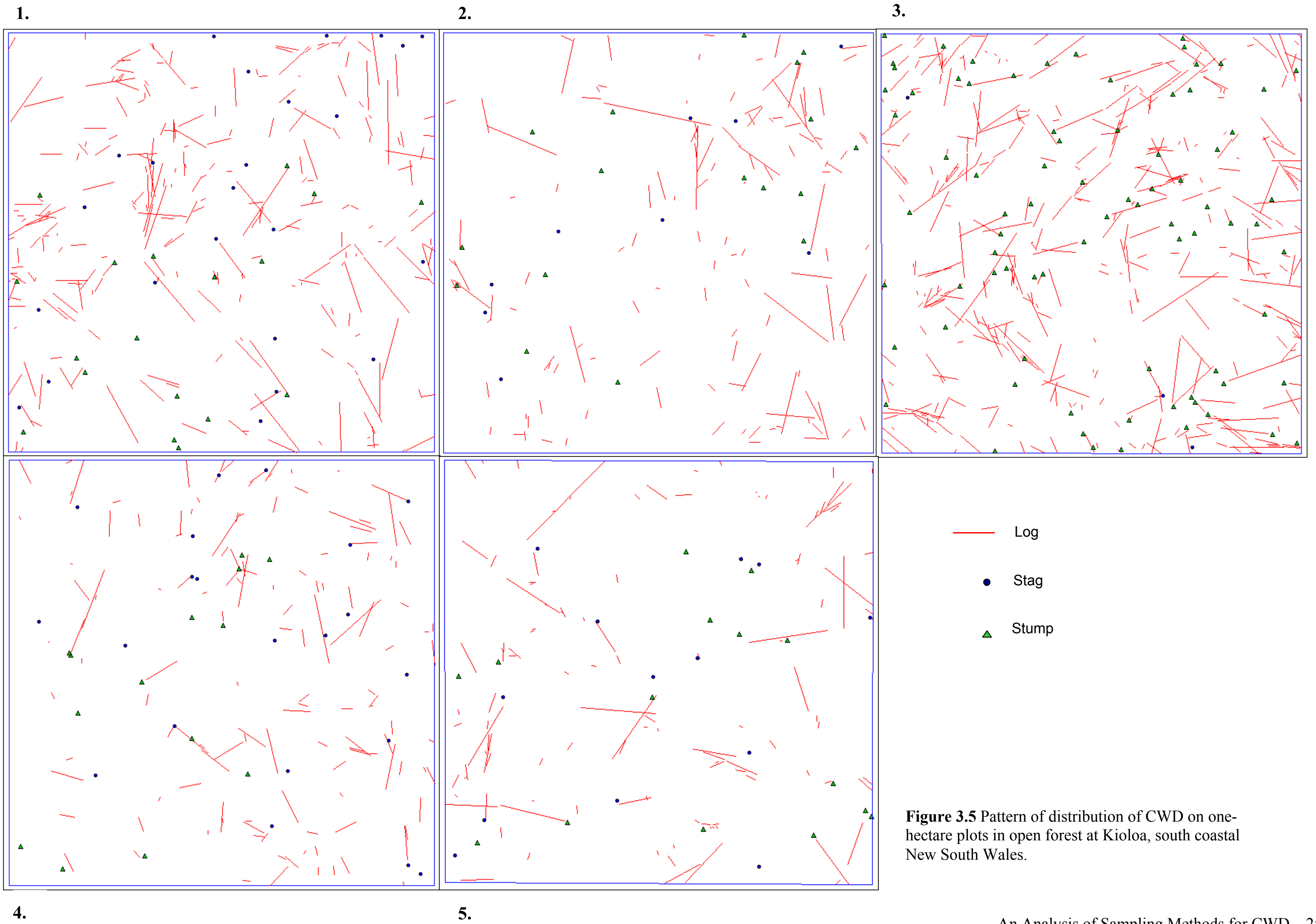


Figure 3.5 Pattern of distribution of CWD on one-hectare plots in open forest at Kioloa, south coastal New South Wales.

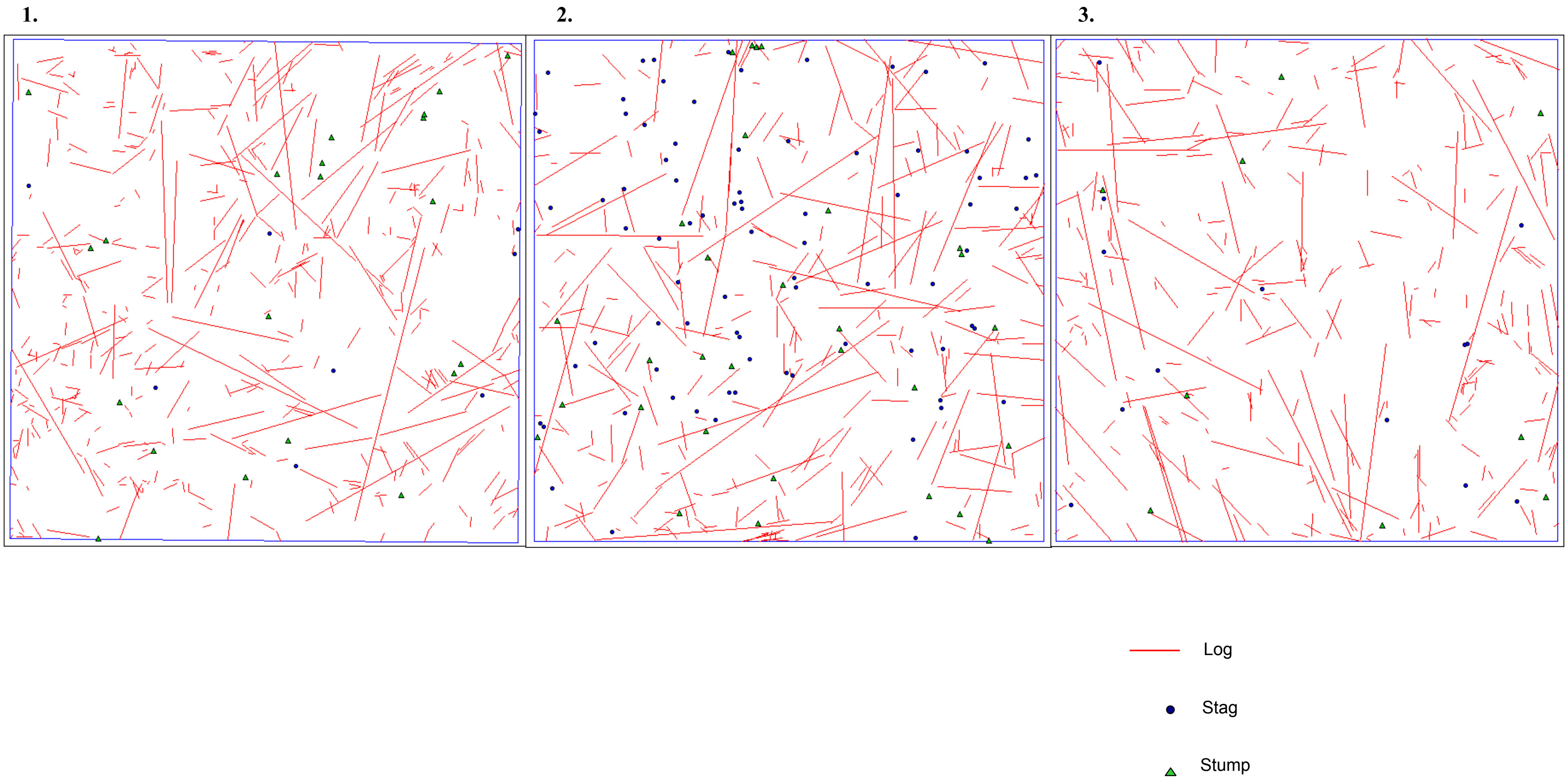
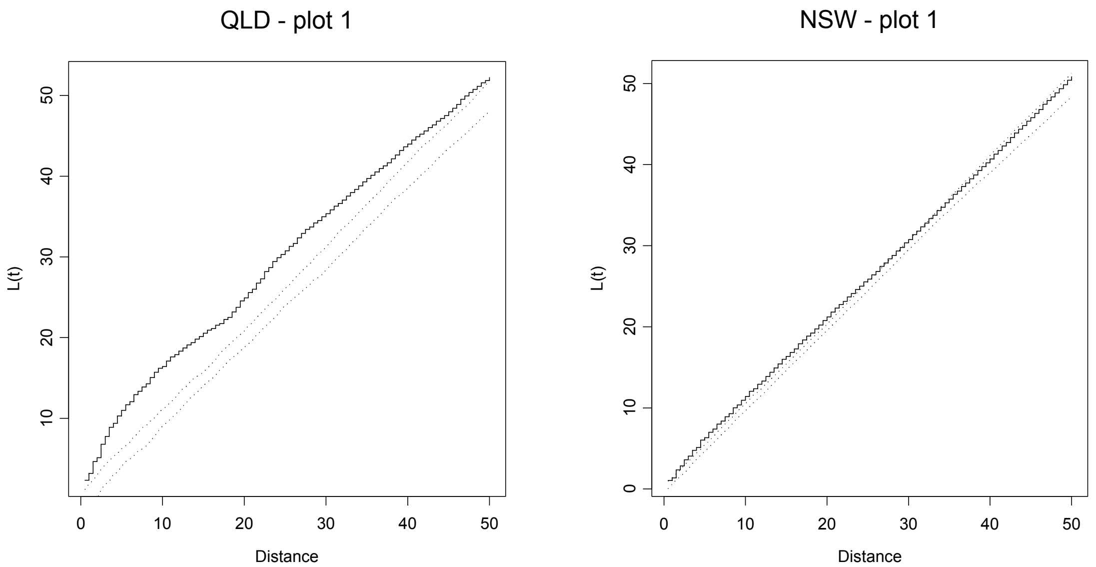


Figure 3.6 Pattern of distribution of CWD on one-hectare plots in tall open forest at Warra, southern Tasmania.

3.1.2 Spatial distribution of CWD

Position of stumps, stags, and logs, as well as the orientation and length of logs sampled on all plots are illustrated in Figures 3.4, 3.5, and 3.6. Most plots appear to have a non-random orientation of logs, although there is some obvious orientation bias of logs in plot QLD1 (Figure 3.4). Some clusters of logs are also evident at a number of plots, where a whole tree or large branch has fallen. Generally, log lengths can be seen to increase from woodland, to open forest, to tall open forest (Figures 3.4, 3.5, and 3.6).

Spatial library routines with a 95% confidence envelope for selected plots in the three forest types are shown in Figure 3.7. Plot TAS1, which had a high density and volume of downed CWD, shows that below 15 m there is strong evidence of significant aggregation of material since the estimate value of *L(t)* is above the 95% confidence envelope. This threshold distance increases to approximately 25 m at NSW1, whereas at QLD1 any distance less than 50 m (and possibly greater) is well outside the 95% confidence envelope.



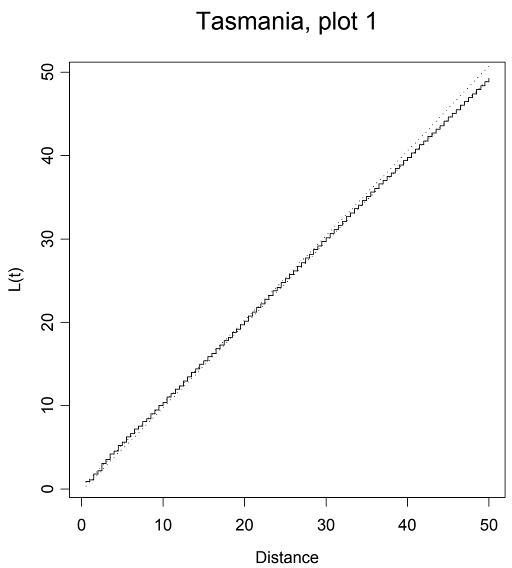


Figure 3.7 Spatial library routines for plots QLD1 in woodland, NSW1 in open forest, and TAS1 in tall open. Dotted lines represent the 95% confidence envelope

3.1.3 Volume and mass of CWD

For each plot, volume and mass of logs, stags and stumps are sorted by decay class and outlined in Tables 3.2 to 3.4. Mean volume and mass of all CWD was 26.20 m^3ha^{-1} and 12.24 t ha^{-1} respectively at the woodland site, 117.25 m^3ha^{-1} and 52.00 t ha^{-1} respectively at the open forest site, and 1350.48 m^3ha^{-1} and 500.00 t ha^{-1} respectively at the tall open forest site.

At the Injune site, plot QLD4 had the highest volume of total CWD (46.38 m^3ha^{-1}) because the dominant tree species occurring at this plot was larger in form than those occurring at the other woodland plots. As much of the CWD at QLD4 was in an advanced stage of decay, plot QLD3 had the highest mass of total CWD (18.98 m^3ha^{-1}) (Table 3.2). Almost all the fallen CWD at the Injune plots appeared to be from natural branch and tree fall, and most stumps and stags appeared to be mortality from natural causes, although some cut white cypress pine stumps were present at plot QLD4.

Quantities of CWD at the Kioloa plots (Table 3.3) increased in the order of: NSW4, a low productivity site with relatively sparse overstorey and no evidence of logging; NSW5, a site of medium productivity with some evidence of logging but no apparent logging residue *in situ*; NSW2, a medium productivity site with some logging residue *in situ*; NSW1, a medium productivity site with a significant amount of logging residue *in situ* including that from on site milling; and NSW3, a medium/high productivity site with a substantial amount of logging residue *in situ* from recent harvesting operations.

At Warra, plot TAS1 had the highest volume of downed CWD (1614.73 m^3ha^{-1}) and stumps (118.40 m^3ha^{-1}) (Table 3.4), mostly from a clearfelling operation 35 years ago. Plots TAS2 had a high volume of downed CWD (1235.68 m^3ha^{-1}) and a significant number (84) and volume (160.61 m^3ha^{-1}) of stags (Table 3.4).

Table 3.2 Volume and mass of forest floor CWD (logs), stags and stumps by decay class for all Injune woodland plots in Queensland.

Decay class	Plot QLD1		Plot QLD2		Plot QLD3		Plot QLD4		Plot QLD5		Mean	
	Volume (m^3/ha)	Mass (t/ha)	Volume (m^3/ha)	Mass (t/ha)	Volume (m^3/ha)	Mass (t/ha)	Volume (m^3/ha)	Mass (t/ha)	Volume (m^3/ha)	Mass (t/ha)	Volume (m^3/ha)	Mass (t/ha)
Logs												
1	0	0	0.05	0.04	0.18	0.15	0.57	0.42	0	0	0.16	0.12
2	5.06	2.80	0.13	0.08	1.02	0.74	0.93	0.46	0.01	0.004	1.43	0.82
3	1.00	0.49	2.30	1.27	16.15	9.58	11.86	5.23	3.97	2.26	7.06	3.77
4	1.04	0.40	3.18	1.16	7.25	2.87	11.17	3.66	2.99	1.12	5.13	1.84
5	0.25	0.07	2.26	0.62	4.26	1.32	15.12	3.88	1.91	0.53	4.76	1.23
Subtotal	7.35	3.76	7.92	3.17	28.86	14.66	39.65	13.65	8.88	3.91	18.53	7.83
	(n = 97)		(n = 108)		(n = 201)		(n = 223)		(n = 80)		(n = 142)	
Stags												
1	7.56	5.08	0	0	0	0	0	0	0.34	0.30	1.58	1.08
2	5.93	3.16	0.33	0.21	2.34	1.69	2.57	2.11	0.69	0.45	2.37	1.52
3	1.58	0.85	1.66	0.84	2.69	1.59	2.30	1.50	0.52	0.23	1.75	1.00
4	0	0	2.44	0.98	1.91	0.72	1.15	0.70	2.08	0.80	1.52	0.64
Subtotal	15.07	9.09	4.43	2.03	6.94	4.00	6.02	4.31	3.63	1.78	7.22	4.24
	(n = 11)		(n = 20)		(n = 37)		(n = 13)		(n = 14)		(n = 19)	
Stumps												
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0.02	0.01	0	0	0.03	0.02	0	0	0	0	0.01	0.01
3	0	0	0.01	0.003	0	0	0.02	0.01	0.04	0.02	0.01	0.01
4	0.05	0.02	0.03	0.01	0.58	0.23	0.27	0.09	0	0	0.19	0.07
5	0.33	0.10	0.11	0.03	0.22	0.07	0.42	0.11	0.14	0.11	0.24	0.08
Subtotal	0.40	0.13	0.15	0.04	0.83	0.32	0.71	0.21	0.18	0.13	0.45	0.17
	(n = 5)		(n = 5)		(n = 6)		(n = 5)		(n = 3)		(n = 4.8)	
Total	**22.82**	**12.98**	**12.50**	**5.24**	**36.63**	**18.98**	**46.38**	**18.17**	**12.69**	**5.82**	**26.20**	**12.24**

Table 3.3 Volume and mass of forest floor CWD (logs), stags and stumps by decay class for all Kioloa open forest plots in New South Wales.

Decay class	Plot NSW1 Volume (m^3/ha)	Plot NSW1 Mass (t/ha)	Plot NSW2 Volume (m^3/ha)	Plot NSW2 Mass (t/ha)	Plot NSW3 Volume (m^3/ha)	Plot NSW3 Mass (t/ha)	Plot NSW4 Volume (m^3/ha)	Plot NSW4 Mass (t/ha)	Plot NSW5 Volume (m^3/ha)	Plot NSW5 Mass (t/ha)	Mean Volume (m^3/ha)	Mean Mass (t/ha)
Logs												
1	1.57	1.00	0.10	0.09	0.05	0.03	0.59	0.39	0.08	0.06	0.48	0.31
2	15.45	8.32	9.12	6.20	46.97	27.11	0.42	0.24	1.10	0.66	14.61	8.51
3	43.41	19.20	31.42	17.78	117.43	55.66	14.13	6.49	42.50	21.62	49.78	24.15
4	41.93	12.36	27.22	10.27	25.43	8.03	11.70	3.58	18.70	6.42	25.00	8.13
5	32.40	7.47	4.81	1.42	3.65	0.90	4.49	1.08	6.79	1.82	10.43	2.54
Subtotal	134.76	48.35	72.67	35.76	193.53	91.73	31.33	11.78	69.17	30.58	100.29	43.64
	(n = 253)		(n = 129)		(n = 381)		(n = 136)		(n = 118)		(n = 203)	
Stags												
1	1.96	1.26	1.08	0.89	0	0	0.35	0.23	0	0	0.68	0.48
2	10.71	5.76	0.69	0.47	0.03	0.02	0.47	0.26	1.29	0.81	2.64	1.46
3	4.10	1.81	15.59	8.82	0.11	0.05	0.95	0.44	1.48	0.76	4.45	2.38
4	1.08	0.32	2.91	1.10	0.20	0.06	2.36	0.72	3.97	1.38	2.10	0.72
Subtotal	17.85	9.15	20.27	11.28	0.34	0.13	4.13	1.65	6.74	2.95	9.87	5.03
	(n = 24)		(n = 9)		(n = 3)		(n = 21)		(n = 13)		(n = 14)	
Stumps												
1	0	0	0	0	0.16	0.11	0	0	0	0	0.03	0.02
2	0.71	0.38	0.72	0.50	6.40	3.69	0	0	0	0	1.57	0.91
3	0.60	0.27	7.48	4.24	4.93	2.34	0.25	0.12	3.37	1.73	3.33	1.74
4	0.77	0.23	0.73	0.28	1.98	0.63	0.34	0.10	2.00	0.73	1.16	0.39
5	0.64	0.15	0.91	0.27	1.06	0.26	0.59	0.14	1.82	0.49	1.00	0.26
Subtotal	2.72	1.03	9.84	5.29	14.53	7.03	1.18	0.36	7.19	2.95	7.09	3.33
	(n = 18)		(n = 17)		(n = 80)		(n = 14)		(n = 15)		(n = 28.8)	
Total	**155.33**	**58.53**	**102.78**	**52.33**	**208.40**	**98.89**	**36.64**	**13.79**	**83.10**	**36.48**	**117.25**	**52.00**

Table 3.4 Volume and mass of forest floor CWD (logs), stags and stumps by decay class for all Warra tall open forest plots in Tasmania.

