Effects of variable retention harvesting on productivity and growth in wet eucalypt forests

by

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Declaration of Originality

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Statement of Co-Authorship

The following people and institutions contributed to the publication of work undertaken as part of this thesis:

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Paper 2, Short-term effects of firebreaks on seedling growth, nutrient concentrations and soil strength in southern Australian wet eucalypt forests.

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Paper 3, Early regeneration results following aggregated retention harvesting of wet eucalypt forests in Tasmania, Australia.

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Abstract

Society's changing expectations for native forest management and an improved understanding of wet-forest ecology have led to the adoption of variable retention silviculture in Tasmania's old-growth wet eucalypt forests. Variable retention aims to maintain biodiversity and ecosystem function in managed forests by retaining patches of forest or individual trees. Retained areas are intended to provide continuity of structure and function, enhance landscape connectivity, and influence the regenerating forest. However, these ecological goals must be balanced against silvicultural considerations such as achieving successful regeneration and avoiding damage to retained trees.

This study is the first to assess regeneration success and related silvicultural outcomes after operational variable retention harvesting in wet eucalypt forests, and to compare these to outcomes after conventional clearfell, burn and sow harvesting. A total of 38 aggregated retention (ARN) coupes and 31 paired clearfell, burn and sow (CBS) coupes harvested from 2003 – 2009 and regenerated from 2007 – 2010 were monitored for up to three years to address questions concerning forest influence and retention levels, the persistence of aggregates, the effects of site preparation including new 'slow burning' methods, and early regeneration results.

Early silvicultural outcomes after operational ARN harvesting in old-growth wet eucalypt forests were generally satisfactory, and compared favourably with outcomes after conventional CBS harvesting. There were no differences in eucalypt seedling stocking, density or height between ARN and CBS coupes at one year of age. At three years of age, seedling density and height did not vary with silvicultural system, and stocking was only 5% lower in ARN coupes when two outliers were removed. This early regeneration success in the

ARN coupes is attributed to the high proportion of burnt seedbed achieved in the regeneration burns on these coupes, the adoption of aerial sowing as a standard operating procedure, and the absence of any increase in browsing pressure or edge-related growth suppression. Seedling height and density were strongly related to the state of the seedbed, and increased with increasing burn intensity, confirming that the creation of burnt seedbed is essential for good early regeneration in wet eucalypt forests. The higher perimeter-to-area ratio of ARN coupes resulted in a higher proportion of the harvested area being affected by firebreaks, although this decreased in more recently harvested openings due to changes in coupe design. Soil disturbance and compaction associated with firebreaks were found to affect soil physical and chemical properties and to reduce eucalypt seedling height growth by 40-60%. To reduce soil disturbance and potential impacts on regeneration, it is recommended that firebreaks be established only where absolutely necessary, and firebreak widths be minimised wherever possible.

Windthrow and harvesting damage were not significantly increased by ARN harvesting, but 2.5 times as much unharvested forest was affected by the regeneration burn in ARN coupes compared to CBS coupes, due largely to burning in the retained aggregates. It is recommended that island aggregates be at least 1 ha in size to avoid excessive burn damage and reduce windthrow risk. The longer-term effects of ARN harvesting on eucalypt productivity remain unknown, and more detailed examination of edge effects is required, but these early results indicate that initial silvicultural goals for regeneration can be met after variable retention harvesting in wet eucalypt forests.

Keywords: Australia, *Eucalyptus*, regeneration, silvicultural systems, variable retention, firebreak, seedbed.

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Chapter 1. Introduction

1.1. Wet eucalypt forest ecology

Wet eucalypt forests are highly productive forests characterised by a tall open eucalypt canopy over a dense understorey layer of shrubs and small trees (Wells and Hickey, 1999). These forests are distributed throughout temperate Australia, occurring where the average annual rainfall is >1000 mm and temperatures are high enough to allow tree growth, and cover over 800,000 ha in Tasmania alone (Forestry Tasmania, 2010a). Wildfire is the major natural disturbance agent in wet eucalypt forests (Gilbert, 1959; Ashton, 1976; Attiwill, 1994). Where fire return intervals are relatively short (from 20 to 100 years), wet sclerophyll forest with an understorey of tall shrubs develops. At longer fire return intervals (100 to 350 years), rainforest species begin to establish in the understorey, resulting in a mixed forest (Ashton, 1981). The dense understorey and deep litter layer that develops in wet eucalypt forests excludes light, preventing natural regeneration of eucalypts unless considerable disturbance takes place (Attiwill, 1994). If fire is excluded for long enough (> 500 years), the eucalypts will die out, leaving a rainforest (Wood *et al.*, 2010).

Natural regeneration of eucalypts in these forests usually follows infrequent but intense wildfires that remove the understorey and litter layer, expose a mineral soil seedbed, increase short-term nutrient availability, induce heavy seedfall from the standing trees and reduce the number of seed-eating insects (Gilbert, 1959). Early attempts at timber management in wet eucalypt forests failed to achieve consistently good regeneration until the 1960s, when clearfelling followed by a high-intensity regeneration burn and aerial sowing was introduced (Hickey and Wilkinson, 1999). This set of practices, formalized as the clearfell, burn and sow or CBS silvicultural system, reduces the high fuel loads that exist following harvesting in wet eucalypt forests (Marsden-Smedley and Slijepcevic, 2001), creates receptive seedbed over most of the harvested area (Gilbert, 1959; Cunningham, 1960), and usually results in abundant and fast-growing eucalypt regeneration (Lockett and Candy, 1984; King *et al.*, 1993a; Neyland *et al.*, 2009b). Clearfelling (also known as clearcutting) is an even-aged silvicultural system that involves the removal of all or nearly all trees from a given area in a single operation (Smith *et al.*, 1997). The minimum area which must be cleared in order to count as a clearfell has been defined on an ecological basis as an opening at least four tree heights across (Bradshaw, 1992; Keenan and Kimmins, 1993). Although clearfelling is a relatively safe, efficient and cost-effective means of harvesting wet eucalypt forests (Mitchell, 1993; Nyvold *et al.*, 2005), social acceptability of this silvicultural system has been and remains low, particularly when it is used in old-growth forests (Public Land Use Commission, 1996; Ford *et al.*, 2009a).