Decay class	Plot TAS1		Plot TAS2		Plot TAS3		Mean	
	Volume (m^3/ha)	Mass (t/ha)	Volume (m^3/ha)	Mass (t/ha)	Volume (m^3/ha)	Mass (t/ha)	Volume (m^3/ha)	Mass (t/ha)
Logs								
1	59.68	32.83	6.64	3.78	1.47	0.84	22.60	12.48
2	299.83	138.52	86.02	41.19	102.38	49.02	162.74	76.24
3	1021.63	387.71	865.97	340.59	424.57	166.98	770.72	298.43
4	186.28	47.13	219.57	57.57	157.10	41.19	187.65	48.63
5	47.31	9.37	57.48	11.79	58.54	12.01	54.44	11.06
Subtotal	1614.73	615.56	1235.68	454.92	744.06	270.04	1198.16	446.84
	(n = 439)		(n = 285)		(n = 295)		(n = 340)	
Stags								
1	0.50	0.28	29.56	16.85	0	0	10.02	5.71
2	26.04	12.03	45.60	21.83	4.89	2.34	25.51	12.07
3	53.17	20.18	39.89	15.69	0	0	31.02	11.96
4	7.35	1.86	45.56	11.95	70.92	18.59	41.28	10.80
Subtotal	87.06	34.35	160.61	66.32	75.81	20.93	107.83	40.53
	(n = 8)		(n = 84)		(n = 13)		(n = 35)	
Stumps								
1	0	0	0.04	0.02	0	0	0.01	0.01
2	0.04	0.02	0.09	0.04	0.03	0.01	0.05	0.02
3	45.56	17.29	3.70	1.45	0.14	0.05	16.47	6.26
4	29.85	7.55	2.49	0.65	2.77	0.73	11.70	2.98
5	42.95	8.50	7.27	1.49	0.33	0.07	16.85	3.35
Subtotal	118.40	33.36	13.59	3.66	3.27	0.86	45.09	12.63
	(n = 21)		(n = 30)		(n = 9)		(n = 20)	
Total	**1820.19**	**683.27**	**1409.88**	**524.90**	**823.14**	**291.83**	**1351.07**	**500.00**

3.1.4 Distribution of log diameters

The frequency of forest floor CWD, in 5 cm diameter classes, has been categorised according to the mean of the small and large end diameters and are illustrated in Figures 3.8 to 3.10 for each forest type. Note that logs 10-15 cm were measured at the woodland site only. Logs with an average diameter >150 cm (Tasmanian site only) are in 10 cm classes due to their relatively low frequency. The maximum diameter (as the mean of small and large ends) of downed CWD measured at the three locations was 53 cm at Injune, 120 cm at Kioloa, and 230 cm at Warra. Wood pieces are more abundant in the small diameter classes and decrease with increasing diameter. Maximum log diameter increases from Injune to Kioloa to Warra.

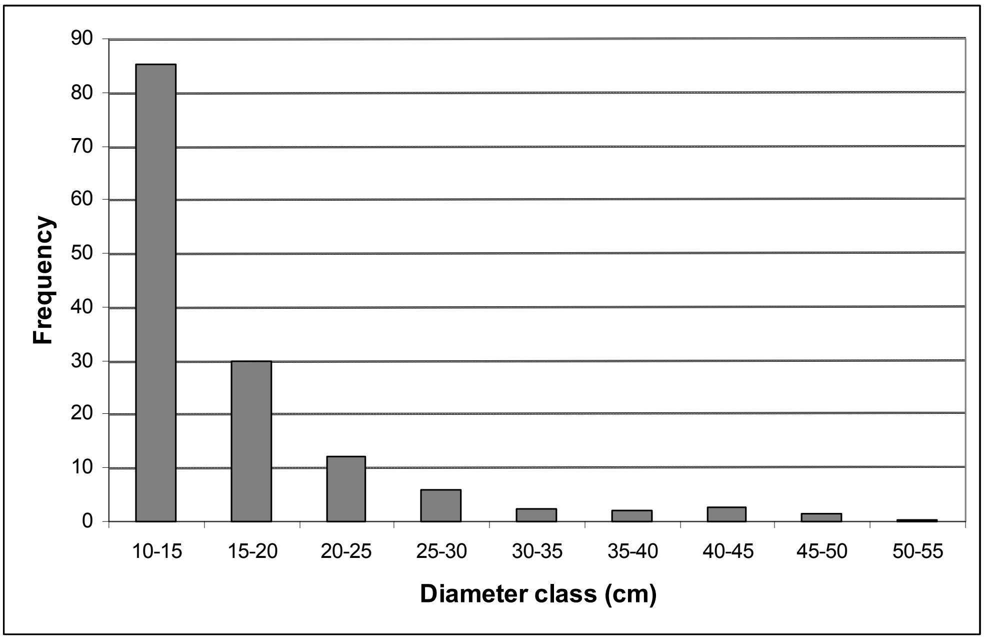


Figure 3.8 Mean frequency of forest floor CWD from the woodland plots at Injune by diameter class. (NB Logs >10 cm were measured)

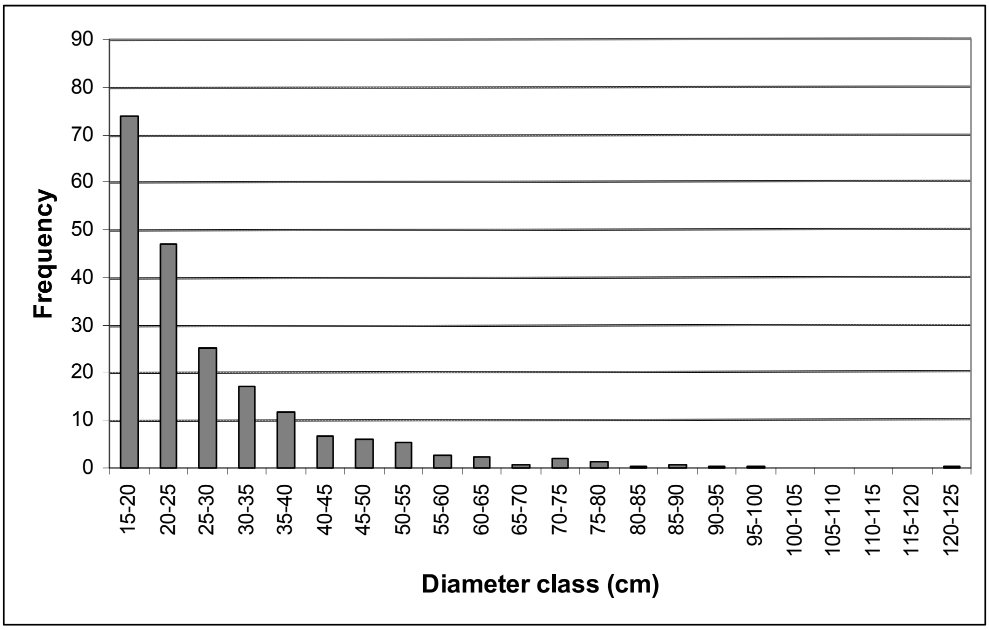


Figure 3.9 Mean frequency of forest floor CWD from the open forest plots at Kioloa by diameter class. (NB Logs >15 cm were measured)

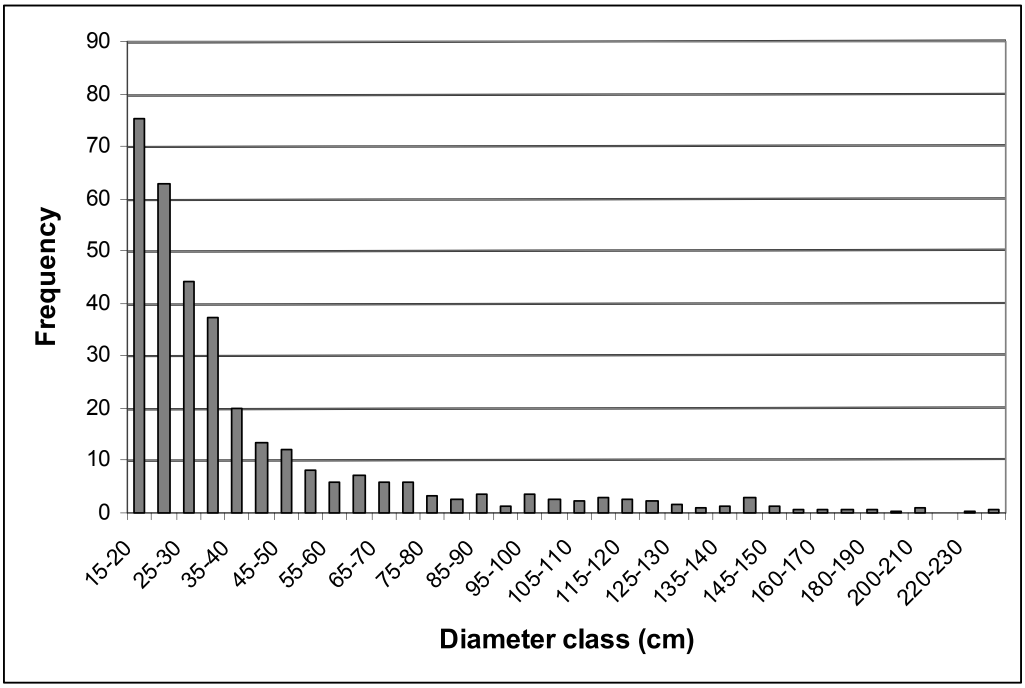


Figure 3.10 Mean frequency of forest floor CWD from the tall open forest plots at Warra by diameter class. (NB Logs >15 cm were measured)

3.1.5 Log decay classes

The distribution of forest floor CWD volume among five decay classes is illustrated in Figure 3.11 as the mean of all plots in a region. The integrity of the wood becomes increasingly decayed from class one to five, so that decay class one represents solid wood, while decay class five represents crumbly wood with a lack of structure. Volume is expressed as a percentage of the total in order to remove the effect of volume and make comparisons between the three regions. Figure 3.11 shows that at the Queensland site more wood occurs in the highly decayed classes, while Tasmania has the least proportion of wood in these classes.

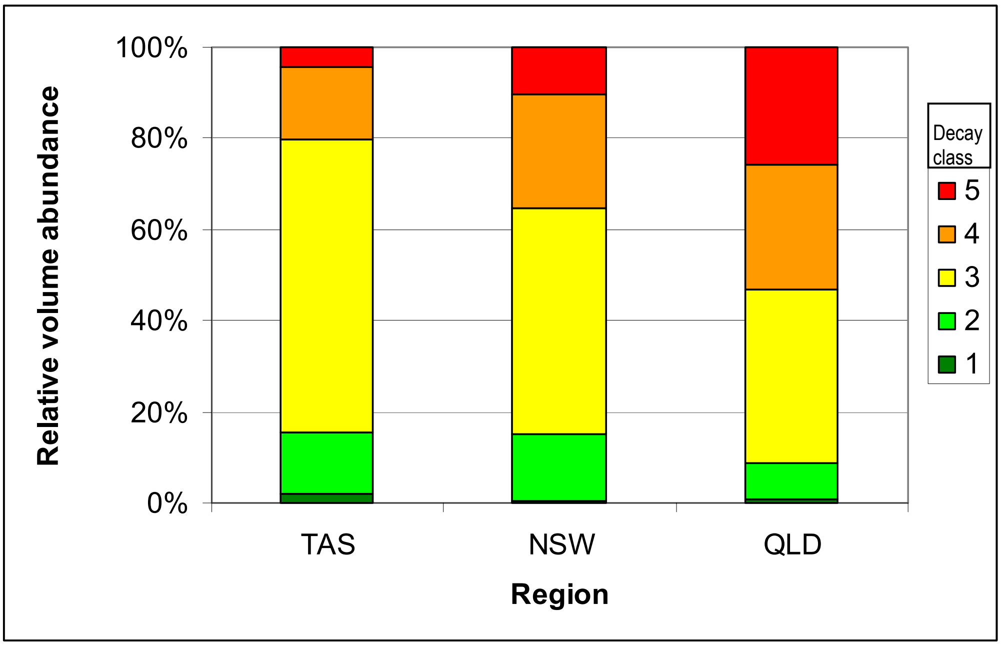


Figure 3.11 Relative distribution of mean total volume of forest floor CWD among five decay classes by region. Decay of wood increases from class 1 to 5.

3.2 Modelled sampling designs

3.2.1 Transect length

Coefficients of variation (CV) from 10,000 replicate estimates declined as the transect length increased (Figure 3.12). The largest decline was observed in Injune woodland plots in Queensland where the CV declined from an average of 373% across the five plots for a 10 m transect, to 135% for an 80 m transect (Table 3.5). The decline in CV was lower in sites where CWD piece density was highest. Overall, CV estimates were generally lowest at Warra and increased at Kioloa, and were highest at Injune.

Across all plots the coefficient of variation initially decreased rapidly and slowed as transect length increased, although substantial increases in precision could still be achieved with increasing transect length. As transect length increased CV decreased by 29.4% from the 10 m to 20 m transects; 28.8% from the 20 m to 40 m transects; 18.7% from the 40 m to 60 m transects; and 14.9% from the 60 m to 80 m transects (Table 3.5).

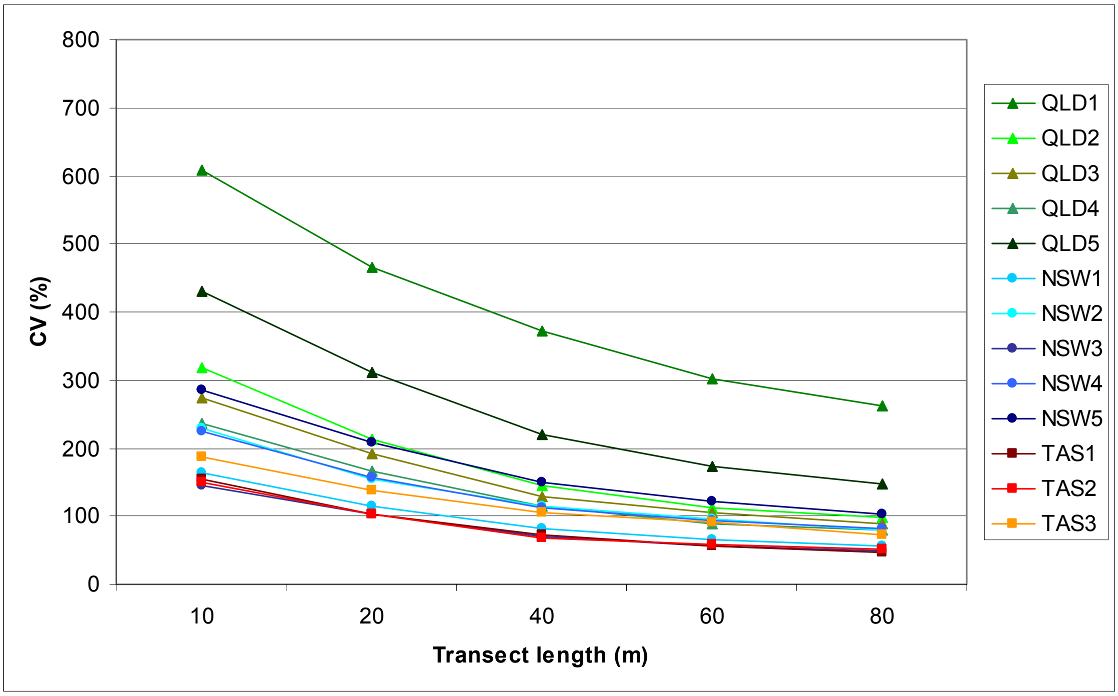


Figure 3.12 Coefficient of variation against transect length for all plots.

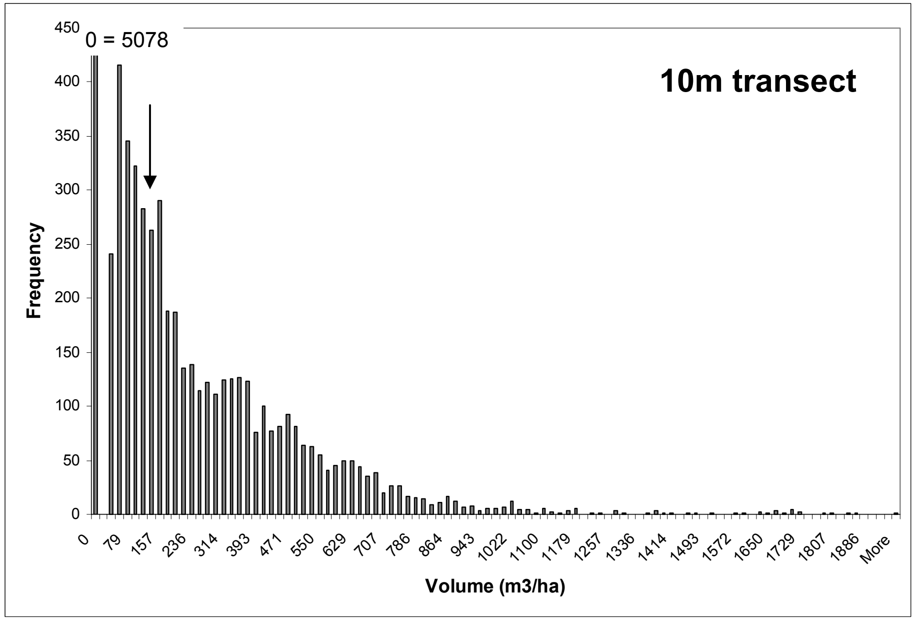
Table 3.5 Mean coefficient of variation estimate by transect length for each region.

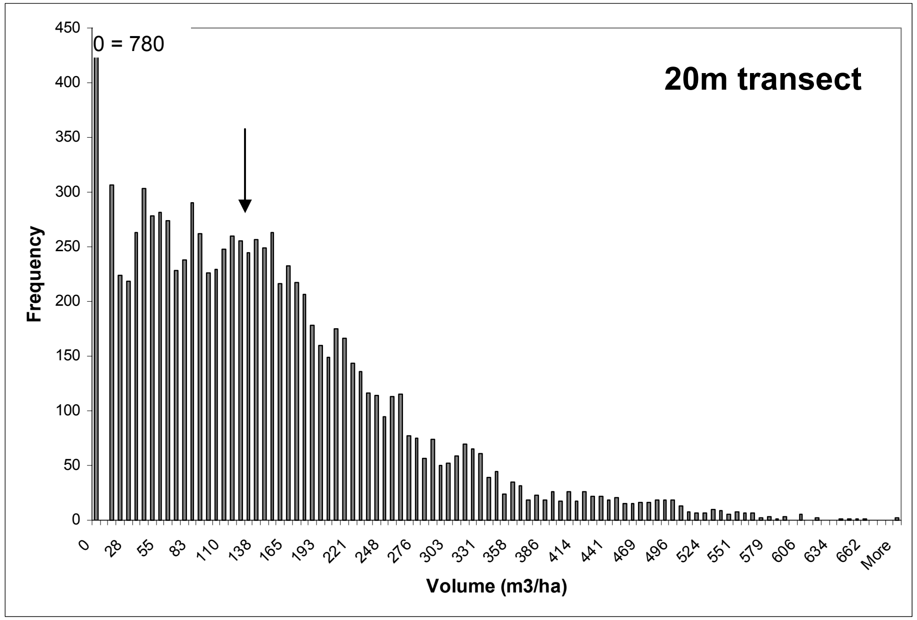
Site	Mean CV (%) by transect length				
	10 m	20 m	40 m	60 m	80 m
Injune woodland	363.2	269.4	195.9	156.8	135.2
Kioloa open forest	209.5	147.5	105.6	86.6	73.5
Warra tall open forest	163.1	114.4	82.2	68.5	56.5

To illustrate the range and frequency of volume estimated derived from various line transect simulations, the histograms in Figure 3.13 show the frequency of downed CWD estimates from 10 m, 40 m, and 80 m transects at plot NSW1. The histograms show that the frequency of volume estimates peaks closer to the actual plot volume as transect length increases. More than half of the 10,000 simulated line transects of 10 m intersected no woody debris, evident by the number of zero volume estimates derived (Figure 3.13). This is not surprising when considering the results of the spatial library routine in Figure 3.7, where a strong aggregation of material occurs below 25 m at NSW1. This suggests that transects shorter than 25 m will not span the spatial variability at this plot. The 20 m transects (Figure 3.13) have resulted in a large number of zero volume estimates, and volume estimates are skewed which again supports this.