There are approximately 1.2 million ha of old-growth forests in Tasmania, of which 79% are reserved (Forestry Tasmania, 2011a). Less than 1000 ha of old-growth forest have been clearfelled annually in the past five years, with 340 ha of old-growth clearfelled in 2010/11 (Forestry Tasmania, 2011a). In wet eucalypt forests, clearfell, burn and sow silviculture is normally applied to areas of about 50 ha ('coupes'), and planned on a 90 year rotation (Whiteley, 1999). The use of CBS silviculture in these forests has raised concerns about aesthetics and impacts on biodiversity, including the possible decline of rainforest species (Lindenmayer and Franklin, 1997; Hickey *et al.*, 2001). Research has demonstrated that high-intensity stand-replacing fires resulting in even-aged regeneration are less widespread in these forests than first believed. Instead, many old-growth wet eucalypt forests are multi-aged as a result of trees surviving through one or more fires (McCarthy *et al.*, 1999; Lindenmayer *et al.*, 2000; Turner *et al.*, 2009). Thus, social pressures against clearfelling in old-growth forests and increasing understanding of wet eucalypt forest ecology led to a search for viable alternative silvicultural systems. This was recognised in the 1997 Tasmanian Regional Forest Agreement, which placed a high priority on research into alternative techniques for harvesting and regenerating wet eucalypt forests (Commonwealth of Australia and State of Tasmania, 1997).

1.2. Alternatives to clearfelling

The search for alternatives to clearfelling in Tasmania has mirrored similar events in North America, South America and Europe (Clayoquot Sound Scientific Panel, 1995; Franklin *et al.*, 1997; Fries *et al.*, 1997; Aubry *et al.*, 1999; Martinez Pastur *et al.*, 2009). In the 1990s, a number of silvicultural systems trials were established in Australia and elsewhere to identify alternatives to clearfelling for different forest types (e.g., Squire, 1990; Arnott and Beese, 1997; Aubry *et al.*, 1999). In Tasmania, the Warra Silvicultural Systems Trial was established beginning in 1998 to test alternatives to clearfelling in tall wet eucalypt forests (Hickey *et al.*, 2001). Two replicates of six different treatments were established, including clearfell, burn and sow with understorey islands, aggregated retention, dispersed retention, single tree/small group selection, a patchfell and a stripfell. Comprehensive evaluations of the ecological, social, economic and silvicultural performance of the trial were undertaken and early results were summarised in 2004 in a series of reports (Forestry Tasmania, 2004a, b, c, d, e). In 2005, the Tasmanian government committed to using non-clearfell methods in a minimum of 80% of the annual old-growth harvest area in State forests by 2010 (Commonwealth of Australia and State of Tasmania, 2005). Based on early results from the Warra Silvicultural Systems Trial, variable retention harvesting using aggregated retention systems (ARN) was chosen as the most feasible alternative to clearfelling in old-growth wet eucalypt forests (Forestry Tasmania, 2005b; Neyland *et al.*, 2012).

Variable retention is an approach to silviculture in which part of the original forest is retained after harvesting and through the next rotation to preserve old-growth species and structures, improve landscape connectivity and decrease the time required for late-successional species to re-establish in harvested areas (Clayoquot Sound Scientific Panel, 1995; Franklin *et al.*, 1997). Retention can be left as dispersed single trees or small clumps of trees, or as patches (aggregates) of undisturbed forest. A mixture of dispersed and aggregated retention may also be used. By retaining some old-growth species and structures at the site level, variable retention seeks to maintain old-growth attributes that could be permanently lost if the forest was harvested under successive clearfell rotations. Variable retention (VR) is a flexible model for forest management, which can be adapted for different forest types and natural disturbance regimes and is now being used in many countries around the world (Gustafsson *et al.*, 2012). In Tasmanian tall wet eucalypt forests, safety issues around the retention of dispersed trees and the use of high-intensity prescribed fire to reduce fuel loads and prepare a seedbed for sowing limits the practical application of VR to aggregated retention (ARN) (Neyland *et al.*, 2012).

1.3. Goals and guidelines for Tasmanian VR

Forestry Tasmania's goals and guidelines for variable retention have evolved as harvesting has moved from an experimental to an operational context. Experimental ARN prescriptions called for retention of 20% of the coupe area in aggregates of at least 0.5 ha (Neyland, 2010). Operational ARN coupes contain fewer, larger aggregates (of at least one hectare) and more edge aggregates that are contiguous with standing forest outside of the coupe (Figure 1-1).

Figure 1-1. A timeline of ARN harvesting showing changes in coupe design. From left to right: one of the experimental ARN coupes at the Warra Silvicultural Systems Trial, an early operational ARN coupe harvested in 2005, and a more recent ARN coupe harvested in 2009. White lines indicate the coupe boundary.

Variable retention silviculture using ARN was implemented operationally in Tasmania beginning in 2005 (Forestry Tasmania, 2005b). In 2007, a set of draft goals and guidelines for variable retention harvesting in old-growth wet eucalypt forests was developed (Baker and Read, 2011; Scott et al., 2011)(Appendix 1). Variable retention, as practised in Tasmania, aims to better emulate natural ecological processes in tall old-growth forests by retaining late-successional species and structures important for biodiversity, and by maintaining a forest influence over the majority of the harvested area for the next rotation (Baker and Read, 2011; Scott *et al.*, 2011).

Forest influence refers to the biophysical effects of the forest stand (or individual trees) on the surrounding environment (Keenan and Kimmins, 1993). To distinguish ARN harvesting ecologically from clearfelling, Forestry Tasmania uses a ‘forest influence’ target, which requires at least half of the harvested area to be within one tree length of standing forest that is retained for the next rotation (Keenan and Kimmins, 1993; Mitchell and Beese, 2002; Baker and Read, 2011). Forest influence is provided by areas of standing trees within or adjacent to the harvested area, which can be either retained aggregates, informal reserves that were excluded from harvesting, or existing formal reserves. In some instances, the area of formal and informal reserves alone may be enough to allow the goals of variable retention to be met (Scott *et al.*, 2011). Where extra retention within the coupe is needed, it can be left either as island aggregates (isolated patches of trees) or as edge aggregates, which are contiguous with standing forest outside of the coupe. Aggregates are intended to broadly include the range of habitat types in the coupe, but should be anchored on sites of specific ecological value where these are present (Baker *et al.*, 2009; Scott *et al.*, 2011). It is recommended that most aggregates should be at least 1 ha in size to ensure that they are able to survive the regeneration burn (Chuter, 2007; Scott *et al.*, 2011). Other goals for variable retention in Tasmania include ensuring safety of forest operations, and establishing adequate and productive regeneration of both eucalypts and other species. As of December 2011, over 50 ARN coupes had been harvested and regenerated across Tasmania.