The pattern of the distribution of estimates in Figure 3.13 is typical among the simulations for increasing transect length, using 10,000 replicates. In common with Figure 3.13 the histograms in Appendix 3 for the Injune (A) and Warra (B) plots, shows that an increase in transect length results in a decrease in the number of zero volume estimates and a decrease in the range of volume estimates produced. The results are unsatisfactory from the transects of 10 m at Warra plot TAS1 (Appendix 3 A) and evident in Figure 3.12 by the high CV. The spatial analysis (Figure 3.7) for plot TAS1 again indicates that aggregation of wood pieces is high below 15 m which supports these results. However CV is still high at this plot for 20 m transects (Figure 3.12). These comparisons cannot be made at plot QLD1 as 50 m was the maximum possible distance that the spatial analysis could be run at, and the maximum transect length of 80 m resulted in estimates with a high variability at most, if not all, woodland plots (mean CV of 135%) (Table 3.5).

This last observation however, was not the case at the Injune woodland plot (Appendix 3, A) as transect length may still need to be increased to show this pattern. When using 80 m transects at the woodland plot, estimates exhibit a higher variability than the open or tall open forest plots – estimates from the woodland plot exceeded the actual volume by 12 times compared to those from the dry (7 times the actual volume) and tall open forests (3 times the actual volume). In addition, the majority of volume estimates at the woodland plot are well below the actual volume.





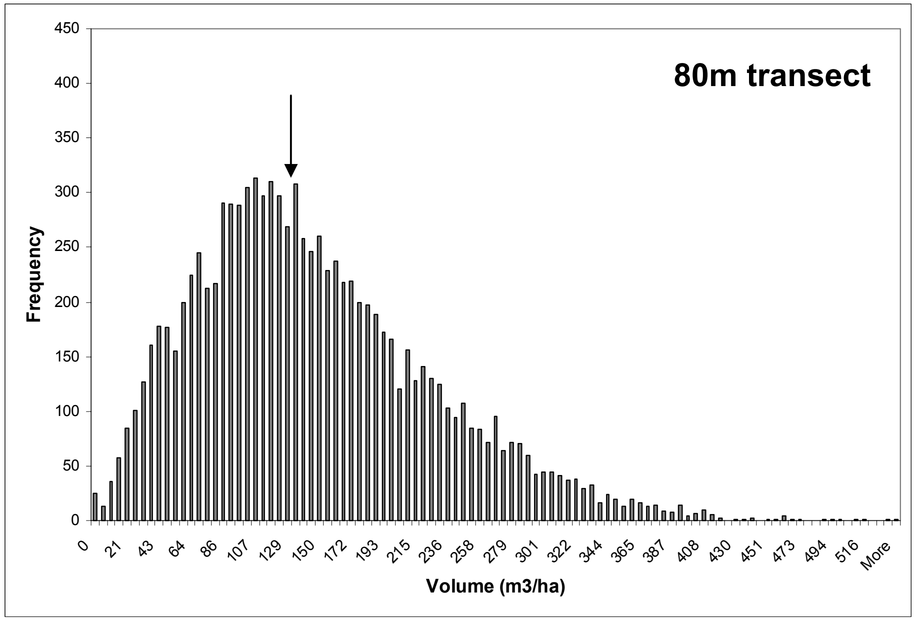


Figure 3.13 Histograms illustrating frequency of volume estimates obtained from 10,000 replicates of the line intersect method using transects lengths of 10 m, 40 m, and 80 m at Kioloa plot NSW1 open forest. Arrows indicate actual volume of all CWD ≥15 cm estimated within the one-hectare plot. (NB Frequency scale has been reduced on the 10 m and 20 m histograms for ease of comparison)

3.2.2 Transect number

Coefficient of variation estimates from sampling transects as a single line or the mean of two, three and four lines, are illustrated in Figure 3.14 for a total transect length of 20 m, and Figure 3.15 for a total of 60 m. The CV decreased at all plots, when fewer, longer transects were used. This was more pronounced at the Injune woodland plots, and becomes increasingly less so with 60 m total transect length and at the Warra tall open forest plots (Figure 3.15). Again, CV estimates were generally highest at Injune and lowest at Warra.

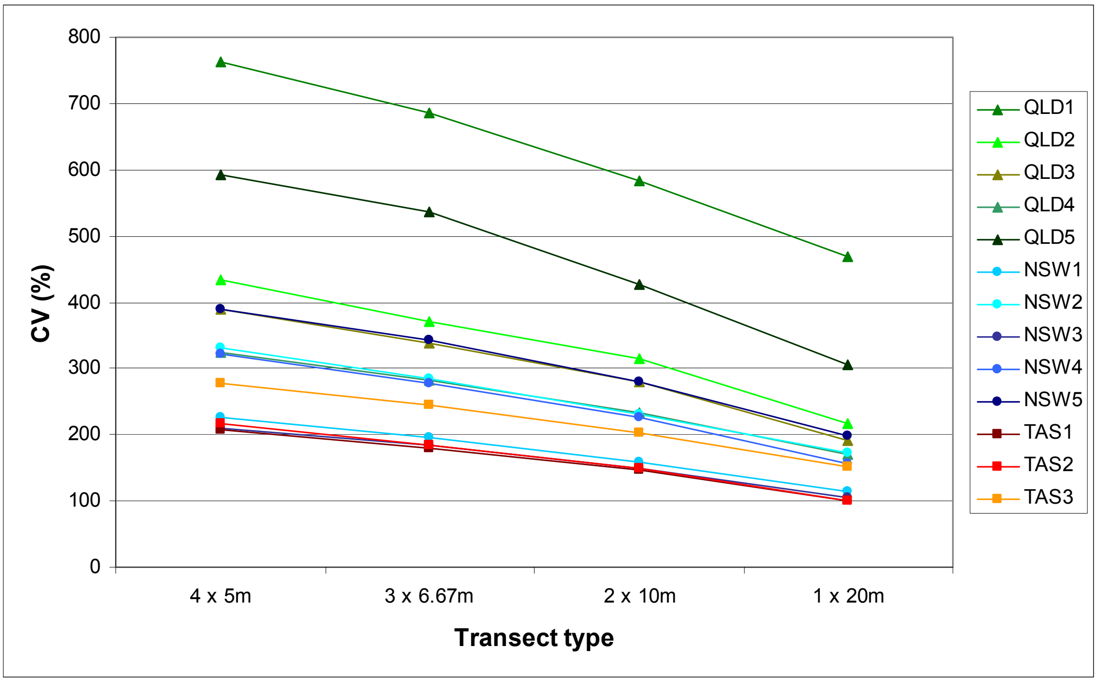


Figure 3.14 Coefficient of variation against a 20 m transect sampled in various divisions.

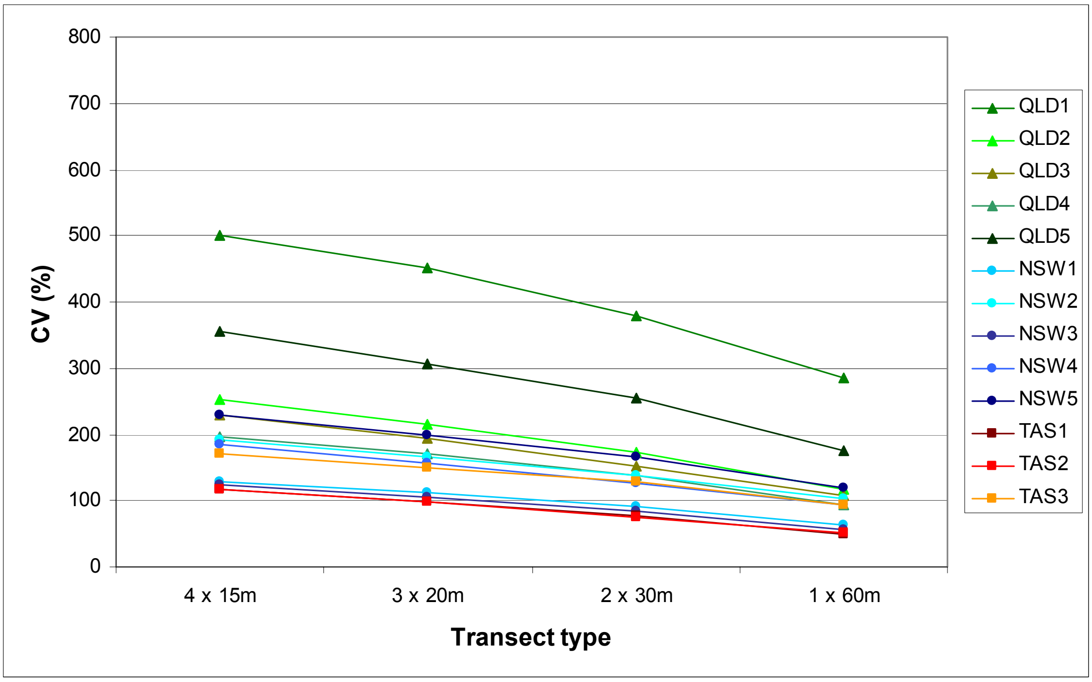


Figure 3.15 Coefficient of variation against a 60 m transect sampled in various divisions.

Histograms of volume estimate frequency obtained from this simulation for a 60m total transect length at selected plots are in Appendix 3 C, D, and E. Across the three plots illustrated, the range of estimates decreases and the number of zero volume estimates decreases as fewer transect of a longer length are used, and from Kioloa (Appendix 3 D) and Warra (Appendix 3 E), the frequency of volume estimates peaks near the actual plot volume.

At QLD1 the frequency of 0 m^3ha^{-1} estimates as a proportion of all estimates derived from the test increased using 1 x 60 m, 2 x 30 m and 4 x 15 m transects from 63% to 79% to 88% respectively (Appendix 3 C); at NSW1 the frequency of 0 m^3ha^{-1} estimates was 2%, 14%, and 27% respectively (Appendix 3 D); and at TAS1 the 60 m transects encountered 0 m^3ha^{-1} only once out of 10,000 replicates, whereas the frequency of 0 m^3ha^{-1} using 30 m transects was 2%, and using 15 m transects was 14% (Appendix 3 E). High numbers of zero volume estimates indicates that transect length is not long enough relative to the density of pieces.

3.2.3 Transect layout

Coefficient of variation estimates from sampling transects arranged in a triangle, a square, three individual lines, and a single line, are shown in Figures 3.16 for a total transect length of 20 m, and Figure 3.17 for a total transect length of 60 m. Histograms showing the frequency of volume estimates from this analysis are given in Appendix 3F, G, and H.

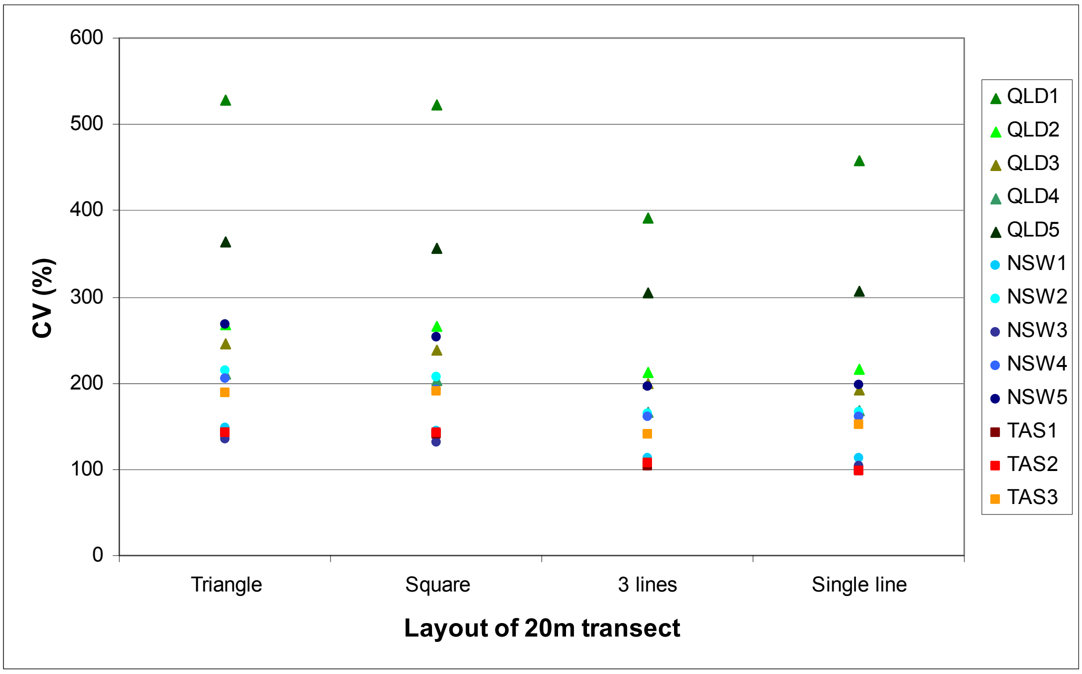


Figure 3.16 Twenty-metre transect in four different configurations: a triangle, a square, three random lines, and a single line.

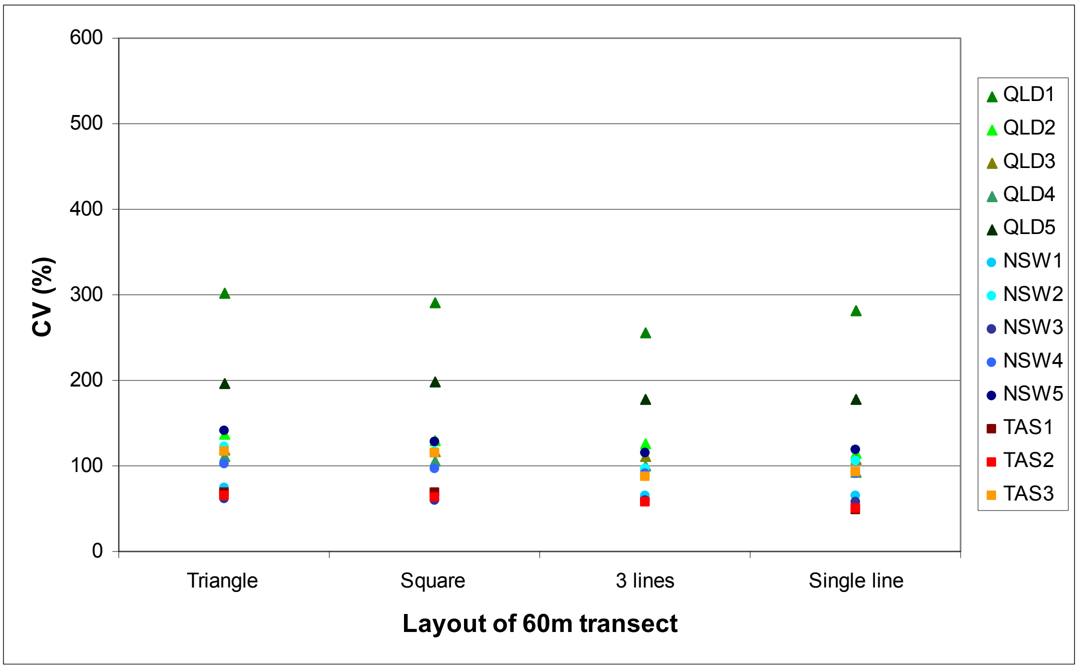


Figure 3.17 Sixty-metre transect in four different configurations: a triangle, a square, three random lines, and a single line.

There was no significant difference between estimates and variances of the four transect arrangements (Figures 3.16 and 3.17). The results from the 20 m transect layouts showed slightly lower coefficients of variation for a single line transect and three random transects than a square or triangle (Figure 3.16), but is not significant and certainly not conclusive. It is more likely an anomaly of the extremely short transect length. Transect lengths used in the layout sampling at all plots (20 m and 60 m) were not long enough to span the spatial variability at the Injune woodland plots, which is apparent from the high CV estimates (Figures 3.16 and 3.17) and the high number of 0 m^3ha^{-1} estimates at plot QLD1 (Appendix 3 F).

Increasing transect length at the woodland plots, a triangle arrangement with a total transect length of 300 m was applied to the four-hectare landscape created from plots QLD 1, 2, 3, and 5. Running 10,000 replicates, the range and frequency of volume estimates is shown in Figure 3.18. The mean volume derived from this simulation is approximately 11.0 m^3ha^{-1} and the coefficient of variation is 85%. The actual plot volume (from field measurements) as the mean from these combined plots is 12.56 m^3ha^{-1}, therefore the volume estimate derived from the simulations varies only marginally.

This resulted in a decrease in the range of volume estimates and the frequency of 0 m^3ha^{-1} estimates (Figure 3.18), compared to the 20 and 60 m total transect layouts. Estimates are still skewed toward the low end of estimates and the coefficient of variation is possibly too high (85%), but is much improved.

Histograms from three selected plots (Appendix 3 F, G, and H) also indicate that volume estimates do not vary significantly between transect layouts. These histograms show estimates derived from a square, three independent lines, and single line transect for a total transect length of 60 m are similar in range and frequency across all plots.

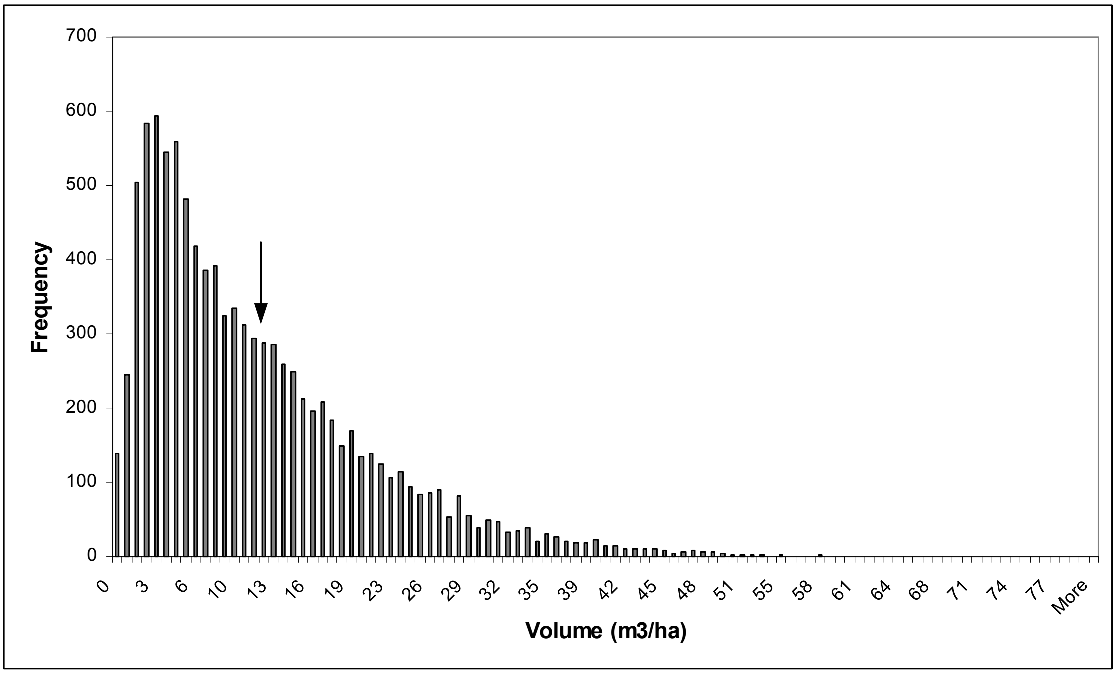


Figure 3.18 Range and frequency of volume estimates obtained using a equilateral triangle with 100 m sides, and applied to a mosaic landscape constructed from plots QLD1, 2, 3 and 5. Arrow indicates actual volume.

3.2.4 Plot-based sampling

The CV estimates from sampling all downed CWD in quadrats 10 x 10 m, 20 x 20 m, and 50 x 50 m in size, are illustrated in Figure 3.19. There is a significant decrease in CV as quadrat size increases. This is particularly evident in the Injune woodland plot QLD1 where CV decreases approximately five times when downed wood is sampled in a 50 x 50 m quadrat compared to a 10 x 10 m quadrat. The CV at all other plots shows a decrease of at least three times.

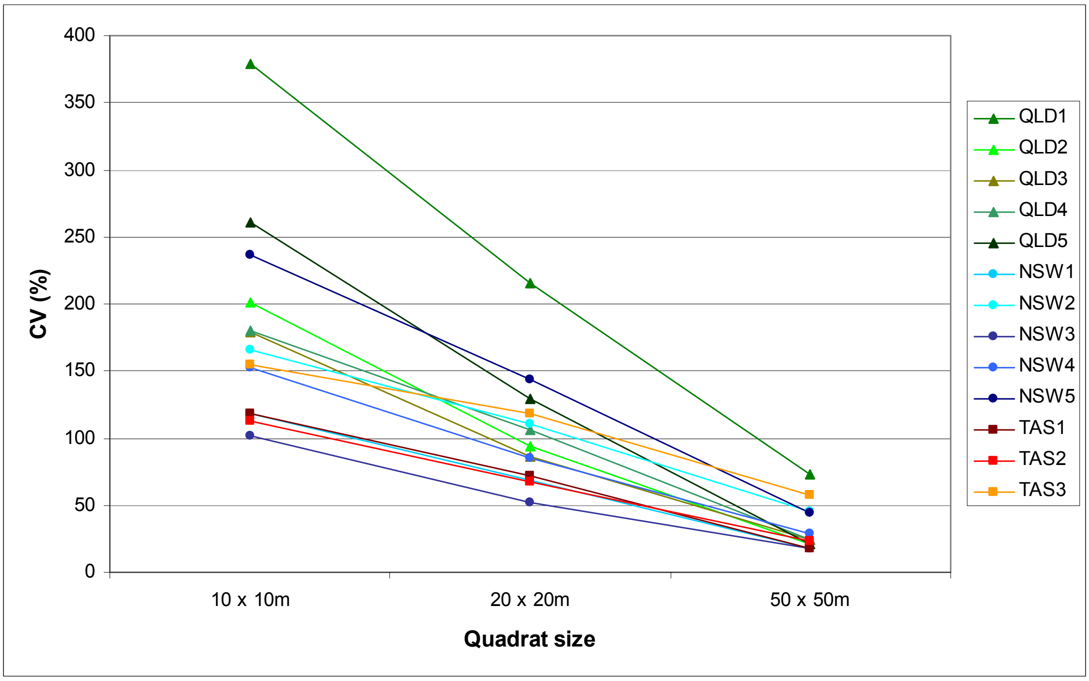


Figure 3.19 Coefficient of variation against quadrat size for all plots.

3.2.5 CV and sample size

The results of the modelled sampling designs (Figures 3.12, 3.14, 3.15 and 3.19) shows that increasing transect length or quadrat size had a significant influence on the CV at all plots. This is particularly true at plots with lower frequencies of CWD pieces, such as the woodland plots in Queensland, where the decrease in CV is more dramatic as transect length increases. Woodland plots QLD1 and QLD5 show the highest CV. These plots had the smallest sample sizes (and two of the three lowest volume estimates) with less than 100 pieces per hectare, even though CWD at all woodland plots was measured to a smaller diameter than the other regions. Figure 3.20 illustrates the CV estimates from a 60 m transect compared with the frequency of wood pieces per hectare. It can be seen from this figure that the decrease in CV estimates correspond to an increase in sample size.

However, it is also evident that some plots show similar CV estimates but the sample size varies. Two New South Wales plots (NSW2 and NSW4) had approximately the same CV estimates as two Queensland plots (QLD3 and QLD4 – all either side of a CV of 100%) and yet there were less wood pieces at the two NSW plots. This is due to piece length; more intersections are made per unit length of sample line because wood pieces are longer and the chance of intersection is increased.

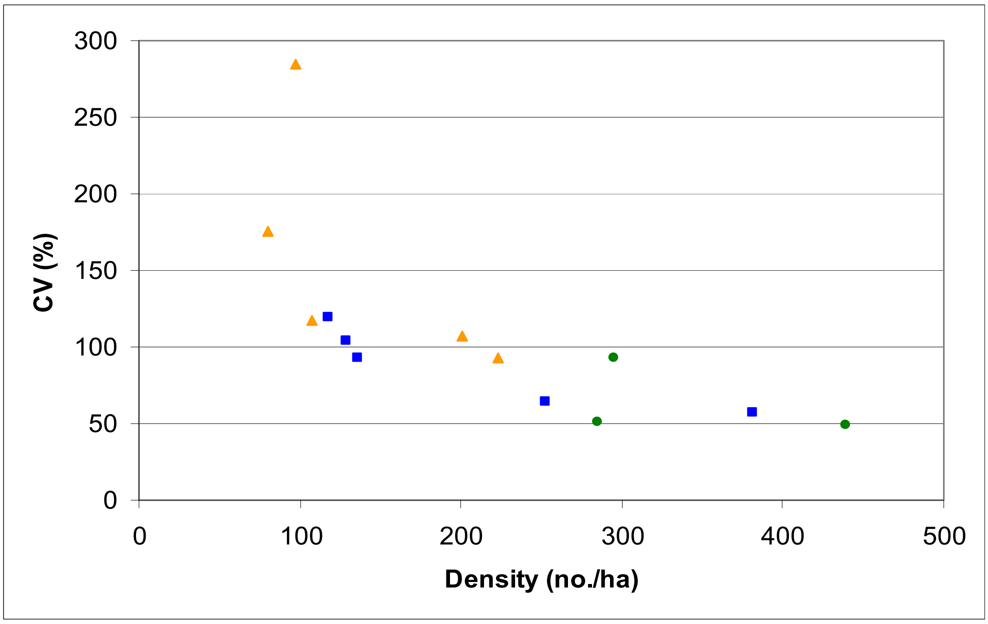


Figure 3.20 Coefficient of variation from 60 m transects against frequency of downed wood pieces for all plots. QLD = orange triangles, NSW = blue squares, TAS = green dots.

4. Discussion

This section presents a discussion of the results from section three, and where possible, compares the findings with published literature. Sections follow those from the results, with the addition of a short discussion on costs relating to CWD sampling, and a section addressing the influence of forest type, environment, and forest management on CWD.

4.1 Stand attributes

4.1.1 Basal area

Regrowth resulting from extensive timber harvesting at plots NSW3 and TAS1 is evident from the small diameter classes of live trees at these plots and by low total basal area. Also, these plots have a high basal area of stumps. The mature status of the stands at plots TAS2 and TAS3 is reflected in the high basal area of live trees in the large diameter classes. Basal areas of live trees at the Injune woodland were fairly consistent across the plots although maximum diameters varied slightly, from 60 cm at plots QLD3 and QLD5 to 100 cm at QLD4.

At plots where the impact of logging was not significant, the basal area of stags generally correlated with the basal of live trees, that is, total stag basal area increased as total basal area of live trees increased. Stag basal area made up approximately 10% (range of 5 – 14%) of all standing tree basal areas both live and dead (>1.3 m in height) at these plots. This is fairly consistent with the study by Nilsson *et al*. (2002) where the basal area of dead trees was about 11% (range of 6 – 21%) of all standing trunks both living and dead in old-growth forests in Sweden. The plots where the proportion of stag basal area fell outside these estimates were NSW3 (0.7%) which had been extensively logged and burnt in recent years, and TAS1 (31%) where all live trees had small diameters as they were the regrowth from clearfelling, and many tall stumps and several large stags where present.

4.1.2 Spatial distribution of CWD

From observations of the spatial distribution of CWD, there appears to be no orientation bias in wood pieces at most plots. A large proportion of downed CWD in the southern half of woodland plot QLD1 (Figure 3.4, 1) was orientated east, as a result of previous flooding of a river, the bed of which, just crossed the southwest corner of the plot. Also, plot TAS3 at the tall open forest site exhibited some orientation bias of CWD, particularly in the steeper southern half of the plot (Figure 3.6, 3), where a high proportion of trees have fallen over in the down-slope direction.

A single unidirectional transect should therefore produce unbiased estimates at most plots based on the assumption from Van Wagner (1968) that wood pieces should be randomly orientated when implementing the line intersect method. Although error is introduced if there is some orientation bias of wood pieces, this can be reduced by running transects in more than one direction and averaging the results (Van Wagner, 1968).

4.1.3 Volume and mass of CWD

Between locations, quantities of total CWD increases from the woodland site at Injune, to the open forest at Kioloa, to the tall open forest at Warra, generally due to forest type and climate. Forest type – tree size and height, and site productivity – determines the direct source of CWD to a forest, whilst climate, and other factors that govern decomposition rate, have a major effect on the retention of CWD in a forest. Input rates are also partially responsible for CWD quantities. The input rate predominantly results from site productivity and disturbance.

Between plots, the highest volume of CWD at Injune was at plot QLD4 where forest type (tree size and height) affected the quantity of CWD. At Kioloa, plot NSW3 had the highest overall volume and mass of CWD. This forest had been harvested 10 years previous and the harvesting residue let on site was substantial. In addition, a hazard reduction burn occurred five years ago which may have resulted in death and subsequent collapse of some trees. Plot NSW4 had the lowest quantities of CWD at Kioloa as it was a fairly low productivity site in comparison to the other Kioloa plots. The overstorey was sparse at this site whereas the understorey was dense in places, predominantly with Banksias and tea-trees. Records from State Forests NSW reported that timber harvesting had occurred in the coupe within which the plot was located. However, it appeared that no trees had been harvested within the plot or directly adjacent to it, possibly due to the low productivity of the site. The highest volume and mass of CWD at Warra was at plot TAS1 due to harvesting residue left on site from a clearfelling operation 35 years ago. This was reflected in the high quantity of forest floor debris and stumps. Clearfelling involves the removal of the entire stand to expose the site and decrease root competition when regeneration begins (Florence, 1996).

Volume and mass of stags varied between plots from Injune and Kioloa, although not dramatically. The number of stags at Injune ranged from 11 to 37 per hectare, while at Kioloa stag numbers ranged from 3 to 24 per hectare. Plot TAS2 at Warra had 84 stags (13% of the total CWD mass at that plot) compared to 8 stags at TAS1 (5% of total CWD mass) and 13 at TAS3 (7% of total CWD mass). Even within a single forest type, it is not unusual to find that proportions vary widely (Harmon and Sexton, 1996) and stags have been found to make up as little as 2% or as much as 98% of total CWD mass (Harmon *et al*, 1986). Many variables determine the ratio of stags to downed CWD including the dominant form of mortality, age of the forest, and tree species (Harmon *et al*, 1986). As tree species are the same across the Warra plots, and age is thought to be approximately the same as TAS3, the form of mortality appears to be the most likely reason for the high number of stags at TAS2.

The mass of forest floor CWD at the Injune woodland plots were below estimates from the literature for Australian woodlands (11.6 to 40.0 t ha^{-1}, mean of 22 t ha^{-1}), compiled in Woldendorp *et al*. (2002). However most of these estimates were from subalpine woodlands where decomposition rates would be lower due to the colder climate, and termite attack would not be as prevalent. Stag biomass at Injune was also below estimates from the literature, although only two estimates from woodlands in Australia were found in the literature, both from Queensland woodlands.

Two forest floor CWD mass estimates from Injune were within the range the literature estimates. From the literature (see Woldendorp *et al*., 2002), mass of forest floor CWD in open forests of Australia ranged from 5.1 to 221.1 t ha^{-1}, and a mean of 50.9 t ha^{-1}. All estimates of forest floor CWD mass from Kioloa fell within this range, and the mean of the Kioloa plots (43.6 t ha^{-1}) was close to the mean from the literature. Stag biomass at Kioloa also fell within the range of estimates from the literature for Australian open forests, which ranged from 0.2 to 26.6 t ha^{-1}. The mean from the literature (9.1 t ha^{-1}) was slightly higher than the mean from the Kioloa plots (5.0 t ha^{-1}).

The estimates obtained from tall open forest plots in Tasmania, particularly plot TAS1 with a volume estimate of approximately 1600 m^3ha^{-1} (mass of 616 t ha^{-1}) of forest floor CWD, are among the highest in the world (see Woldendorp *et al*., 2002). The only other estimates found in the literature to exceed this are also from *Eucalyptus obliqua* forest in southern Tasmania (approx. 40 km south of the Warra site) where a 63 year old forest regenerated from fire had 1089 t ha^{-1} of forest floor CWD >1 cm in diameter, and a mixed age forest regenerated from fire which had 774 t ha^{-1} of downed CWD (Turnbull and Madden, 1986). As CWD was only measured >15 cm in diameter for this study, it could be expected that estimates would be slightly greater if wood was sampled to a diameter minimum of 1 cm. The estimates of forest floor CWD biomass at Warra exceeded all other estimates from the literature for tall open sclerophyll forests in other Australian States. Stag biomass at Warra was within the range from the literature although the Warra mean (40.5 t ha^{-1}) was higher than the literature mean (26.8 t ha^{-1}) mainly due to the large amount at TAS2.

4.1.4 Distribution of log diameters

The size of CWD in a forest reflects the size of the trees present, or the size of the trees from the previous stand. In all forests, downed CWD is more abundant in the smaller diameter classes and becomes increasing less frequent as diameter class increases. This is evident from the results where the pattern of distribution of log diameters is similar at all three sites. The largest log sizes were at the Warra site where tree species were large, and conversely, the smallest maximum log size was at the Injune site due to the small woodland trees.

4.1.5 Log decay classes

Across all three forest types the intermediate decay classes contained the largest proportion of forest floor CWD volume (Figure 3.10), which is typical in most forest types around the world (Harmon *et al*., 1986). The proportion of forest floor CWD in the higher decay classes increased as site location decreased in latitude. This is a typical trend that can be seen in forests around the world – decay rates increase closer to the tropics as temperature and moisture increases.

In addition, CWD at the Injune woodland plots showed a high occurrence of termite attack, where much of the wood had been eaten away and remaining wood was fragmented and crumbly. The two tree species at Warra (*E. obliqua and E. regnans*) are not considered to be particularly resistant to decay (Mackensen and Bauhus, 1999). Therefore, the persistence of logs at the Warra plots in the less decayed classes may be attributed to the cool climate of the region which slows the decomposition rate, and large logs would take longer to decay because of their sheer size.

4.2 Modelled sampling designs

4.2.1 Transect length

Between all locations and plots, CV increased as density of wood pieces and volume decreased. As transect length is increased, CV decreases across all plots. Sampling effort is increased and more pieces are intersected by longer transects. When transect length was increased the chance of obtaining a null volume estimate was reduced. In general, the longer each individual line transect is, the smaller the variability will be among lines (Marshall *et al*., 2000).

Using 80 m transects at sites with low volumes of CWD has resulted in high CV, probably due to low density and/or the spatial distribution and the length of wood pieces. This is evident at the woodland plots where the mean of CV estimates for 80 m transects is approximately 135%. If the spatial distribution is highly variable, that is, wood pieces are aggregated and many gaps are present, then the volume will be overestimated if the transect falls on a cluster of woody debris, and conversely, an underestimate of volume will result if the transect falls between the clusters. Transects need to be long enough to span the inherent aggregation or variability, therefore reducing the variability among individual line transect estimates and increasing the precision of estimates at a site (Hazard and Pickford, 1986). Harmon and Sexton (1996) suggest that although there has been a tendency for researchers to use transects <100 m in the past, this is generally too short for most forest types.

The spatial library routines for plots QLD1, NSW1 and TAS1 emphasise the high degree of variability in the aggregation of CWD encountered in each region. It confirms the necessity to use longer transects for sites with low frequencies of CWD, as the length below which aggregation is significant (based on a 95% confidence envelope) increases from the site in Tasmanian to New South Wales to Queensland.

For a given transect length, the precision of estimates is also influenced by the sample size, in this case, the frequency of the wood pieces which is discussed in section 4.2.5. The effect of sample size applies not only to total CWD in a forest ecosystem, but also to pieces by diameter classes. As the frequency of woody debris generally increases with decreasing diameter size, some methodologies determine the length of transect (or length of a transect section) to be sampled by the diameter of woody debris, particularly when fine woody debris is included (eg. Delisle *et al*., 1988; and USDA Forest Service, 2001). For a given transect length, all woody debris is measured on the first section of transect, and then for each subsequent section, the smallest diameter class is disregarded. This ensures that over-sampling does not occur for the small-sized wood pieces, and that a sufficient number of the largest-sized pieces are sampled.

The size of CWD pieces in the population has an influence on the CV estimates for a given transect length, just as the frequency and spatial distribution of wood pieces is important. Obviously longer wood pieces in a population result in higher quantities of CWD than the same number of shorter wood pieces with the same diameters. The line intersect method will capture this as longer wood piece are more likely to be intersected by a transect than shorter pieces, for a given transect length (Marshall and Davis, 2002). Plot NSW1 had more than three times the volume of CWD than QLD4 and yet a similar number of wood pieces were measured. This resulted in a CV, estimated from 80 m transects, of 55% at NSW1 and 79% at QLD4. The larger volume of downed CWD at plot NSW1 compared to QLD4 is also apparent from the mapped CWD showing the pattern of CWD distribution.

4.2.2 Transect number

The CV estimates for a given total transect length were lowest for long transects with less replicates rather than multiples of short transects (Figures 3.13 and 3.14). The results concur with the findings of Pickford and Hazard (1978) where simulated line transects showed that CV was highest when 50 ft (15.24 m) transects were sampled at 2.5 time the intensity of 125 ft (38.10 m) transects, even though total length for both was the same. Similarly, they sampled a total transect length of 750 ft (228.66 m) and divided into six different transect lengths. These transects were replicated proportional to each individual length. Pickford and Hazard found that the CV decreased with increasing transect length, and therefore with decreasing transect number.

The frequency of 0 m^3ha^{-1} estimates obtained from the simulations for transect number was lowest for the Tasmania plots where the density of forest floor CWD is high, whereas many more 0 m^3ha^{-1} estimates were encountered at the Queensland plots where density of CWD is low. Most of the transect lengths used in this analysis are too short for most forest conditions regardless of the number of replicates. This would go some way to explain the steep decrease in CV as transect length increased. If all transect lengths are above the minimum required to span spatial heterogeneity at a plot, this decrease in CV should level out. Marshall *et al*. (2000) explained how, for example, sampling a total of 1000 m of line transect as twenty-five 40 m transects or forty 25 m transects, the precision of estimates from both should be similar. However at the extremes, this does not hold, as the precision of estimates would not be similar between two 500 m transects and one-thousand 1 m transects (Marshall *et al*., 2000). Many of the line transects used in this study are most likely at the extremes (the short transect extreme), particularly for the sparse plots.

Another consideration when determining the number of transects to be used is the taper of wood pieces. A stand containing wood pieces with a significant taper may require more transects than a stand with relatively cylindrical pieces to achieve accurate results. Van Wagner (1968) and Pickford and Hazard (1978) found that although taper of CWD pieces does not introduce bias, it may increase estimate variability. Testing populations of CWD by computer simulations, Pickford and Hazard (1978) determined for a given transect length, the CV estimates were higher for a population of cones compared to cylinders when all other parameters were identical. Therefore, a larger number of sample lines were required to sample a population of tapering CWD pieces, to achieve the same confidence level as a population of cylinders.

4.2.3 Transect layout

Many studies recommend using a transect arrangement with lines occurring at various angles (BC Ministry of Environment *et al*., 1998; Marshall *et al*., 2000; and USDA Forest Service, 2001). The aim of arranging transects in various orientations such as a square, triangle, 'L' shape, or three transects radiating from a single point, are to reduce the effects of orientation bias of CWD. Orientation bias of CWD can occur from harvesting operations, windthrow, flooding, and steep slopes. CWD will be underestimated if a transect is orientated parallel to the downed wood pieces, and will be overestimated if a transect is orientated perpendicular to the downed wood. The shape (and length) of a line transect depends on site characteristics and the data requirements. For example, the BC Ministry of Forests often uses a triangle with 30m sides for determining fuel loading prior to a prescribed burn, while an 'L' shape with two 24m lines is used in their Vegetation Resources Inventory (Marshall *et al*., 2000).