1.4. Silvicultural implications

The ultimate goal of variable retention silviculture is to sustain the yield of ecological, social and production values in the managed forest landscape (Gustafsson *et al.*, 2012; Lindenmayer *et al.*, 2012). Although the ecological basis for variable retention is clear and supported by an ever-increasing body of scientific evidence (Rosenvald and Lõhmus, 2008; Gustafsson *et al.*, 2010), and social acceptability of variable retention harvesting is generally greater than for clearfelling (Ribe, 1999; Tönnes *et al.*, 2004; Ford *et al.*, 2009a), the implications for forest productivity and timber production are only beginning to be understood, particularly in wet eucalypt forests.

Variable retention harvesting is expected to decrease timber production per unit area when compared to clearfelling, due both to the foregone timber contained in retained trees and to the suppressive effects of those trees on the regenerating forest (Forestry Tasmania, 2004c). Some proportion of the stand remains unharvested in variable retention coupes, which either results in a loss of productivity over the land-base, or requires more coupes to be harvested to maintain the same level of production. A simple method to account for yield losses is to discount future production by an amount proportional to the retained basal area (Zielke *et al.*, 2008). However, this does not account for the suppressive effects of the retained trees on regeneration in adjacent areas or possible growth responses in the retained trees themselves. The impact of retained trees on growth of eucalypt regeneration can be significant (Bradshaw, 1992; Bassett and White, 2001), particularly where openings are small (Faunt *et al.*, 2006; Wang *et al.*, 2008; Kinny *et al.*, 2012). Forestry Tasmania estimated that yield in variable retention coupes would be reduced by 20-30% with regeneration growth rates reduced by a further 10%, assuming a target retention level of 20-30% (Forestry Tasmania, 2004a).

The persistence, health and growth of the retained trees in variable retention coupes are also of interest. Retained trees are intended to provide benefits through the next rotation, but may be at greater risk of damage due to harvesting, windthrow and the regeneration burn (Neyland, 2004; Scott and Mitchell, 2005; Gibbons et al., 2008; Steventon, 2011; Lavoie et al., 2012). These disturbance processes may affect overall stand health, and may compromise some of the intended functions of the retained trees. Other functions, such as provision and recruitment of coarse woody debris, will still be achieved or may even be enhanced.

Successful establishment and growth of regenerating trees is a key measure of the success of any silvicultural system and an important criterion for sustainable forest management (Smith *et al.*, 1997). In Tasmanian wet eucalypt forests, unlike most other forest types where VR is practised, regeneration is achieved through prescribed high-intensity fire, which is followed by aerial seed application. In a conventional clearfell, a mineral earth firebreak is cleared around the edges of the coupe, and a helicopter-mounted drip-torch is used to light the central portions of the coupe first, followed by the edges. The convection column thus formed helps to draw the fire away from the forested edges, reducing the risk of escapes (Forestry Tasmania, 2005a). Coupe shapes with regular edges and low perimeter-to-area ratios are preferred for this type of burning (Forest Practices Board, 2000; Forestry Tasmania, 2005a). The complex designs used in aggregated retention harvesting make conventional high-intensity burning difficult, and have required the development of new burning methods (Chuter, 2007). 'Slow burning' methods aim to minimise convection and rely on reduced lighting intensity and a slow spread of the fire through a relatively dry fuelbed to ensure that most fine fuels are still consumed (Chuter, 2007). These methods may therefore result in less burnt seedbed and less intensely-burnt seedbed than are achieved following a conventional high-intensity burn, leading to reduced eucalypt seedling growth and establishment (Neyland *et al.*, 2009b).

Other potential effects relate to the increased amount of edge associated with variable retention harvesting. ARN harvesting may increase negative impacts on the soil due to more constrained harvesting patterns, and the practice of putting firebreaks and access tracks around coupe edges and aggregates (Forest Practices Board, 2000). Higher perimeter-to-area ratios may also lead to increased browsing pressure in ARN coupes when compared to clearfells (Mount, 1976).

Given the increased use of variable retention harvesting in Tasmania and elsewhere, there is a need to address basic silvicultural questions about this type of harvesting. This thesis addresses a number of these questions by comparing operational and silvicultural outcomes in ARN coupes established in old-growth wet eucalypt forests with outcomes in conventional CBS coupes established in the same forest type.

1.5. Research questions and thesis outline

The main questions addressed by this thesis are as follows:

1. How do retention and influence levels in aggregated retention (ARN) coupes compare to those harvested using conventional clearfell, burn and sow (CBS) methods? Did Forestry Tasmania meet its retention and influence objectives for ARN?
2. How well do retained aggregates persist? To what extent are they affected by windthrow, harvesting damage or the regeneration burn?
3. How well do new burning methods developed for ARN work? How does ARN harvesting and associated site preparation affect the soil and the proportion of burnt and disturbed seedbed compared to CBS?
4. How well do ARN coupes regenerate compared to CBS coupes, and what impact do the changes associated with this kind of harvesting have in the short-term on regeneration?

This thesis consists of seven chapters, including this one, which provides the general introduction. Chapter 2 reviews the concepts of forest influence and retention that underpin the variable retention silviculture system and examines whether Forestry Tasmania's VR harvesting has met its objectives for retention and influence. Chapter 3 examines the effect of variable retention harvesting on windthrow and harvesting damage and compares this to outcomes after clearfell harvesting. Chapter 4 describes new burning methods developed for areas harvested using variable retention, and compares burning outcomes in ARN and CBS coupes. Chapter 5 quantifies the short-term (2 year) effects of firebreak construction on seedling growth and soil characteristics in both ARN and CBS coupes, and Chapter 6 compares short-term (3 year) regeneration responses in ARN coupes to those achieved after clearfelling. Chapter 7 provides a synthesis of the results of the preceding chapters, discusses the implications of these findings for forest management, and makes recommendations regarding areas for future study and research.

Chapters 4 and 5 have been published previously as journal articles, while chapter 6 has been submitted for publication; for this reason there is some repetition of information in the introduction and methods sections.