A transect layout recommended in the carbon sampling protocols by McKenzie *et al*. (2000) is a variation on the 'L' arrangement. McKenzie *et al*. recommend sampling CWD >2.5 cm in diameter using two 10 m transects arranged at right angles to each other, when >10 pieces of CWD occur in a 25 x 25 m plot. Starting from a random point in the plot, the first 10 m transect is laid out in a random direction. If the plot boundary is intersected before the full 10 m, the second transect is started at right angles to the first. This is continued (turning at right angles whenever the plot boundary is intersected) until a total of 10 m in both directions is reached. The McKenzie *et al.* methodology states that "the transect length or orientation, or both, can be altered where there is a large or small amount of CWD to cater for site variability", and mentions that an equilateral triangle with 20 m sides can be used. However, there is no explanation of how or what alterations should be made in relation to what type of site variability.

In the absence of orientation bias, there is no advantage in using one arrangement over another as one arbitrary line encounters the same distribution of orientation angle as any other arbitrary line when there is a lack of orientation bias (Bell *et al*., 1996). Therefore, at sites with randomly orientated pieces there is no apparent benefit in using a methodology such as the variation on the 'L' arrangement recommended in McKenzie *et al*. (2000), if a single line transect will provide similar results. The more complex transect arrangements are more time consuming to set out, so when cost is considered, a single transect is more cost effective. If orientation bias of wood pieces is present, the effect can be greatly reduced by running individual sample lines in more than one direction and averaging the results (Van Wagner, 1968). Howard and Ward (1972, cited in Nemec and Davis, 2002) recommended using randomly orientated straight line to reduce bias in situations where non-random patterns of CWD are likely to arise.

Downed CWD will usually be aggregated to some degree at a site. Line transect shapes that sample a larger area from a given sampling point are likely to capture more information than shapes with a grouped arrangement (e.g. a 30 m straight line versus a triangle of three 10 m sides) (Marshall *et al*., 2000). If total transect length is not sufficiently long to account for the spatial heterogeneity at a site, a triangle or square transect arrangement may be more likely to fall on clustered downed CWD from which an overestimate will result, and if it falls between clusters then an underestimate will result. In this case, transect length must be considered as other studies have also shown (eg. Van Wagner, 1968; Hazard and Pickford, 1986; Bell *et al*., 1996; and O'Hehir and Leech, 1997).

From the simulated transect arrangements, the range and distribution of estimates were similar with all transect layout configurations, indicating that there was no advantage in using a particular transect arrangement. Some transect arrangements and sampling designs may have an advantage over others in terms of efficiency of implementation, and therefore could prove to be more cost effective. Delisle *et al*. (1988) found that sampling CWD in natural lodgepole pine stands using an equilateral triangle, resulted in overly precise estimates for the small diameter classes (<7 cm) and was inadequate for the large classes (>7 cm). They proposed that small wood pieces should be measured on a portion of the transect, while more transects are required for large pieces to achieve the desired precision levels. Their results suggested that the use of independently located transects may be more useful in natural stands of lodgepole pine than a triangular arrangement.

Comparing a square arrangement with a triangular one for sampling in pine plantations, Bell *et al*. (1996) found that the CV obtained by using a square of four 100 m transects was approximately 18%, and for a triangle of three 100 m transects the CV was 20%. They concluded that if the difference in error is considered trivial, the triangular configuration should be adopted. Only short transect lengths were used in the sampling simulations for this project – for a 60 m total transect length, a triangle with 20 m sides resulted in CV estimates ranging from 300% in the woodland plots to 62% in the tall open forest plots, and for a square with 15 m sides, CV ranged from 290% in the woodland to 60% in the tall open forest. Further sampling at the woodland site indicated that a 5 times increase in transect length (300 m triangle at the four-hectare woodland mosaic) resulted in a reduction in the CV estimates of 3½ times.

4.2.4 Plot-based sampling

By comparing the CV between quadrats of varying sizes, the results are as expected – the smallest quadrat (10 x 10 m) produced the highest CV and the largest quadrat (50 x 50 m) had the lowest CV (Figure 3.18). In comparison with the line intersect method, the 50 x 50 m quadrat resulted in lower CV estimates (most being below 50%) than the longest line transect (80 m) at all plots. However, it is generally impractical to sample all forest floor CWD within a 2500 m^2 plot in many forests, whereas sampling with 80+ m transects is very realistic.

Measuring CWD using a 50 x 50 m quadrat was the only method from all tests, where the CV fell below 100% for all woodland plots, specifically, below 25% for four woodland plots and 73% for the other. This is where the CWD sampling method recommended by McKenzie *et al.* (2000) has an advantage over adhering to a line transect only approach. When there are ≤10 pieces of CWD within a 25 x 25 m plot, McKenzie *et al.* (2000) recommend measuring the dimensions of all pieces within the plot. The woodland plots that repeatedly produced the highest variance in estimates when sampled using the line intersect method (QLD 1, 2 and 5) had ≤160 pieces of CWD per hectare (an equivalent per hectare amount to the McKenzie *et al.* recommendation), and showed the greatest improvement in CV estimates when all CWD pieces where measured in quadrats (i.e. steepest decreases in CV).

However, using plots smaller than 50 x 50 m resulted in very high CV from the woodland plots. This suggests that measuring forest floor CWD in 25 x 25 m plots at sites with low CWD frequencies as suggested in McKenzie *et al*., will still result in a high variance in the estimates. By sampling all CWD in a quadrat 50 x 50 m, when ≤40 pieces of CWD are present, results should be satisfactory and yet sampling time should not be excessive. Based on sampling times from the field measurements undertaken for this study, it should take a party of four, just over two hours to measure a 50 x 50 m plot with ≤40 pieces of CWD, in a woodland or open forest, on flat, open terrain.

4.2.5 CV and sample size

The frequency of wood pieces had a major influence on between site variation as results have shown. The transect of 80 m (or even 60 m) may give satisfactory results in the plots with a large sample size such as those in the tall open forests, but may give highly variable and unsatisfactory results in the woodland plots where sample sizes are small. Sampling precision increases as the number of CWD intersections per unit length of sample line increases (Nemec and Davis, 2002).

Therefore transect length is inversely proportional to piece frequency. A similar result was found from line transect simulation studies by Pickford and Hazard (1978), where increasing the population of wood pieces by 3.9 times, CV decreased by about 50%. Therefore, they concluded “sample size decreases proportional to increases in density of pieces in the population”. At plots with low frequencies of CWD, a minor increase in the number of wood pieces can considerably reduce CV because precision increases rapidly with increases in sample size when sample sizes are small (Marshall *et al*., 2000).

4.3 Sampling cost

In considering the optimal sampling design for assessing CWD, cost will almost always be a limiting factor. The biggest cost for sampling in the field is predominantly travel to and from the sample locations, as well as time spent sampling. If the field method is efficient, more samples can be taken at each location, therefore making better use of the travel time and reducing overall costs.

Hazard and Pickford (1984) examined cost functions for sampling forest residue in the Pacific Northwest using the line intersect method, based on the tasks of entering a site, moving between sample points, lay out of the sample line, measuring residue, and returning to the starting point, as well as taking bearings and measuring slope. They found it was more cost effective to measure few long sample lines rather than more short ones, as adding line length at a given location is quicker than moving to a new location. The disadvantage with this is that the sample lines will not be as well distributed over the sample area (Hazard and Pickford, 1984).

For sampling logging residue, Howard and Ward (1972, cited in Nemec and Davis, 2002) found that randomly orientated straight lines took more time to establish than unidirectional lines, but resulted in a relatively CV in CWD volume. Marshal *et al*. (2000) suggested that in situations where a more complex transect arrangement is used, measurement times may be shorter for a transect shape that brings the field crew back to the starting point, e.g. a triangle as opposed to three lines radiating from a single point. It is rare that a sampling strategy involves measuring CWD alone, and the transect arrangement is usually considered in relation to the other forest components to be sampled.

4.4 Influences of forest type, environment and forest management

There are many characteristics of a forest that influence the amount of CWD present. The amount of CWD is primarily a result of forest type, forest productivity, and disturbance regime. Results from this study have demonstrated how this impacts on amounts of CWD. For example, forest type – increasing quantity of CWD from woodland to open forest to tall open forest; forest productivity – open forest plots with low productivity had lower amounts of CWD compared to those from more productive open forest plots; and disturbance – heavily logged plots that had a high amount of stumps and logs compared to plots with little logging.

Forest type is generally distinguished by tree height, crown density, and species composition. Increased stocking density will result in higher frequencies of forest floor CWD, and increased tree size will result in larger CWD. Site productivity can be attributed to soil fertility, topographic position, elevation, rainfall and temperature and will determine the rate at which a forest grows. Climate also has an impact on the longevity of CWD in a forest. Climatic factors, specifically moisture and temperature, affect the rate of decomposition of CWD. Generally, detrital biomass in a forest increases with increasing latitude (see Figure 1 in Woldendorp *et al*., 2002). As climate affects decomposition of CWD and decay rates are higher toward the equator, expected amounts of CWD by decay class can also be assumed. This is apparent from the results that show the proportion of CWD in the higher decay classes increases from Tasmania to New South Wales to Queensland.

The type and intensity of disturbances will affect amounts of CWD in a stand. For example, fires may burn much forest floor CWD but the death and collapse of trees post-fire increases the CWD pool. Logging operations may leave residues *in situ* but decrease standing biomass which is the source of CWD, and events such as floods and windthrow can result in inputs to forest floor CWD (Harmon *et al*., 1986). Other factors affecting the quantity of woody debris in a forest are outlined in Woldendorp *et al*. (2002). From this study, it was evident in plots TAS1 and NSW3 that the majority of CWD was a legacy of the previous stand, as live trees were numerous but basal area was small and CWD quantities were large, resulting from previous logging operations. On the other hand, less disturbed plots show a general pattern of increasing forest floor CWD with increasing basal area of live trees.

Examining and considering forest characteristics in a stand where CWD is to be quantified could assist in determining the size, amount and spatial distribution of CWD that is expected in a stand. This information can provide a basis on which an effective and efficient sampling methodology can be designed. Alternatively, CWD amounts could be predicted from other stand data. Much of the information that is required to predict CWD amounts is available for many forests, particularly managed forest. Chojnacky and Heath (2002) examined ways of predicting down CWD biomass from other forest inventory variables so that CWD did not need to be measured directly. They found that down CWD biomass most related to stag and cut stump variables such as basal area, biomass, stand density index, and number of stags and stumps, rather than live tree variables. Other studies have examined down CWD in relation to stand age and management regime (Spies *et al*., 1988; McCarthy and Bailey, 1994; McGee *et al*., 1999; and Spetich *et al*., 1999).

5. Conclusions and recommendations

The overall aim of this project was to investigate and report on alternative methods for sampling CWD. This was achieved through a comprehensive field survey and simulations of the line intersect method for sampling downed CWD. Stag and stump volume or biomass is generally quantified using plot-based sampling. The focus of the analysis has been on downed CWD, as the line intersect sampling strategies used to quantify this biomass pool are as diverse as the forests in which the method is implemented. Estimates with a desired level of accuracy can be achieved in most forest conditions, providing transect length, replicates, and layout are appropriate for that forest condition.

The line intersect method is efficient, giving a high degree of precision for less effort compared to plot-based sampling for downed CWD. The method is flexible enabling estimates by decay class and diameter class, and transect length can vary with diameter class. However, the results demonstrated that plot-based sampling is more appropriate at sites with a small sample size of small pieces. In many instances CWD is measured in conjunction with other forest biomass pools such as live overstorey and understorey biomass, leaf litter, and sometimes belowground components and soil. Therefore many CWD sampling strategies need to be designed with the other objectives of a project in mind.

Key points from the modelled sampling designs were:

- Transect length and number of transects are key determinants in the precision of CWD estimates. Long transects (> 60 m) will provide estimates with higher precision for the same sampling effort than the same length split into shorter transects.

- The maximum transect length (80 m) used in the sampling simulations still resulted in low precision (CV >100% of the mean) in woodland types. Therefore transects well over 80 m may be required at sites with low densities of CWD. To achieve a CV less than 50% at most sites, transects at least 100 m are likely to be required. For very sparse woodland debris, transects well over 100 m may still result in a CV in the order of 100%.

- Fewer long transects will be easier to measure and lay out than many short transects. If more complex layouts are used, those that bring the field crew back to the starting point can potentially be more efficient.

- There was no significant difference in the estimates of CWD from transects arranged in a triangle, square, three separate lines or a single line. Other studies have shown that the arrangement of transects is an important consideration when there is bias in piece orientation, but this is of less importance at sites with randomly orientated CWD such as those measured for this project.

- In stands where there is no significant orientation bias of wood pieces, the most efficient method is a single line transect at each site. Replicate sites can be arranged at random angles.

- At plots with a low density of downed CWD and small piece sizes such as the woodland site, a higher precision was achieved through sampling on fixed-area plots, particularly plots 50 x 50 m. We found that there was still a high degree of variability in estimates from 20 x 20 m plots. Plots 50 x 50m produced estimates with higher precision.

CWD amounts can be related to factors such as dominant tree height, stocking, disturbance, latitude, climate, soil, topographic position, and elevation. Considering these factors when designing a sampling strategy may assist in determining the optimal transect length, arrangement of transects, and number of replicates.

This project is an early step toward developing a better understanding of CWD amounts in native forests. Knowledge of the status and condition of CWD in Australian forests could be further improved through the following:

1. The computer program used to test sampling designs for this project could be developed further to explore additional approaches to implementing the line intersect method. The tests used for this project were based on actual field data but it would be possible to generate a wide variety of CWD populations and scenarios such as create larger areas of CWD, adjust sample sizes, and increase or decrease spatial heterogeneity of wood pieces. Different measurement regimes that are applicable in the field can be compared, and variables of the line intersect method can be tested including using longer transects than those used in this project. Sampling cost can be integrated into the program based on cost per unit length of transect measured and cost per piece, as well as time for laying transects out, for example. There is huge scope for the utilisation of this program.

2. Although the forest types used in this project were considered representative of the amount and condition of CWD in a considerable proportion of native eucalypt forests, an increased understanding of the application of CWD methods could be achieved by examining other eucalypt and non-eucalypt dominated forest types, and modelling CWD methods in these forests.

3. It is important to improve our understanding of decomposition processes of CWD and stags in different forest types and latitudes. Understanding turnover times of CWD will inform us of the longevity of this biomass pool in forests across Australia. This is important not only in terms of carbon storage, but also in light of nutrient cycling and ecological processes.

4. It may be advantageous to investigate the use of remote sensing data for providing information on amounts of CWD in different forest types. This was briefly discussed in Woldendorp *et al*. (2002), the first report from this study. Remote sensing could aid the stratification process including identifying disturbance, forest productivity, and vegetation types, from which expected amounts of CWD can be estimated. In some instances, CWD can even be identified from air photos and possibly quantified in this way.

5. Estimations of CWD biomass and carbon can be determined from other stand data (eg. forest inventory data) or from data sources where some assessment of CWD has been made such as those investigated in Woldendorp *et al*. (2002). This sort of work has been explored in studies such as Chojnacky and Heath (2002) where US forest inventory data was examined for its use in estimating carbon at a national scale, or linking inventory data with additional information from models.

The results of this study will be incorporated into the proposed continental forest monitoring framework being developed by the National Forest Inventory.

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Appendix 1. Data sheets

(in the following five pages)

COARSE WOODY DEBRIS ASSESSMENT – SITE INFORMATION AND DISTURBANCE

PLOT NO: …………………… **DATE:** ………………………………..

OBSERVERS: ……………………………………………………………………………………

Site photos taken? YES NO Photo numbers ………………………………………

LOCATION: …………………………………………………………..

General locality: ……………………………………………………………………………… Map No:……………………

TOPOGRAPHY Situation: …………………… Slope pos: …………………… Slope (deg): ……………………..

Aspect (deg): …………………… Elevation: ……………………….m

VEGETATION Forest type: ……………………………………………. Canopy cover: …………………………%

Main overstorey species :……………………………………………………………………………………………..

Main understorey species:……………………………………………………………………………………………

Groundcover density: …………………………………%

DISTURBANCE

Type	Severity 0 – 3 (0 = nil, 3 = severe)	Year of last event	Observation type 1 = visual estimate, 2 = records, 3 = informant	Comments
Wildfire				
Prescribed burn				
Logging				
Silvicultural treatment				
Grazing				
Clearing				
Regeneration				
Other (specify)				

Notes:

COARSE WOODY DEBRIS ASSESSMENT – FALLEN WOODY MATERIAL

Plot No: ………………………… Date: ……………………………………

Observers: ………………………………………………………………………………

Record all pieces of downed woody debris down to a small end diameter ≥15 cm (≥10 cm in woodlands).

No.	1 End diameter (cm)	2 End diameter (cm)	Length (cm)	Decay class	Species	No.	1 End diameter (cm)	2 End diameter (cm)	Length (cm)	Decay class	Species
1						46					
2						47					
3						48					
4						49					
5						50					
6						51					
7						52					
8						53					
9						54					
10						55					
11						56					
12						57					
13						58					
14						59					
15						60					
16						61					
17						62					
18						63					
19						64					
20						65					
21						66					
22						67					
23						68					
24						69					
25						70					
26						71					
27						72					
28						73					
29						74					
30						75					
31						76					
32						77					
33						78					
34						79					
35						80					
36						81					
37						82					
38						83					
39						84					
40						85					
41						86					
42						87					
43						88					
44						89					
45						90					

Decay classes for downed woody material:
1 = Fresh solid wood, bark and twigs present;
2 = Some bark present, twigs absent, signs of decay present;
3 = Bark absent, more extensive decay but structurally sound, herbs etc present, some invading roots some termite damage;
4 = Log can't support own weight, cleaves into pieces when kicked, some solid chunks, branch stubs rotted down (can be removed by hand), herbs etc present, invading roots throughout, more extensive termite damage producing hollows;
5 = Flattened, spread out, soft, powdery (when dry), doesn't support own weight, often just a mound, herbs etc present, invading roots throughout, termite damage has collapsed log or hollow with a thin shell.

COARSE WOODY DEBRIS ASSESSMENT – STANDING DEAD TREES

Plot No: ………………………… Date: ……………………………………

Observers: ……………………………………………………………………………….

Record all stags with a DBH ≥15 cm (≥10 cm in woodlands).

No.	DBH (cm)	Height (m)	Decay class	Species	No.	DBH (cm)	Height (m)	Decay class	Species
D1					D48				
D2					D49				
D3					D50				
D4					D51				
D5					D52				
D6					D53				
D7					D54				
D8					D55				
D9					D56				
D10					D57				
D11					D58				
D12					D59				
D13					D60				
D14					D61				
D15					D62				
D16					D63				
D17					D64				
D18					D65				
D19					D66				
D20					D67				
D21					D68				
D22					D69				
D23					D70				
D24					D71				
D25					D72				
D26					D73				
D27					D74				
D28					D75				
D29					D76				
D30					D77				
D31					D78				
D32					D79				
D33					D80				
D34					D81				
D35					D82				
D36					D83				
D37					D84				
D38					D85				
D39					D86				
D40					D87				
D41					D88				
D42					D89				
D43					D90				
D44					D91				
D45					D92				
D46					D93				
D47					D94				

Decay classes for standing dead trees:
1 = Recently dead, branches and twigs present, bark intact and tight on bole;
2 = Much of crown broken but large branches present, bark loose and/or partly absent, bole firm;
3 = Top may have broken, large branch stubs may be present, bark generally absent, bole still standing but decayed, partial termite damage;
4 = Branches and crown absent, broken top, bark absent, wood is heavily decayed, may be soft and blocky, hollow due to termite damage.

COARSE WOODY DEBRIS ASSESSMENT – STUMPS

Plot No: ………………………… Date: ……………………………………

Observers: ……………………………………………………………………………….

Record all stumps with a top diameter ≥15cm (≥10 cm in woodlands).