Chapter 2. Retention and forest influence

2.1. Introduction

The variable retention approach was intended to encompass the entire range of retention levels from 0 to 100% (Clayoquot Sound Scientific Panel, 1995; Franklin et al., 1997); however, public pressure against clearfelling and a desire for clarity in describing new silvicultural systems resulted in a need to distinguish VR silvicultural systems from conventional clearfells (Mitchell and Beese, 2002). The concept of forest influence provides an ecological rationale for separating the two systems (Mitchell and Beese, 2002; Zielke and Beese, 2002). Forest or residual tree influence includes the biophysical effects of the forest or individual trees on the surrounding environment (Keenan and Kimmins, 1993). These include effects on microclimate, light availability, seed and litter-fall and evapotranspiration, among other things. The distance forest influence extends will vary with the type of influence being considered and with the type of forest retained; however, most types of influence begin to decrease at a distance of about one tree height from the retained tree or trees (Figure 2-1) (Keenan and Kimmins, 1993). One co-dominant tree height has therefore been adopted as a practical value for calculating forest influence over harvested areas (Mitchell and Beese, 2002; Beese *et al.*, 2003). A clearfell has been defined as an area from which all of the trees and most of the forest influence has been removed (Bradshaw, 1992; Kimmins, 1997). Therefore, to qualify as a non-clearfell approach, variable retention coupes need to be planned with enough retention to maintain forest influence over the majority (> 50%) of the harvested area.

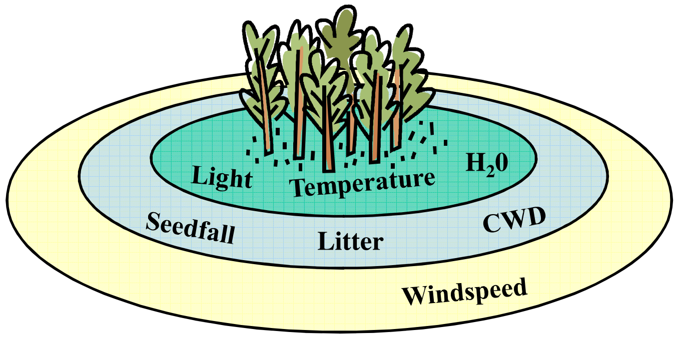


Figure 2-1. A retained patch of trees influences various ecological processes within the surrounding harvested area. This influence extends to different distances depending on the process. Not to scale. Adapted from Scott *et al.*, 2011.

A set of draft goals and guidelines for Tasmanian variable retention was developed in 2007 (Forestry Tasmania, 2009a). Two of the key goals for VR in wet eucalypt forests are: 1) to better emulate natural ecological processes by retaining old-growth species and structures over the long-term, and 2) to maintain forest influence over the majority of the harvested area. To achieve these goals, Forestry Tasmania relies on guidelines for opening width and visual quality and a GIS-based planning tool which is used to calculate forest influence levels for each coupe (Scott *et al.*, 2011). Forest influence is provided by areas of standing trees within or adjacent to the harvested area, which can be either retained aggregates, informal reserves that were excluded from harvesting, or existing formal reserves. To be counted as providing forest influence, these areas must consist of native forest at least 15 m tall and must also remain unharvested for the next rotation (Scott *et al.*, 2011). Under Forestry Tasmania's mapping system, areas of forest intended to provide influence for VR coupes (including aggregates) must be designated as Special Management Zones. This designation (Flora-Variable Retention or FLVR) ensures that the areas will be retained for the next rotation. Although FLVR zoning is applied to areas both within and outside of ARN coupes, only those areas inside the coupe boundary that would otherwise have been harvested are considered to be VR-specific 'retention'. Areas of FLVR outside of the coupe will be referred to in the remainder of this thesis as forest providing influence outside of the coupe (FPIoc).

Although other regions have employed minimum retention levels for variable retention harvesting (Clayoquot Sound Scientific Panel, 1995; Tuchmann, 1996; Beese *et al.*, 2003), Forestry Tasmania relies solely on the influence requirement to ensure that sufficient biological legacies are retained and that retention is well-distributed. Tasmania has among the highest levels of forest reservation in the world, with 47% of its native forests formally reserved. Of the remaining productive forest land that is available for harvesting, up to 25% is typically placed in informal reserves and not harvested due to unfavourable topography, low timber value or other constraints (Forestry Tasmania, 2009a). In some instances, these formal and informal reserved areas may allow the goals of variable retention to be met with no need for additional retention. Where extra retention within the coupe is needed, it can be left either as island aggregates (isolated patches of trees) or as edge aggregates, which are contiguous with standing forest outside of the coupe. Aggregates are intended to broadly include the range of habitat types in the coupe, but should be anchored on sites of specific ecological value where these are present and not be disproportionately located on sites of lower timber volume or productivity (Baker *et al.*, 2009; Scott *et al.*, 2011).

Implementing variable retention silviculture in Tasmania has been an adaptive process. Early ARN guidelines called for 0.5 ha aggregates and 100% forest influence, but this led to excessive levels of soil disturbance from firebreaks and resulted in coupes that were difficult to burn (see Chapter 4). Current guidelines call for most aggregates to be at least 1 ha in size and for greater use of edge aggregates (Scott *et al.*, 2011). Planned influence levels must be reported in the forest practices plan for each coupe, along with a map of intended aggregate locations and sizes. Each year, a formal quality standards review is undertaken to determine whether ARN coupes have met the 50% influence target (Forestry Tasmania, 2011b). An informal but more thorough review of a number of performance measures was also undertaken after the first several years of ARN harvesting (Baker *et al.*, 2009). As of December 2011, over 50 aggregated retention coupes had been harvested and regenerated in wet eucalypt forest around Tasmania. In 2007 a monitoring program was begun to quantify retention and influence levels in operational ARN coupes, to compare planned outcomes to actual outcomes, and to allow comparisons between the ARN and CBS silvicultural systems.

2.1.1. Research questions

This chapter examines the following questions:

1. Did aggregated retention coupes meet Forestry Tasmania's goals for influence and structural retention immediately after harvest?
2. What was retained and where? Did this change over time?
3. Did planned influence and retention levels differ from those actually achieved after harvest?
4. How do retention and influence levels within ARN coupes relate to reservation in the surrounding landscape?
5. How do ARN coupes compare to clearfell, burn and sow coupes in terms of influence and retention levels?

2.2. Methods

2.2.1. Study area and sample population

Retention and influence levels were assessed in 38 ARN coupes harvested from 2004 – 2009 (burnt from 2007 – 2010), and in 31 paired clearfell, burn and sow (CBS) coupes (Figure 2-

2). Paired coupes were matched as closely as possible on the basis of proximity, size, soil type, aspect, forest type, and harvest year. However, there was some variation in all of these factors, and CBS pairs could not be found for some ARN coupes due to the limited number of coupes harvested in a given year. All coupes were located in mature wet eucalypt forest, or a mixture of regrowth and mature forest. Detailed information on coupe locations and characteristics can be found in Appendix 2.

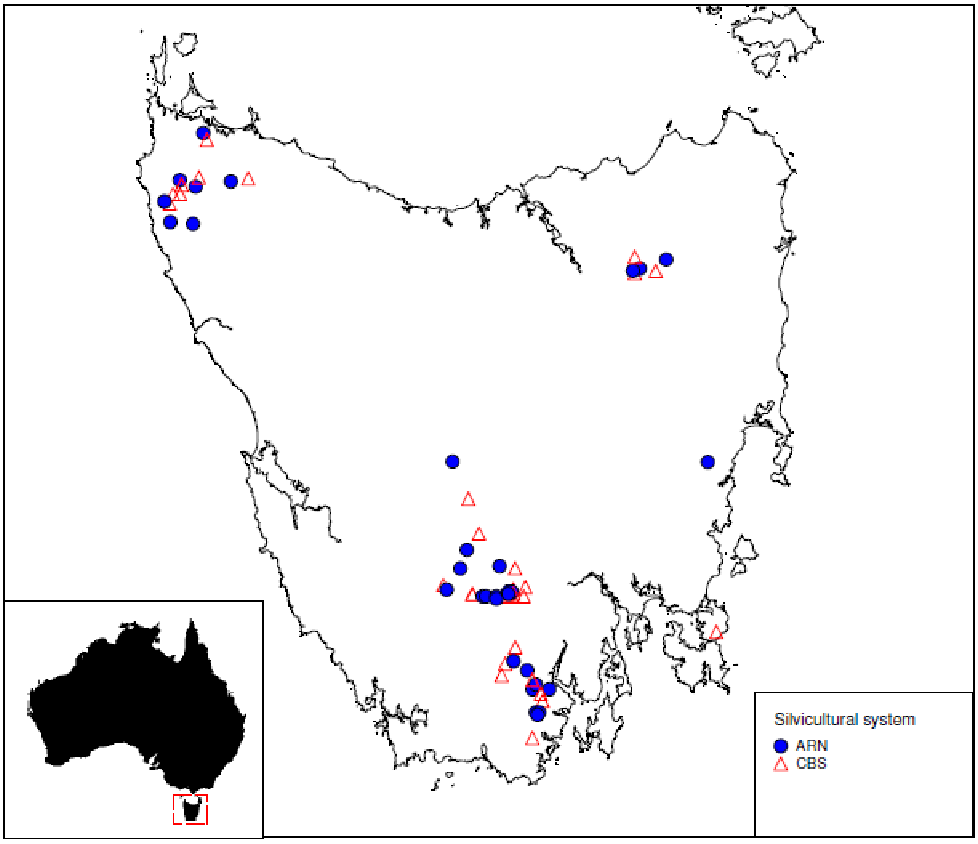


Figure 2-2. Map of Tasmania showing coupe locations by silvicultural system.

2.2.2. Mapping and derived variables

Following harvesting all coupes were mapped to a Geographic Information System (GIS) using either Global Positioning Systems or ortho-rectified aerial photos. Perimeter length (m), harvested area (ha), the number of aggregates in each coupe, and individual aggregate areas (ha) were obtained from the GIS. Perimeter-to-area ratios were calculated for each coupe by dividing the perimeter length (m) by the harvested area (ha). Retention includes all unharvested areas within the coupe that will remain unharvested for the next rotation. Retention level (%) was calculated for each coupe as:

$$\Sigma \text{ (aggregate area) / (harvested area + } \Sigma \text{ (aggregate area))*100}$$

The stand composition in and around each coupe was assessed using photo-interpreted (PI) stand types derived from high-resolution aerial photographs taken across Forestry Tasmania's forest estate (Stone, 1998). These PI types indicate the major and minor components of the pre-harvest forest stand (e.g., mature eucalypt, regrowth eucalypt, myrtle rainforest, scrub) and provide information about canopy cover and stand height (Stone, 1998). The distribution of different stand types was determined for the retained aggregates, the area of forest providing influence outside of the coupe and for the harvested area in each coupe.

Forest influence was calculated as the proportion of the harvested area within one tree height of native forest that will be retained over the next rotation (all FLVR including aggregates and FPIoc). The tree height used is based on the photo-interpreted stand types of the aggregates and the surrounding forest, and varies across the coupe as the stand type changes (Stone, 1998; Scott *et al.*, 2011). A software program (the VR calculator) was developed and used to calculate influence and retention levels in each coupe (Scott, 2008) (Figure 2-3a). Planned influence and planned retention levels were determined from Forest Practices Plan maps for each coupe showing areas intended for harvesting and as aggregates, while actual post-harvest influence and retention levels were determined based on aerial photos or GPS surveys of harvested and retained areas taken immediately after harvesting. These influence and retention calculations provide only a snapshot of the coupe at a particular moment in time, and do not account for any windthrow or burning damage that may have occurred within the aggregates after harvesting.

To place coupe-level retention into the context of the larger landscape around each coupe, a number of metrics were calculated for the area within a 1128 m radius (a 400 ha circle) of each ARN and CBS coupe. This spatial scale is appropriate for strategic-level conservation planning, and is equivalent to the area usually shown in a coupe planning map (Forestry Tasmania, 2011a). Values that were calculated include the total area of public forest, production forest, retained aggregates, forest providing influence (FPIoc) and formal and informal reserves within a 400 ha circle around each coupe (Figure 2-3b). In addition, the proportion of the area of public forest in the 400 ha area around each coupe that was retained in aggregates, in forest providing influence, and in formal and informal reserves was determined.