No.	**Diameter (cm)**	**Height (cm)**	**Decay class**	**Species**	**No.**	**Diameter (cm)**	**Height (cm)**	**Decay class**	**Species**
S1					S44				
S2					S45				
S3					S46				
S4					S47				
S5					S48				
S6					S49				
S7					S50				
S8					S51				
S9					S52				
S10					S53				
S11					S54				
S12					S55				
S13					S56				
S14					S57				
S15					S58				
S16					S59				
S17					S60				
S18					S61				
S19					S62				
S20					S63				
S21					S64				
S22					S65				
S23					S66				
S24					S67				
S25					S68				
S26					S69				
S27					S70				
S28					S71				
S29					S72				
S30					S73				
S31					S74				
S32					S75				
S33					S76				
S34					S77				
S35					S78				
S36					S79				
S37					S80				
S38					S81				
S39					S82				
S40					S83				
S41					S84				
S42					S85				
S43					S86				

Decay classes for stumps (as per forest floor CWD):
1 = Fresh solid wood, bark and twigs present;
2 = Some bark present, twigs absent, signs of decay in sapwood (cannot be pulled apart by hand);
3 = Bark absent, sapwood decayed but some may be present (can be pulled apart by hand), heartwood decayed but structurally sound, herbs etc present, invading roots in sapwood, some termite damage;
4 = Cleaves into pieces when kicked, some solid chunks of heartwood, sapwood and bark mostly absent, branch stubs rotted down (can be removed by hand), herbs etc present, invading roots throughout, more extensive termite damage;
5 = Flattened, spread out, soft, powdery (when dry), doesn't support own weight, often just a mound, herbs etc present, invading roots throughout, termite damage has produced a hollow shell.

COARSE WOODY DEBRIS ASSESSMENT – 10 x 10 m GRIDS

Plot No: ……………………… Grid Nos: ………………………. Date: …………………………

Observers: ……………………………………………………………………………………..

- Sketch location and orientation of all fallen woody material, stags, and stumps ≥15 cm diameter (≥10 cm in woodlands).
- Number each piece and record dimensions. Include **D** for standing dead tree and **S** for stump.

***NB. 1 m = 1 cm on grid**

Plot orientation

Grid # …..	Grid # …..
Grid # …..	Grid # …..

Appendix 2. Plot descriptions

Queensland

Plot No.: QLD1_144(13.5)

Original plot measurement history: Research site; 50 x 50m. Measurements included all overstorey biomass for DBH and height, foliage cover and canopy dimensions, for calibrating remotely sensed data from LIDAR and aerial photography.

Plot orientation (top of plot): North (0°)

Relationship of plot positions: Same centre point

Location: State Forest, Injune study area.

Grid reference (plot centre): UTM East 547100.0, UTM North 7147571.5

Topography

Situation: South end in shallow creek bed

Slope angle: <1° **Aspect:** 145° **Elevation:** 530m

Vegetation

Forest type and structure: Grassy woodland, with some species regeneration.

Disturbance history: Downed trees adjacent to creek bed due to periodic inundation. Vehicular track present.

Main overstorey species: *Callitris glaucophylla* (white cypress pine) *C. glaucophylla* x *C. preisii* ssp. *verrucosa* (family pine), *Eucalyptus chloroclada, E. tereticornis* (forest red gum), *E. melanophloia* (silver-leaved ironbark).

Main understorey species: *Lomandra longifolia*; regenerating overstorey species; various grasses.

Percentage canopy cover: 29% **Percentage ground cover:** 50-60%

Stand structure information: BA = 15.12m^2/ha

Stocking density = 308 stems/ha (≥10cm DBH)

Plot No.: QLD2_148(16)

Original plot measurement history: Research; 50 x 50m. Measurements included all overstorey biomass for DBH and height, foliage cover and canopy dimensions, for calibrating remotely sensed data from LIDAR and aerial photography.

Plot orientation (top of plot): North (0°)

Relationship of plot positions: Same centre point

Location: State Forest, Injune study area.

Grid reference (plot centre): UTM East 561511.9, UTM North 7147567.5

Topography

Situation: Flat plain

Slope angle: 0.5° **Aspect:** 165° **Elevation:** 535m

Vegetation

Forest type and structure: Grassy woodland with some species regeneration.

Disturbance history: Vehicular track present

Main overstorey species: *Callitris glaucophylla* (cypress pine), *E. microcarpa* (grey box), *E. populnea* (poplar box), *E. melanophloia* (silver-leaved ironbark).

Main understorey species: *Notelaea microcarpa* var. *microcarpa, Opuntia tomentose* (prickly pear), *Hovea longipes*, *Eremophila* sp., and juvenile *Callitris.*

Percentage canopy cover: 36% **Percentage ground cover:** 30%

Stand structure information: BA = 9.49m^2/ha

Stocking density = 152 stems/ha (≥10cm DBH)

Plot No.: QLD3_142(18)

Original plot measurement history: Research; 50 x 50m. Measurements included all overstorey biomass for DBH and height, foliage cover and canopy dimensions, for calibrating remotely sensed data from LIDAR and aerial photography.

Plot orientation (top of plot): North (0°)

Relationship of plot positions: Same centre point

Location: Leasehold land, Injune study area.

Grid reference (plot centre): UTM East 539927.4, UTM North 7147593.3

Topography

Situation: Flat plain

Slope angle: 0° **Aspect:** NA **Elevation:** 547m

Vegetation

Forest type and structure: Grassy woodland

Disturbance history: Grazing. Vehicular track and fencing present

Main overstorey species: *Eucalyptus populnea* (poplar box)

Main understorey species: *Hakea fraseri*, and juvenile *Callitris glaucophylla* (white cypress pine).

Percentage canopy cover: 33% **Percentage ground cover:** 30%

Stand structure information: BA = 10.83m^2/ha

Stocking density = 256 stems/ha (≥10cm DBH)

Plot No.: QLD4_124(19)

Original plot measurement history: Research; 50 x 50m. Measurements included all overstorey biomass for DBH and height, foliage cover and canopy dimensions, for calibrating remotely sensed data from LIDAR and aerial photography.

Plot orientation (top of plot): North (0°)

Relationship of plot positions: CWD plot moved ~15m north to avoid wood piles from road clearing

Location: State Forest, Injune study area.

Grid reference (plot centre): UTM East 547380.5, UTM North 7155612.3

Topography

Situation: Flat plain

Slope angle: <0.5° **Aspect:** NA **Elevation:** 555m

Vegetation

Forest type and structure: Open forest

Disturbance history: Evidence of logging cypress pine

Main overstorey species: *Angophora leiocarpa* (smooth-barked apple), *Eucalyptus chloroclada; Callitris glaucophylla* (white cypress pine).

Main understorey species: *Bossiaea rhombifolia* subsp. *concolor, Leucopogon mitchellii, Acacia leptostachya, A. macradenia.*

Percentage canopy cover: 35% **Percentage ground cover:** 15%

Stand structure information: BA = 16.03m^2/ha

Stocking density = 388 stems/ha (≥10cm DBH)

Plot No.: QLD5_148(21)

Original plot measurement history: Research; 50 x 50m. Measurements included all overstorey biomass for DBH and height, foliage cover and canopy dimensions, for calibrating remotely sensed data from LIDAR and aerial photography.

Plot orientation (top of plot): North (0°)

Relationship of plot positions: Same centre point

Location: State Forest, Injune study area.

Grid reference (plot centre): UTM East 561732.3, UTM North 7147544.5

Topography

Situation: Flat plain

Slope angle: 0° **Aspect:** NA **Elevation:** 536m

Vegetation

Forest type and structure: Grassy woodland with some species regeneration

Disturbance history: Vehicular track present

Main overstorey species: *Callitris glaucophylla* (white cypress pine), *Eucalyptus populnea* (poplar box), *E. microcarpa* (grey box).

Main understorey species: *Acacia harpophylla* (brigalow), *Dodonaea viscose* subsp. s*patulata*, and juvenile *Callitris glaucophylla* (white cypress pine).

Percentage canopy cover: 31% **Percentage ground cover:** 25%

Stand structure information: BA = 8.39m^2/ha

Stocking density = 140 stems/ha (≥10cm DBH)

New South Wales

Plot No.: NSW1_58

Original plot measurement history: Research site; 60 x 60m. Measured all aboveground biomass >20cm DBH, estimated biomass 2-20cm DBH, and CWD >5cm in diameter, for relating to RADAR data.

Plot orientation (top of plot): North (0°)

Relationship of plot positions: CWD plot centre was 20m south and 20m east of original plot centre (i.e. original plot in NW corner of CWD plot). Moved to avoid road.

Location: Dam Rd, just past Link Rd., Murramarang National Park.

Grid reference (plot centre): UTM East 256667, UTM North 6060874

Topography

Situation: Mid-slope on an indistinct ridge

Slope angle: 6° **Aspect:** 45° **Elevation:** 110m

Vegetation

Forest type and structure: Multi-aged, open, dry sclerophyll forest

Disturbance history (by coupe): Harvested for sawlogs in 1962.

Last fire event occurred in 1968

Harvested for poles in 1986.

Main overstorey species: *Eucalyptus piperita, E. gummifera*

Main understorey species: *Leptospernum* sp., *Elaeocarpus* sp., *Banksia spinulosa, Acacia* spp., *Pturidium* sp.

Percentage canopy cover: 25-30% **Percentage ground cover:** 75%

Stand structure information: BA = 37.10m^2/ha

Stocking density = 183 stems/ha (≥10cm DBH)

Plot No.: NSW2_76

Original plot measurement history: Research site; 60 x 60m. Measured all aboveground biomass >20cm DBH, estimated biomass 2-20cm DBH, and CWD >5cm in diameter, for relating to RADAR data.

Plot orientation (top of plot): 40°

Relationship of plot positions: CWD plot centre was 40m south-west (220°) of original plot centre. Moved to avoid dense 2m high cutting grass in creek line.

Location: Livingston Creek Rd, 100m SE past bridge, Murramarang National Park.

Grid reference (plot centre): UTM East 256496, UTM North 6056396

Topography

Situation: Mid- to lower slope on an indistinct ridge

Slope angle: 4° **Aspect:** 45° **Elevation:** 75m

Vegetation

Forest type and structure: Multi-aged, open, dry sclerophyll forest of medium productivity.

Disturbance history (by coupe): Wildfire occurred in 1900.

Harvested for sawlogs in 1968.

Harvested for mining timber in 1980.

Harvested for poles in 1987.

Hazard reduction burn in 1992.

Main overstorey species: *Eucalyptus maculata*

Main understorey species: *Acacia* spp., *Gahnia* sp., *Synoum gladulosum, Elaeocarpus* sp.

Percentage canopy cover: 35% **Percentage ground cover:** 40%

Stand structure information: BA = 47.13m^2/ha

Stocking density = 449 stems/ha (≥10cm DBH)

Plot No.: NSW3_1

Original plot measurement history: Research site; 60 x 60m. Measured all aboveground biomass >20cm DBH, estimated biomass 2-20cm DBH, and CWD >5cm in diameter, for relating to RADAR data.

Plot orientation (top of plot): North (0°)

Relationship of plot positions: Exact position of original plot could not be located, therefore CWD plot was positioned to best capture the variability of the site. Original plot was approximately in the NE corner.

Location: Spotted Gum Rd, opposite Ryans Creek Rd., Murramarang National Park

Grid reference (plot centre): UTM East 252450, UTM North 6055635

Topography

Situation: Mid-/lower slope in a gully

Slope angle: 3° **Aspect:** 188° **Elevation:** 30m

Vegetation

Forest type and structure: Young open, dry sclerophyll forest, regenerating after recent logging and burning.

Disturbance history (by coupe): Timber stand improvement (ringbarking) in 1921.

Wildfire occurred in 1946.

Harvested for sawlogs in 1967.

Salvage logged in 1980.

Harvested for sawlogs in 1992.

Hazard reduction burn in 1997.

Main overstorey species: *Eucalyptus piperita, E. scias, E. sieberi, E. maculata*

Main understorey species: *Elaeocarpus* sp., *Acacia* spp., *Bracken* sp. *Gahnia* sp., juvenile eucalypts

Percentage canopy cover: 25-30% **Percentage ground cover:** 70%

Stand structure information: BA = 19.41m^2/ha

Stocking density = 297 stems/ha (≥20cm DBH)

Plot No.: NSW4_130

Original plot measurement history: Research site; 60 x 60 m. Measured all aboveground biomass >20cm DBH, estimated biomass 2-20cm DBH, and CWD >5cm in diameter, for relating to RADAR data.

Plot orientation (top of plot): North (0°)

Relationship of plot positions: CWD plot centre was 30 m east and 30 m north of original plot centre. Moved to avoid anthropogenic disturbance, and creek bed with predominantly Banksia and Hakea.

Location: Pebbly Beach Rd, NW of track 1.5km from Princes Hwy, Murramarang National Park

Grid reference (plot centre): UTM East 253802, UTM North 6060295

Topography

Situation: Mid-slope

Slope angle: 1° **Aspect:** 60° **Elevation:** 40m

Vegetation

Forest type and structure: Low productivity, open, dry sclerophyll forest with no evidence of logging.

Disturbance history (by coupe): Harvested for sawlogs in 1971.

Harvested for poles in 1986.

Harvested for mining timber in 1991.

Hazard reduction burn in 1995.

Main overstorey species: *Angophora floribunda; Eucalyptus consideniana; E. globoidea; E. sieberi*

Main understorey species: *Banksia serrata; B. spinulosa; Hakea* spp.*; Leptospernum* sp.*; Casuarina littoralis; Isopogon anthifolius*

Percentage canopy cover: 20% **Percentage ground cover:** 80%

Stand structure information: BA = 29.82m^2/ha

Stocking density = 326 stems/ha (≥10cm DBH)

Plot No.: NSW5_84

Original plot measurement history: Research site, circular plot 30m radius. Measured all aboveground biomass >10cm DBH.

Plot orientation (top of plot): North (0°)

Relationship of plot positions: Same centre point.

Location: Old Princes Hwy, 350 m southeast of The Sheep Track, South Brooman State Forest.

Grid reference (plot centre): UTM East 255113, UTM North 6066565

Topography

Situation: Mid to lower slope across a ridge

Slope angle: W side 13°; centre 9°; E side 16° **Aspect:** W side 235°; centre 185°; E side 130°

Elevation: 85m

Vegetation

Forest type and structure: Multi-aged open, dry sclerophyll forest, medium productivity.

Disturbance history (by coupe): Harvested for sawlogs in 1955.

Harvested for sawlogs in 1973.

Harvested for sawlogs in 1984.

Timber stand improvement (ringbarking) in 1984.

Harvested for poles in 1990.

Main overstorey species: *E. maculata, E. muelleriana, E. paniculata, E. pilularis*

Main understorey species: *Acacia* spp., *Acmena* sp.

Percentage canopy cover: 50% **Percentage ground cover:** 10%

Stand structure information: BA = 35.51m^2/ha

Stocking density = 414 stems/ha (≥10cm DBH)

Tasmania

Plot No.: TAS1_1227

Original plot measurement history: CFI plot, 0.1 ha (20 x 50m). Measured according to the guidelines set out in Edgley (1985), in 1981, 1987, and 1997.

Plot orientation (top of plot): 67°

Relationship of plot positions: Bottom (SW end) of CFI plot centred and level with bottom of CWD plot

Location: Arve Rd, approx. 600m past Edwards Rd junction, in Arve Valley.

Grid reference (plot centre): UTM East 482290, UTM North 5226190

Topography

Situation: Lower slope

Slope angle: 17°

Aspect: NNW side 140°; centre 125°; SSW side 120°

Elevation (at centre): 215m

Vegetation

Forest type and structure: Young tall open forest regenerating after clearfelling

Disturbance history: Site selectively logged in 1950's. Clearfell logged in 1966.

Main overstorey species: *Eucalyptus regnans; E. obliqua; Acacia dealbata*

Main understorey species: *Phyllocladus aspeniifolius* (Celery-top pine); *Acacia dealbata* (Silver wattle) and *Acacia melanoxylon* (Blackwood) regeneration; *Eucryphia lucida* (Leatherwood); *Nothofagus cunninghamii* (Myrtle); *Atherosperma moschara* (Sassafras); *Dicksonia antarctica* (Manfern); *Gahnia grandis* (Cutting grass)

Percentage canopy cover: Upper canopy 35%; subcanopy 80%

Percentage ground cover: 1%

Stand structure information: BA in 1981 = 13.89 m^2/ha; 700 stems/ha (≥10cm DBH)

BA in 1987 = 22.11 m^2/ha; 760 stems/ha (≥10cm DBH)

BA in 1997 = 34.99 m^2/ha; 770 stems/ha (≥10cm DBH)

Plot No.: TAS2_1087

Original plot measurement history: CFI plot, 0.2 ha (20 x 100m). Measured according to the guidelines set out in Edgley (1985), in 1968, 1973, and 1995.

Plot orientation (top of plot): 330°

Relationship of plot positions: CFI plot down centre of CWD plot

Location: 'Bird track', Manuka Rd, Warra LTER site.

Grid reference (plot centre): UTM East 470655, UTM North 5228747

Topography

Situation: Upper slope of small ridge

Slope angle: SW side 5°; centre 6°; NE side 7.5°

Aspect: SW side 111°, centre 92°; NE side 44°

Elevation (at centre): 160m

Vegetation

Forest type and structure: Tall open forest with minimal disturbance

Disturbance history: Wildfire of moderate severity occurred in 1934. No logging

Main overstorey species: *Eucalyptus obliqua*

Main understorey species: *Nothofagus cunninghammii* (Myrtle); rainforest spp.; *Gahnia grandis* (Cutting grass); *Dicksonia antarctica* (Manfern)

Percentage canopy cover: 20% **Percentage ground cover:** 30%

Stand structure information: BA in 1968 = 145.31 m^2/ha; 1010 stems/ha (≥10cm DBH)

BA in 1973 = 128.98 m^2/ha; 645 stems/ha (≥10cm DBH)

BA in 1995 = 146.90 m^2/ha; 600 stems/ha (≥10cm DBH)

Plot No.: TAS3_5703

Original plot measurement history: CFI plot, 0.1 ha (20 x 50m). Measured according to the guidelines set out in Edgley (1985), in 1988 and 1992.

Plot orientation (top of plot): 232°

Relationship of plot positions: CWD plot moved down 10m from top (SW end) of CFI plot to avoid downed trees from road clearing

Location: Riveaux Rd., Picton Valley.

Grid reference (plot centre): UTM East 474840, UTM North 2556750

Topography

Situation: Mid to lower slope

Slope angle: Top (SW) half 15°; bottom (NE) half 25°

Aspect: 30°

Elevation (at centre): 170m

Vegetation

Forest type and structure: Multi-aged tall open forest

Disturbance history: Wildfire of moderate severity occurred in 1944. No logging

Main overstorey species: *Eucalyptus obliqua*

Main understorey species: *Phyllocladus aspeniifolius* (Celery-top pine); *Nothofagus cunninghamii* (Myrtle); *Dicksonia antarctica* (Manfern)

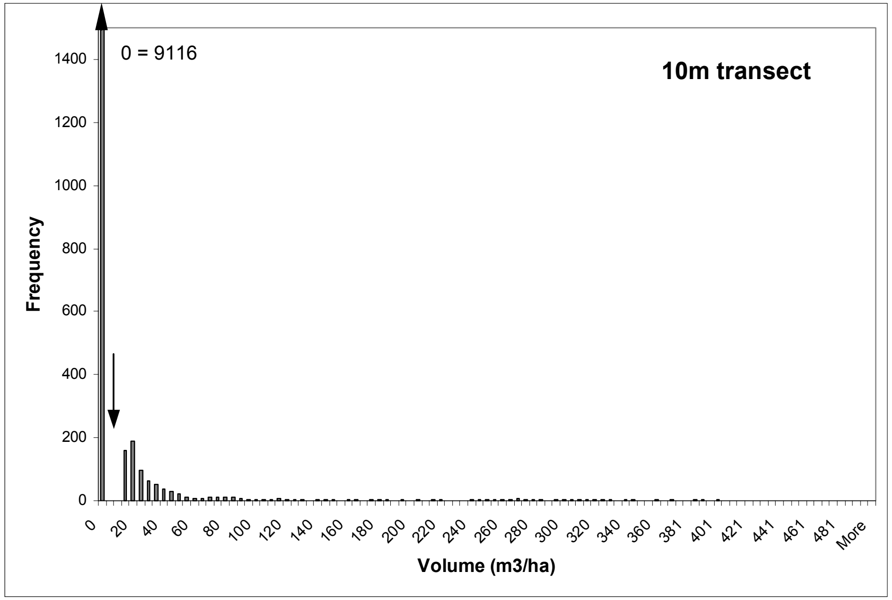
Percentage canopy cover: 40% **Percentage ground cover:** 5%

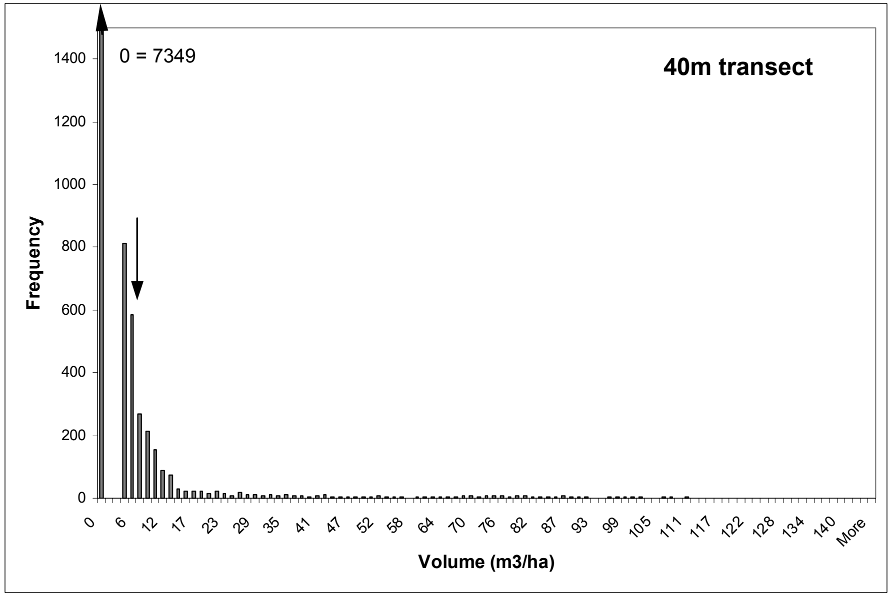
Stand structure information: BA in 1988 = 149.93 m^2/ha; 490 stems/ha (≥10cm DBH)

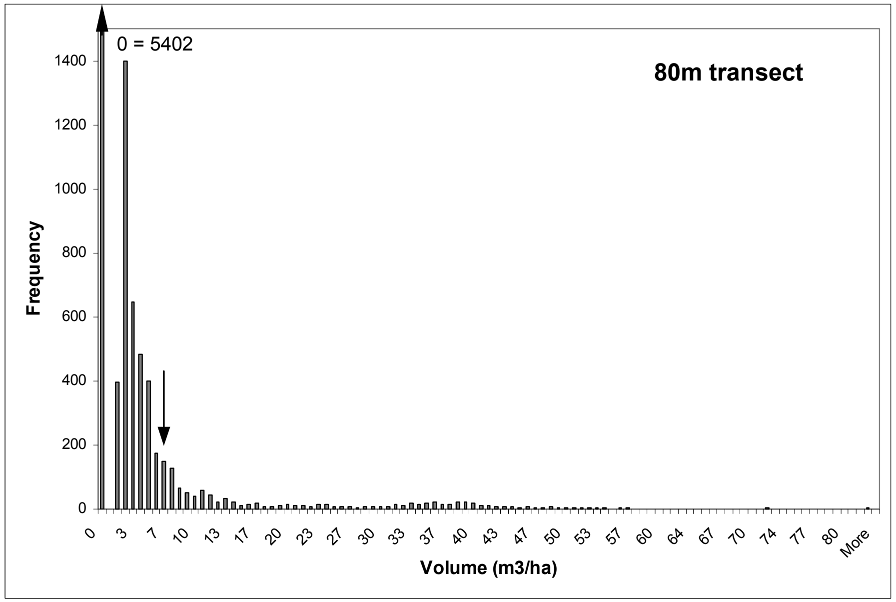
BA in 1992 = 153.54 m^2/ha; 450 stems/ha (≥10cm DBH)

Appendix 3. Histograms of CWD volume estimate frequency for transect length, number, and layout

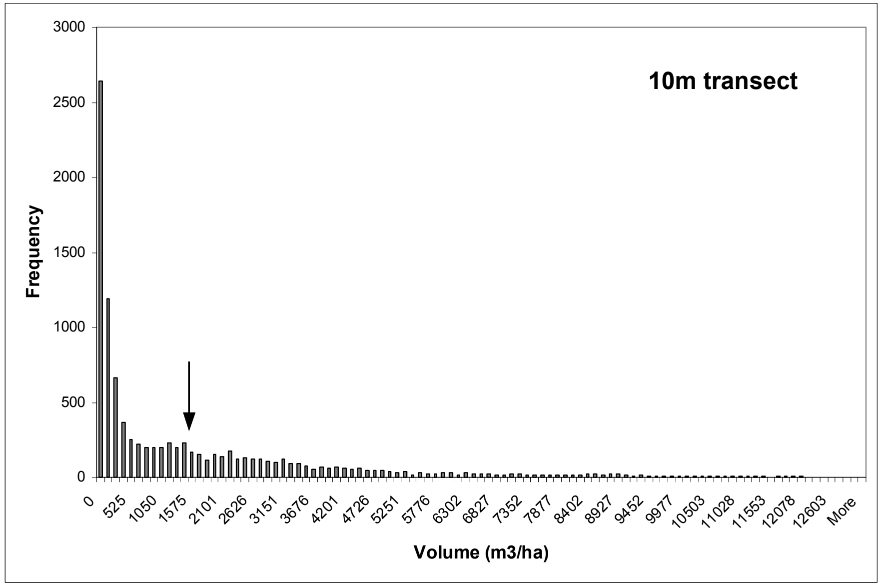
(NB. Arrows indicate volume of all forest floor CWD above the minimum size threshold calculated from entire one-hectare plot. Note that scales may differ for each set of histograms. Scales on the y-axis of some histograms have been reduced to show values clearer when frequency of 0 volume is large.)

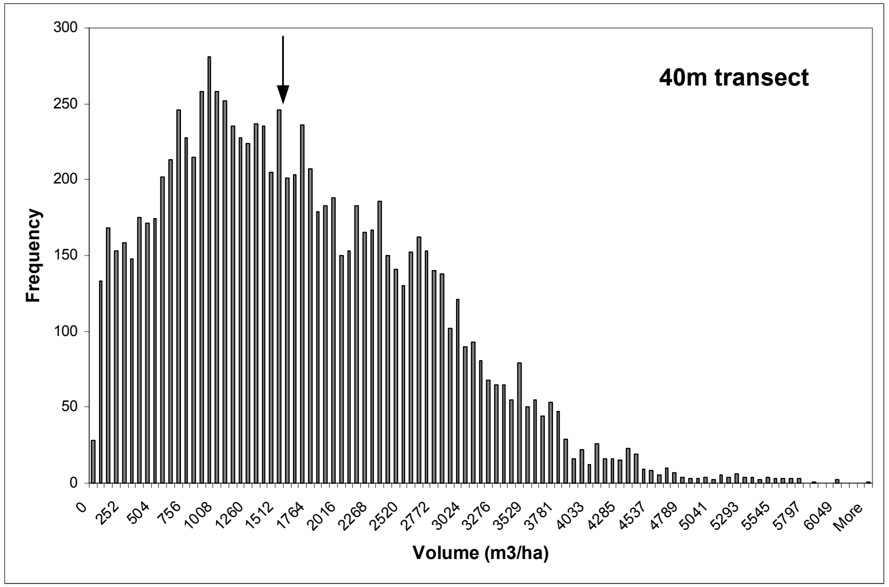


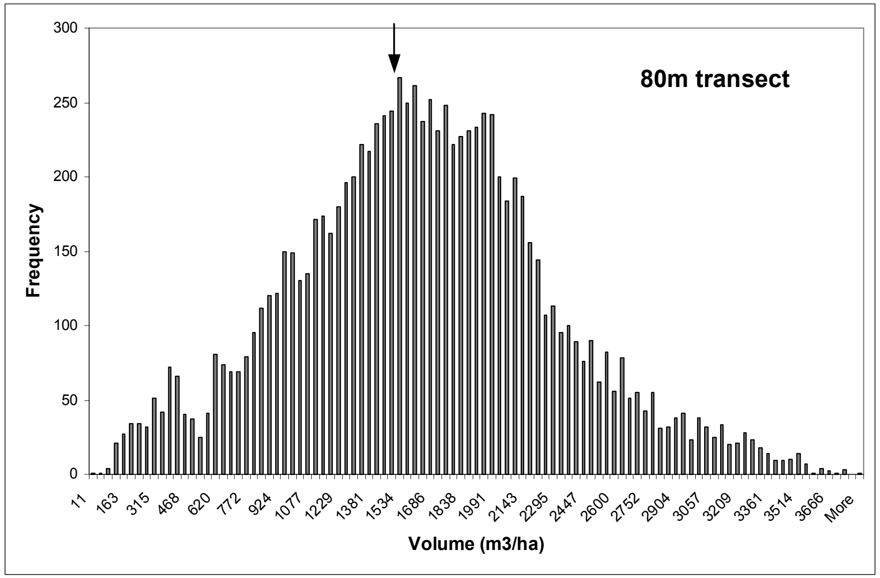




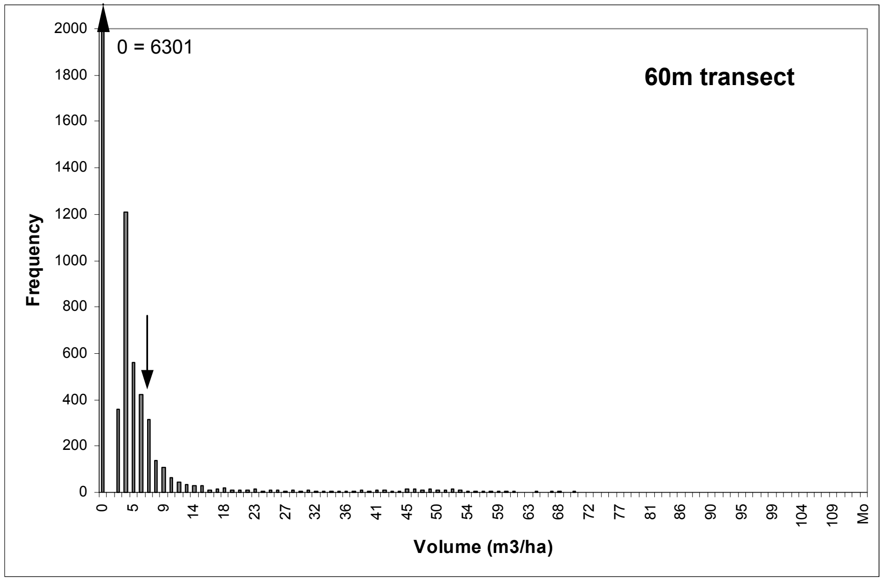
A. Transect lengths of 10m, 40m, and 80m from plot QLD1 in the woodland.

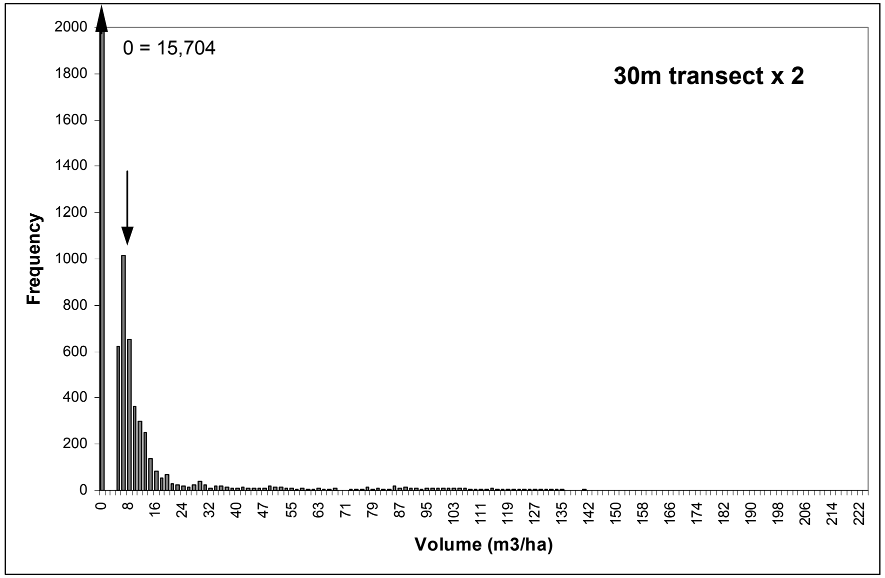


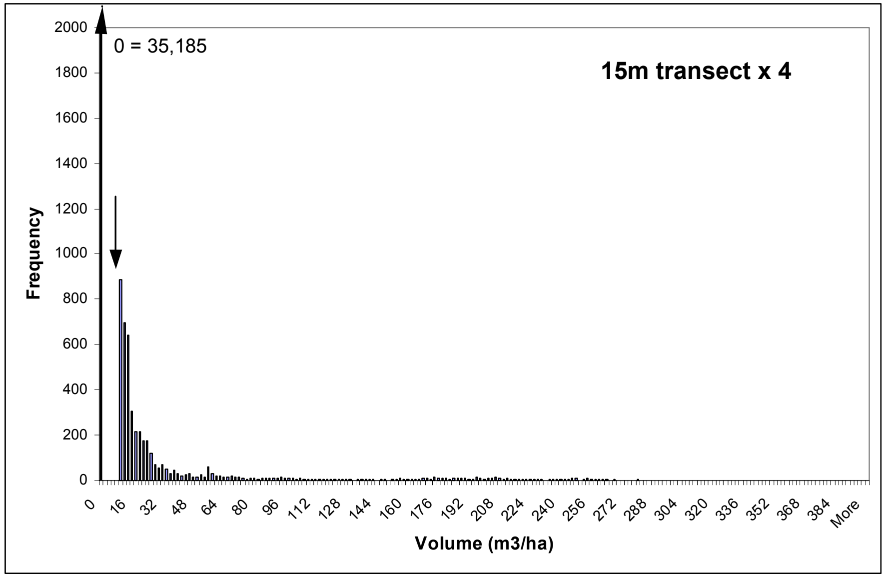




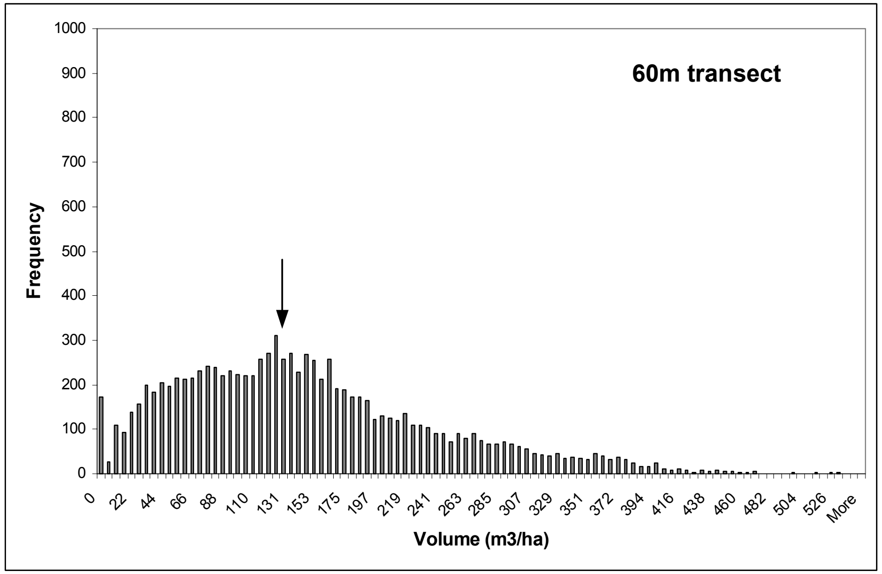
B. Transects lengths of 10m, 40m, and 80m from plot TAS1 in the tall open forest. (NB Varying frequency scales)

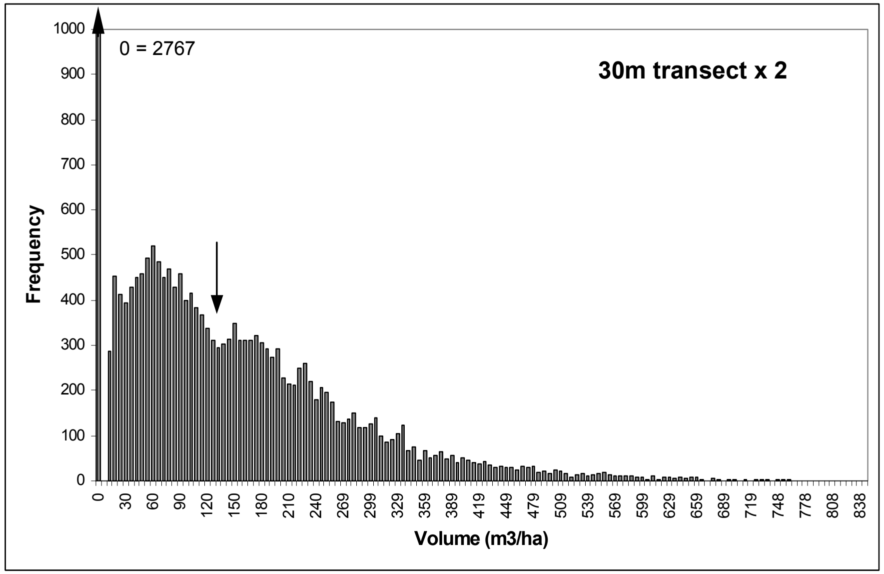


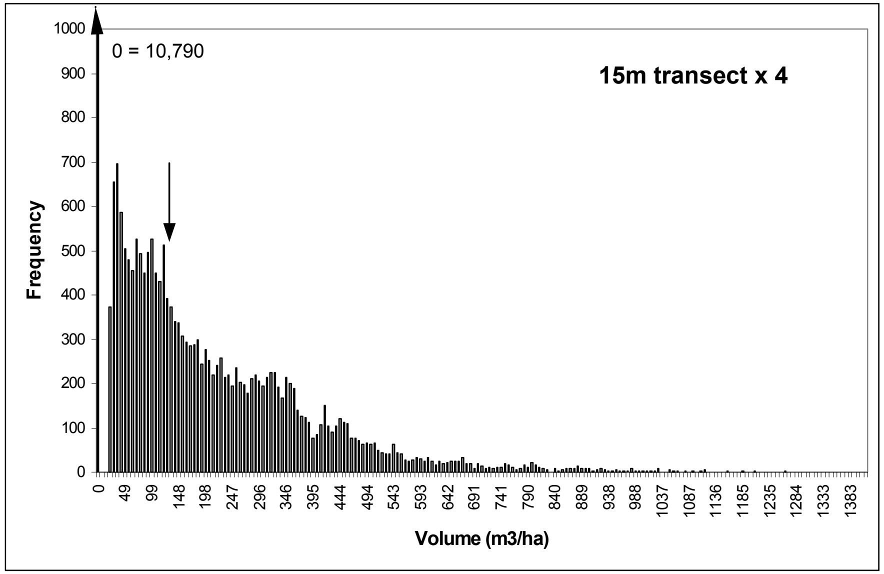




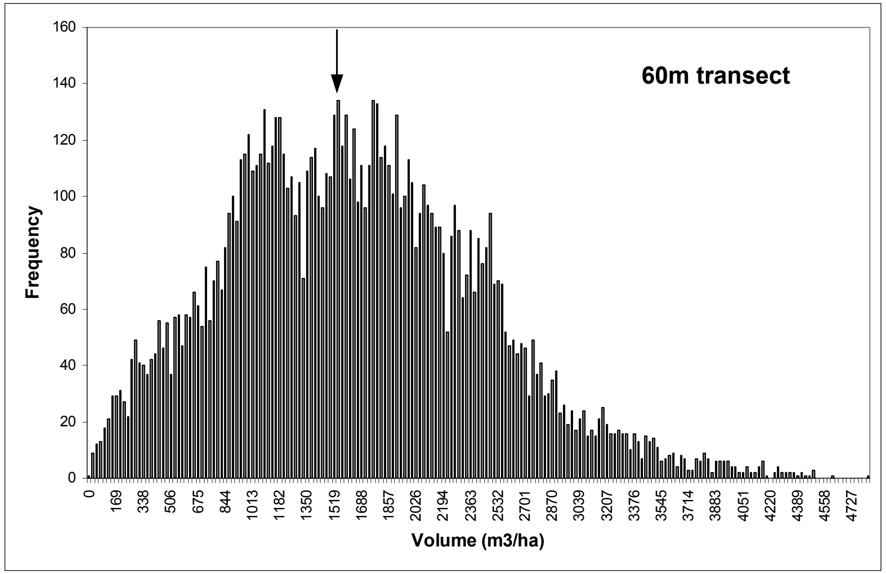
C. Equal sampling efforts using transect lengths of 60m, 30m, and 15m at plot QLD1 in the woodland - 10,000 replicates of 60m transect, 20,000 replicates of 30m transect, and 40,000 replicates of 15m transect. (NB Frequency scales have been reduced)