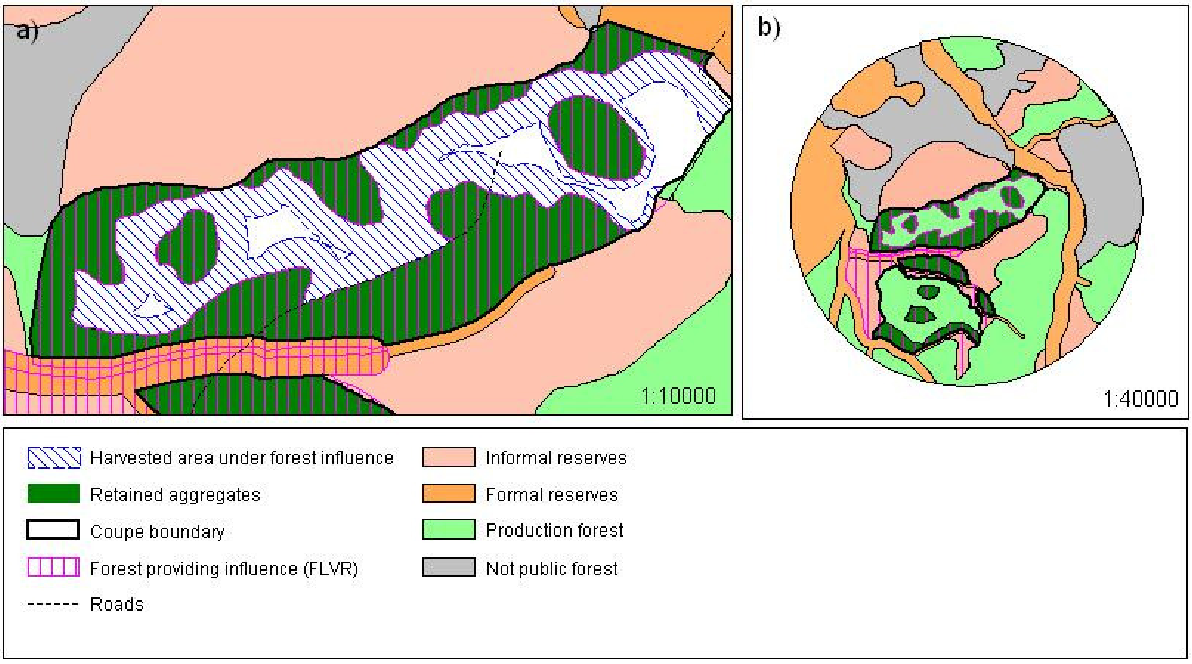


Figure 2-3. Example of the GIS map layers used to calculate a) retention and influence within an ARN coupe, and b) the area of formal and informal reserves, retained aggregates, forest providing influence (FLVR), production forest and non-public forest within a circle of 400 ha centred around a coupe.

2.2.3. Data analysis

Spearman correlations were used to examine relationships between variables while graphical analysis and the Shapiro-Wilks test were used to check for normal distributions. Paired t-tests or the Wilcoxon paired signed-ranks test were used to test differences between the ARN and CBS silvicultural systems, as well as to test differences between what planned and actual influence and retention levels in ARN coupes. Either one-way ANOVA or the non-parametric Kruskal-Wallis test was used to test for differences between years. Chi-squared tests were used to determine whether harvested areas, retained aggregates and areas of FPIoc were distributed independently of stand type.

2.3. Results

2.3.1. Did initial ARN coupes meet Forestry Tasmania's influence target?

Forest influence in the ARN coupes ranged from 36% to 96% immediately after harvesting, with an average influence level of 71% (SD = 14%, n = 38). Thirty-four of thirty-eight ARN coupes (89%) met the target of at least 50% forest influence (Figure 2-4a). Mean influence levels in ARN coupes decreased over time (from 81% in 2007 to 69% in 2010), although the change was not significant ($F_{3, 34} = 2.14$, $p = 0.11$).

a) b)

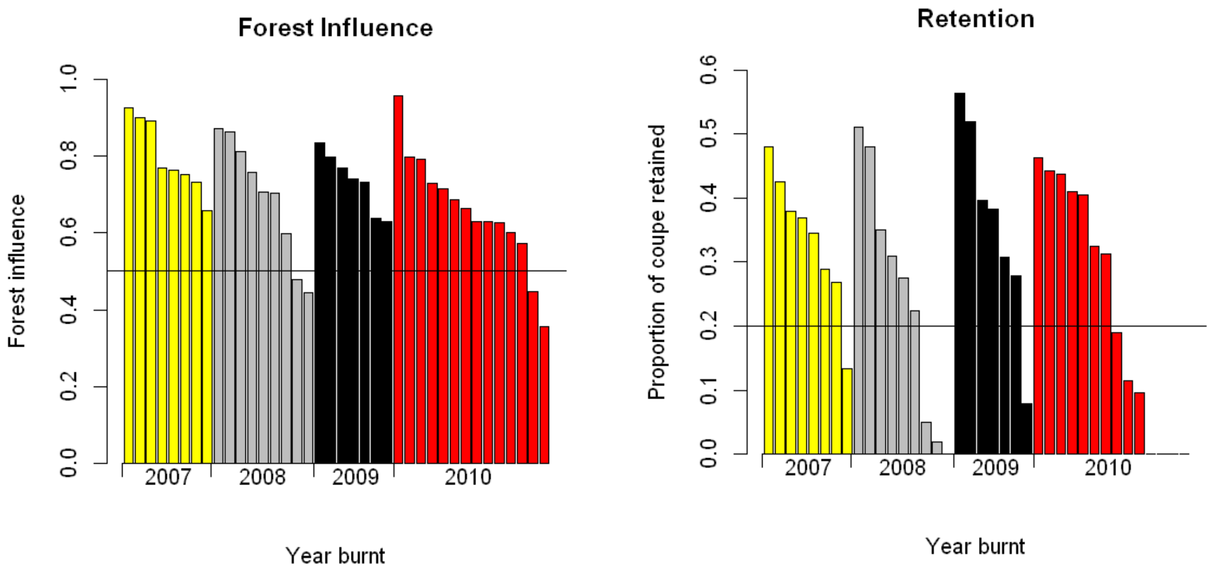


Figure 2-4. a) Forest influence and b) retention levels in ARN coupes by year burnt. Horizontal lines show a) the 50% influence target, and b) modelled retention levels of 20%.

2.3.2. Did planned influence and retention differ from actual?

There were differences between planned coupe configurations and what was actually harvested in ARN coupes, resulting in differences in planned and actual post-harvest influence levels. Actual influence levels immediately after harvesting were 12% higher than planned, on average (Table 2-1). In contrast, actual retention levels immediately after harvesting were very similar to what was planned, with a difference of only 1% (Table 2-1). Although the gap between planned and actual post-harvest influence decreased over time (from 16% in 2007 to 7% in 2010), the differences between years were not significant ($F_{3, 34} = 2.36$, $p = 0.09$).

Table 2-1. Mean difference in planned and actual influence and retention levels calculated immediately after harvest for ARN coupes. Planned and actual means are shown (standard deviation in brackets), as well as the mean difference (Actual - Planned). Tests used, test statistics, n and p-values are shown. Significant differences are shown in bold.

Variable	**Actual Mean (SD)**	**Planned Mean (SD)**	**Mean difference (SD)**	**Test used**	**Test-statistic**	**n**	***p*-value**
Forest influence	0.71 (0.14)	0.59 (0.12)	0.12 (0.10)	Paired t	7.6	38	**<.0001**
Retention	0.28 (0.17)	0.27 (0.27)	0.01 (0.18)	Wilcoxon	330	38	0.381

2.3.3. What was retained and where? Did this change over time?

The average area harvested within 38 ARN coupes was 22.2 ha (SD = 14.2). An average of 10.4 ha was retained in aggregates within each coupe, while an additional 14.2 ha outside of each coupe was designated as forest providing influence (FPIoc). A total of 193 aggregates were retained in 38 ARN coupes, or an average of 5.0 aggregates per coupe (SD = 3.6, n = 38). Forty percent of aggregates were edge aggregates, but these accounted for 60% of all retained area. Edge aggregates averaged 3.0 ha (SD = 3.5, n = 78) in size, while island aggregates were about half the size (mean = 1.4 ha, SD = 1.1, n = 115). Within coupe retention ranged from 0% to 56%, with an average of 28% (SD = 17%). One coupe burnt in 2008 and four coupes burnt in 2010 were planned and harvested with no internal retention (Figure 2-4b). The number of island aggregates retained decreased over time from 5.9 aggregates per coupe in 2007 to 1.6 in 2010

(Kruskal-Wallis $\chi^2 = 16.0$, df = 3, $p = 0.02$). There was also a shift in the size distribution of island aggregates over time (Figure 2-5). Mean island aggregate size increased from 1.1 ha in 2007 to 2.1 ha in 2010 (Kruskal-Wallis $\chi^2 = 15.9$, df = 3, $p = 0.002$).

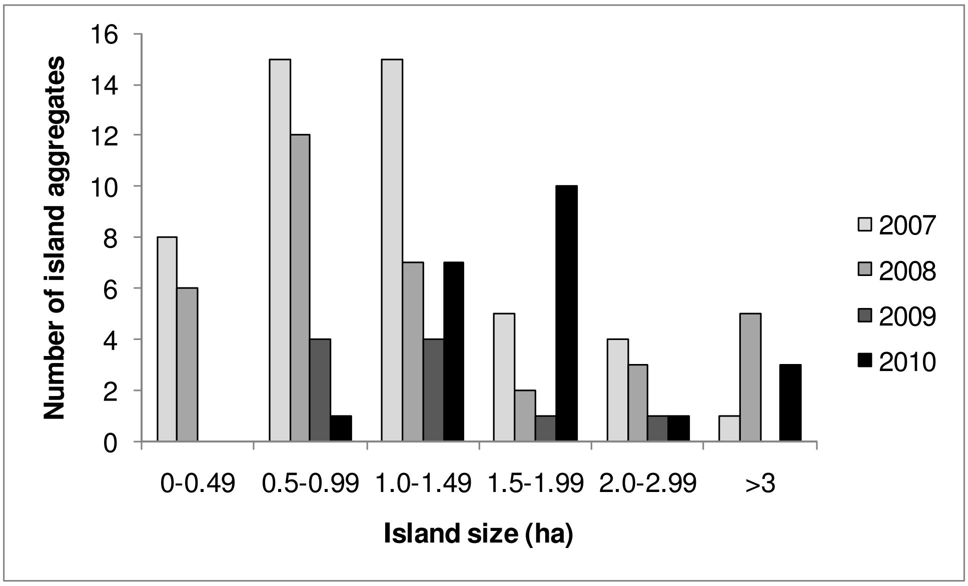


Figure 2-5. Distribution of aggregate size for 115 island aggregates retained in 38 ARN coupes burnt from 2007 to 2010.

The stand types retained in aggregates in ARN coupes were broadly similar to what was harvested (Figure 2-5, $\chi^2 = 7.5$, df = 4, $p = 0.113$). However, areas of forest providing influence outside of the coupe (FPIoc) contained a higher proportion of rainforest and a lower proportion of mature eucalypt forests than did the harvested areas ($\chi^2 = 102.3$, df = 4, $p < 0.0001$) or retained aggregates ($\chi^2 = 35.4$, df = 4, $p < 0.0001$). The composition of the retained aggregates was intermediate between that of the harvested area and that of the surrounding forest providing influence (Figure 2-6).

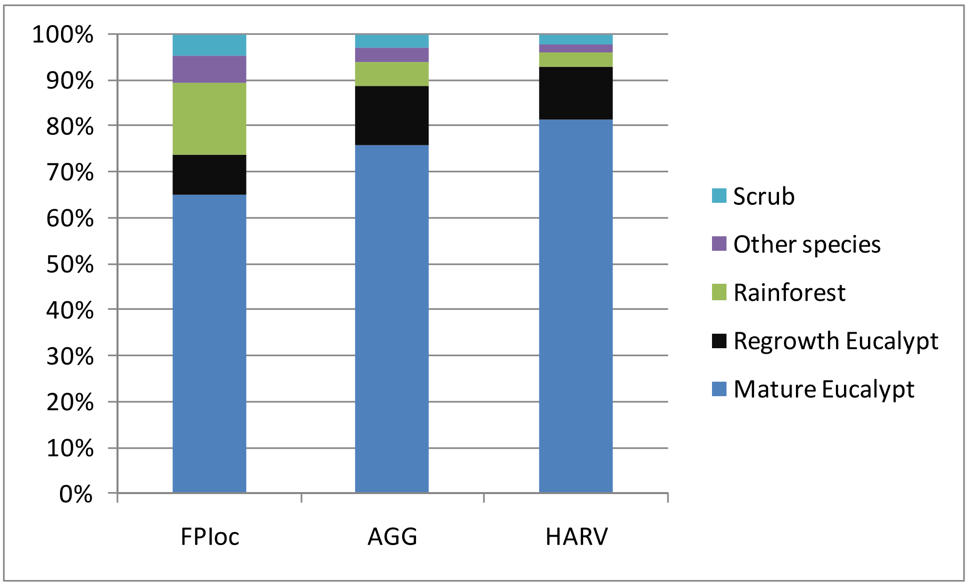


Figure 2-6. Distribution of stand types in areas of forest providing influence (FPIoc), retained areas (AGG) and harvested areas (HARV).

2.3.4. How do retention and influence levels within ARN coupes relate to reserves in the surrounding landscape?

On average, 85% of the 400 ha area around each ARN coupe consisted of public forest (i.e., 338 ha out of 400 ha) although this varied from a minimum of 40% to a maximum of 100%. Four percent of the public forest within a 400 ha circle around each coupe was retained in aggregates, and five percent was retained as forest providing influence (FPIoc). An additional 11% was retained in informal reserves, and 26% in formal reserves. Of the public forest in a 400 ha area around each ARN coupe, an average of 45% will not be harvested for at least the next rotation.