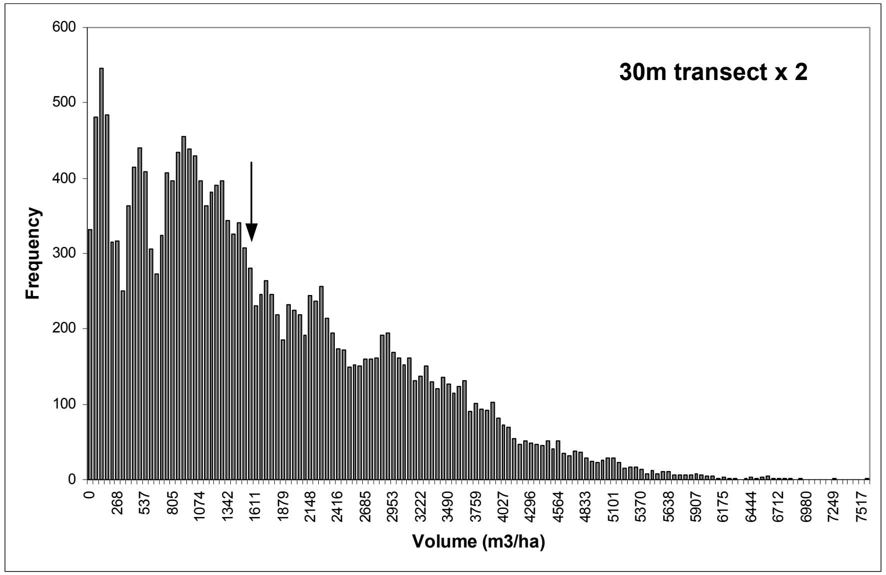


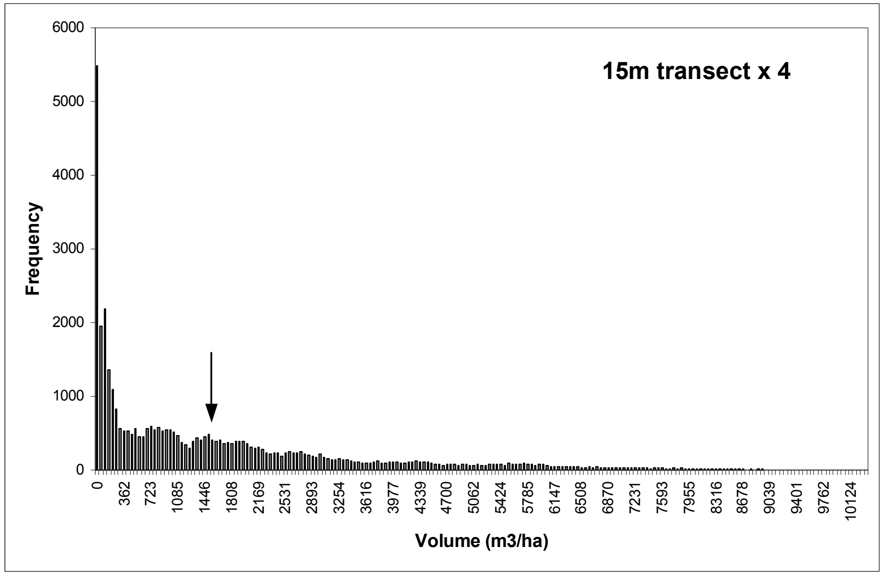




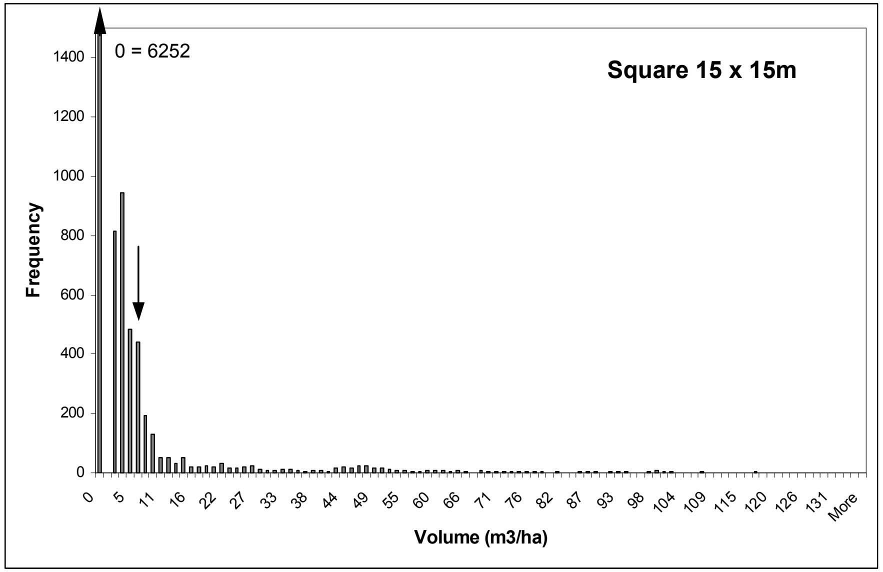
D. Equal sampling efforts using transect lengths of 60m, 30m, and 15m at plot NSW1 in open forest - 10,000 replicates of 60m transect, 20,000 replicates of 30m transect, and 40,000 replicates of 15m transect. (NB Varying frequency scales)

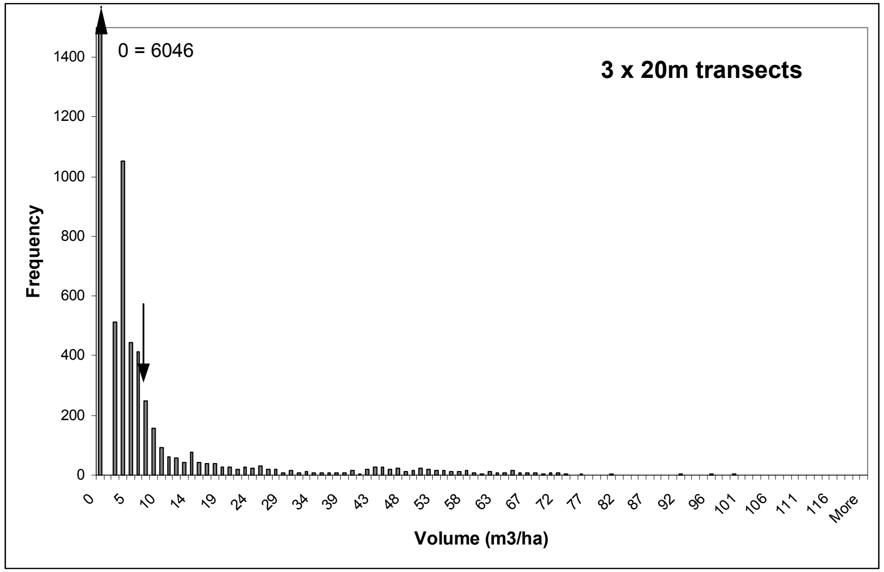


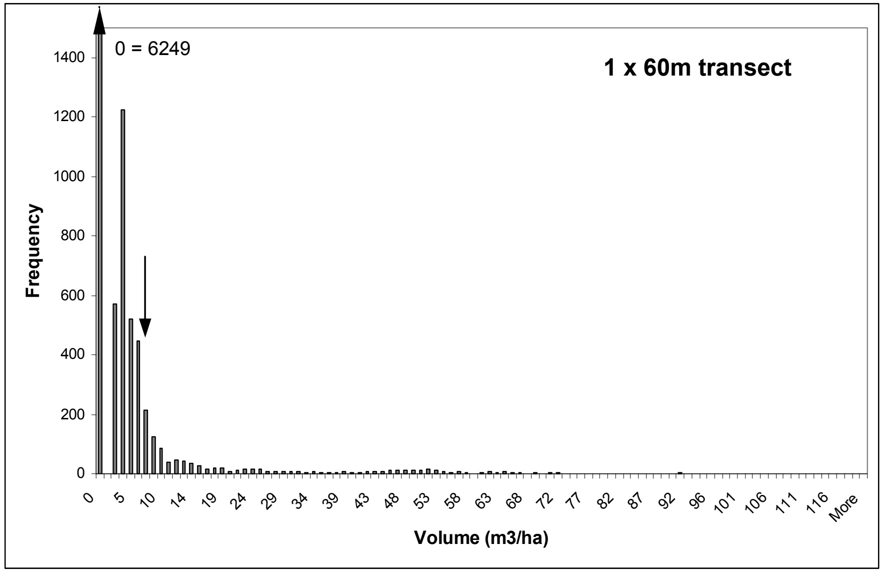




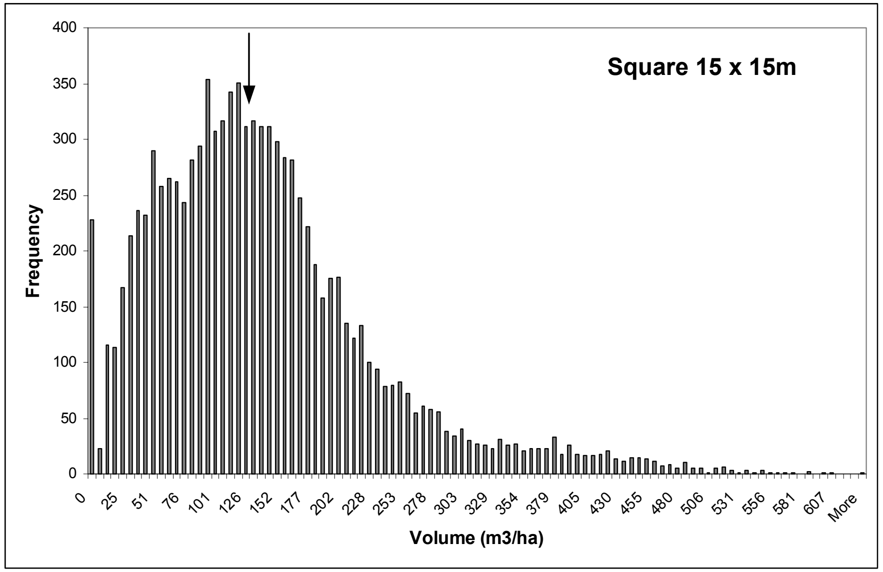
E. Equal sampling efforts using transect lengths of 60m, 30m, and 15m at plot TAS1 in the tall open forest - 10,000 replicates of 60m transect, 20,000 replicates of 30m transect, and 40,000 replicates of 15m transect. (NB Varying frequency scales)

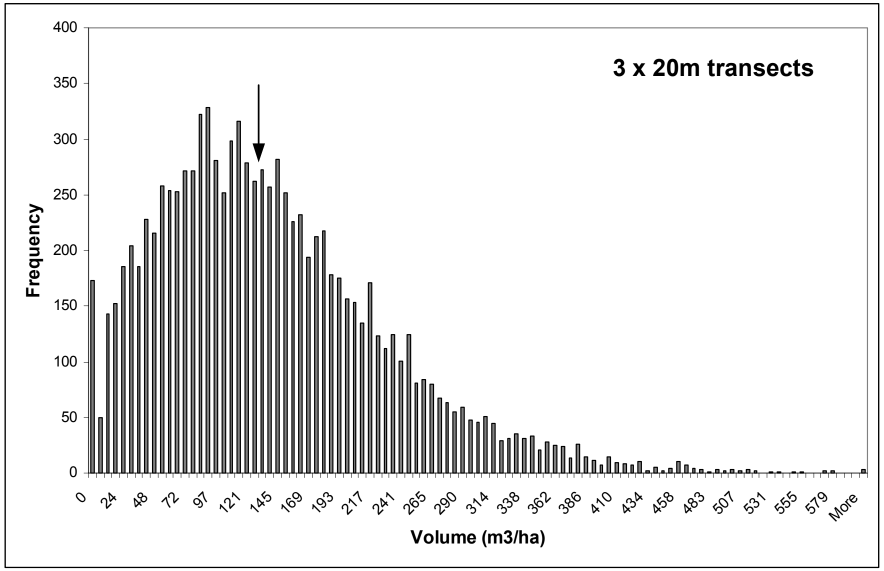


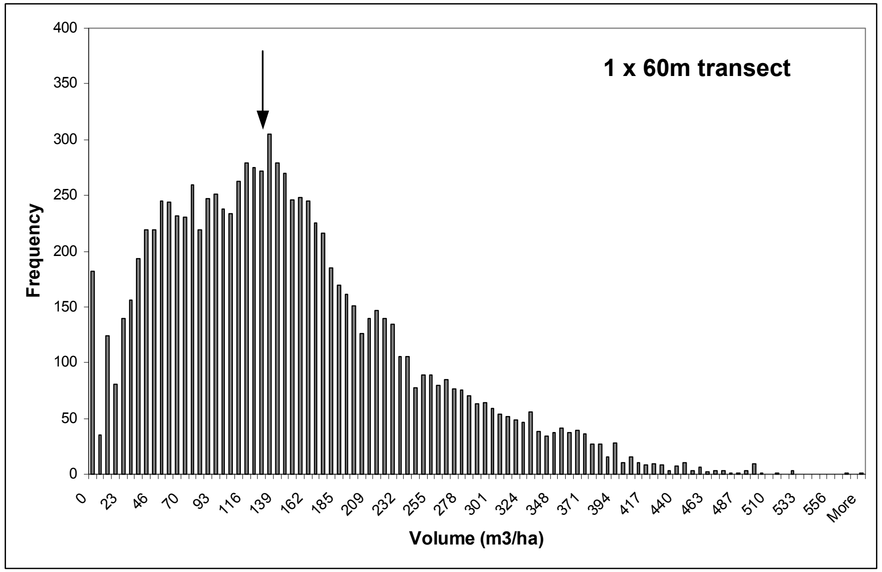




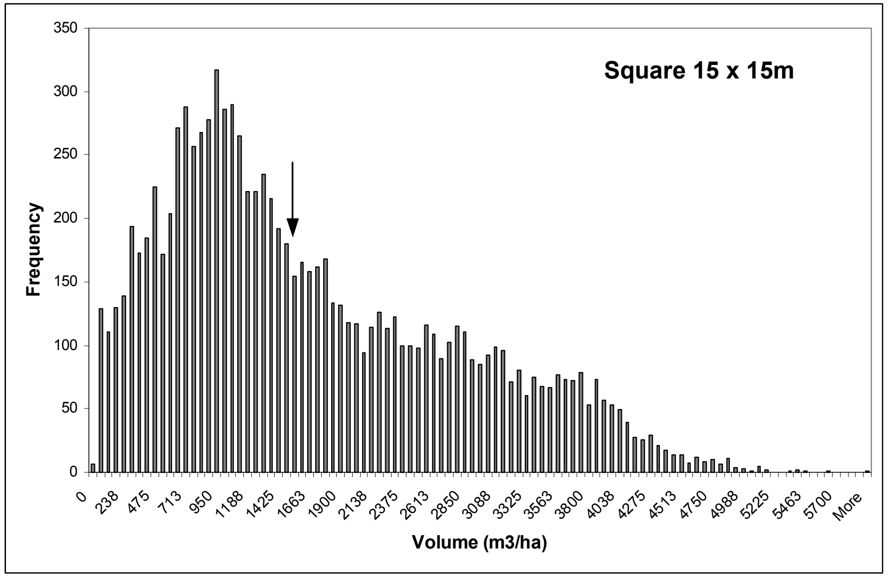
F. Layouts for a total transect length of 60m at plot QLD1 in the woodland using a square 15 x 15m, three transects 20m each, and a single 60m transect. (NB Frequency scales have been reduced)

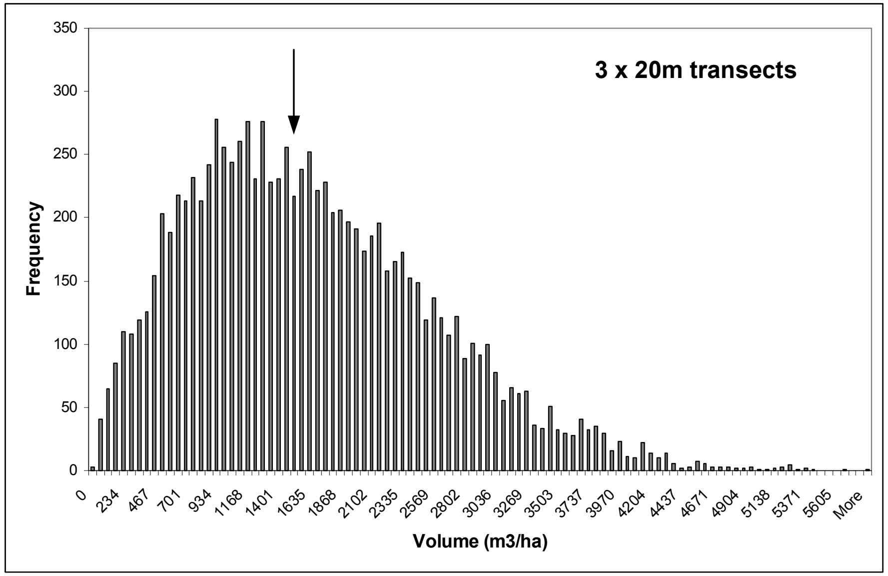


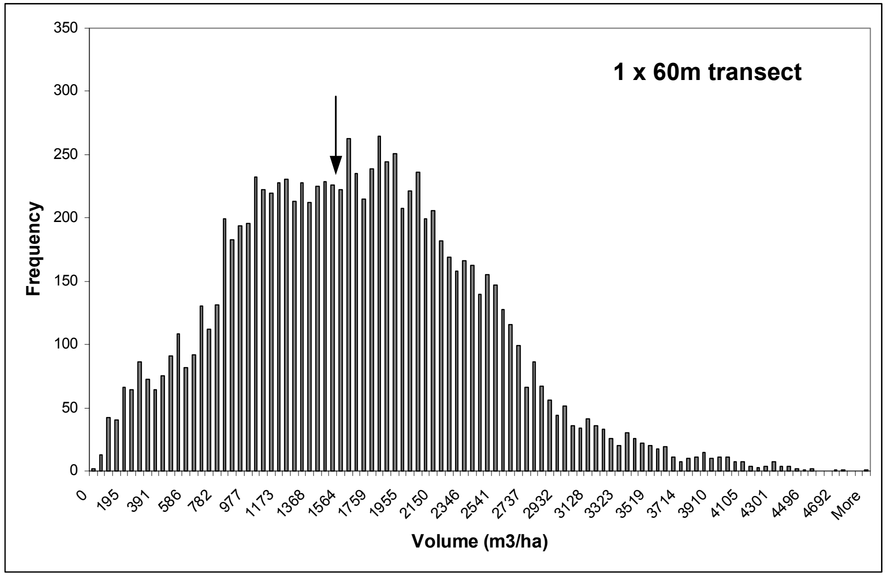




G. Layouts for a total transect length of 60m at plot NSW1 in the open forest using a square 15 x 15m, three transects 20m each, and a single 60m transect.







H. Layouts for a total transect length of 60m at plot TAS1 in the tall open forest using a square 15 x 15m, three transects 20m each, and a single 60m transect.