2.3.5. Differences between silvicultural systems

There were a number of differences in configuration between the two silvicultural systems at the coupe-level. Perimeter lengths were significantly higher in ARN coupes, while harvested areas were lower, leading to much higher perimeter-to-area ratios in ARN coupes (Table 2-2). Forest influence was 41% higher in ARN coupes than in paired CBS coupes, reflecting the high retention levels within the ARN coupes (Table 2-2).

Table 2-2. Mean difference in influence and retention variables for paired ARN and CBS coupes at two spatial scales. Means for each silvicultural system are shown (standard deviation in brackets), as well as the mean difference between the paired coupes (ARN – CBS). Tests used, test statistics, n and p-values are shown. Significant differences between the silvicultural systems are shown in bold.

Variable	**ARN mean (SD)**	**CBS mean (SD)**	**Mean difference (SD)**	**Test used**	**Test-statistic**	**n**	***p*-value**
Within each coupe							
Perimeter (m)	4642 (2257)	2836 (945)	1806 (1965)	Paired t	5.12	31	**<.0001**
Harvested area (ha)	20.7 (10.1)	28.5 (17.6)	-7.7 (17.1)	Paired t	-2.5	31	**0.0175**
Perimeter-to-area ratio	224 (59)	127 (60)	98 (86)	Wilcoxon	465	31	**<.0001**
Forest influence	0.73 (0.11)	0.33 (0.24)	0.41 (0.26)	Paired t	8.66	31	**<.0001**
Retention	0.30 (0.17)	0.00 (0.00)	0.30 (0.17)	Wilcoxon	378	31	**<.0001**
Within a 400 ha circle around each coupe							
Public forest (ha)	338 (62)	335 (59)	3.9 (71)	Paired t	0.30	31	0.7638
Aggregates (ha)	13 (10)	1 (2)	12.5 (10)	Paired t	7.14	31	**<.0001**
Forest providing influence (ha)	16 (12.4)	1 (2.4)	15.9 (12.7)	Wilcoxon	465	31	**<.0001**
Informal Reserves (ha)	36 (27)	37 (37)	-0.7 (40)	Paired t	-0.10	31	0.9217
Formal Reserves (ha)	88 (54)	81 (56)	7.1 (81)	Paired t	0.48	31	0.6306
Production forest (ha)	185 (63)	216 (71)	-30.8 (93)	Paired t	-1.84	31	0.0756

At larger spatial scales, there were fewer differences between the silvicultural systems, and most of these differences were related to within-coupe retention. Within a 400 ha area around the coupes, the amount of public forest, production forest and formal and informal reserves did not differ between ARN and CBS coupes (Table 2-2). At the 400 ha spatial scale there was significantly more area retained in aggregates and as forest providing influence around ARN coupes than around CBS coupes (a combined area of 29 ha out of 400 ha (7%) for ARN coupes, compared to only 2 ha out of 400 ha (0.5%) for CBS coupes).

2.4. Discussion

This chapter quantifies retention and influence levels immediately after variable retention harvesting in Tasmania, compares planned outcomes to actual post-harvest outcomes, and makes comparisons between aggregated retention (ARN) and conventional clearfell, burn and sow (CBS) silvicultural systems. Forestry Tasmania's goals for variable retention include maintaining forest influence over the majority of the harvested area in ARN coupes, and ensuring that they are ecologically different from clearfells. These results demonstrate that almost 90% of ARN coupes established over four years met the target of at least 50% influence after harvesting, which is a success rate similar to that experienced during the implementation of variable retention in coastal British Columbia (Bunnell *et al.*, 2009). Whether the same level of forest influence can be maintained throughout the rotation will depend on the persistence of the aggregates and the effects of damage due to wind, burning or harvesting (Chapters 3 and 4). Of the four ARN coupes which did not meet the influence target, all except one had at least 45% influence, which is considered to be an acceptable level in rare cases, so long as the other objectives for aggregated retention are met (Baker *et al.*, 2009). The coupe with the lowest influence levels (36%) did not meet Forestry Tasmania's quality standard for variable retention, largely because it was surrounded on all sides by production forest and not enough consideration was given to conditions in adjacent coupes during planning. In many cases, retention and forest providing influence can be shared between coupes, reducing the overall amount of retention needed (Scott *et al.*, 2011). Planning several coupes at the same time allows for more efficient coupe design.

The significant difference in the proportion of the harvested area under long-term forest influence between ARN and CBS coupes (41%) should ensure that the harvested areas in ARN coupes develop under different conditions to harvested areas in conventional clearfelled coupes. Recent research has shown that species richness and abundance of disturbance-sensitive birds, plants and beetles within 25-50 year old harvested areas is sensitive to the amount of mature wet eucalypt forest in the surrounding landscape (Wardlaw *et al.*, 2012). Threshold distances beyond which no influence of the mature forest on species richness could be detected varied from 150 m for disturbance-sensitive beetles, 400 m for dense forest birds, and 600 m for rainforest plants (Wardlaw *et al.*, 2012). The harvested areas of current ARN coupes, which are largely within one or two tree heights (50-100 m) of mature forest, should therefore maintain species-richness and abundances of these disturbance-sensitive guilds, well into the future.

A second key objective for variable retention is the retention of old-growth species and structures for the long-term. On average, 28% of the area of the coupes examined here was retained, while 45% of the area of the public forest within a 400 ha area around ARN coupes was retained for at least the next rotation. These results are based solely on area, and did not examine specific species or structures retained within the aggregates such as tree-ferns, hollow-bearing trees, or large pieces of coarse woody debris; however, the PI type analysis indicates that broadly the same stand types are being retained as are being harvested. The retention of habitat elements tends to increase proportionally with retention levels when aggregated retention is used (Huggard *et al.*, 2009), thus it is likely that many of the species and structures that were present before harvest have been retained. Biodiversity monitoring at the Warra Silvicultural Systems Trial and in eight early operational ARN coupes indicates that aggregates retained substantial numbers of mature and hollow-bearing trees, along with large numbers of regrowth eucalypts and rainforest species (Baker *et al.*, 2008; Forestry Tasmania, 2009a; Garandel *et al.*, 2009).

There were changes in variable retention coupe design over the course of this study. The number of island aggregates per coupe decreased over time, and the average size of island aggregates increased from ~ 1 ha to 2.1 ha. These changes were made largely to facilitate the use of prescribed fire and to reduce the risk of fire damage to the retained aggregates (Chuter, 2007). The guidelines provided to contractors and District staff regarding forest influence also changed. Initial guidelines recommended a target influence level of 60%; however, due to the large and consistent differences between planned and actual post-harvest influence, guidelines were changed and planners were encouraged to target the minimum level of 51% influence. Similar trends in retention and influence levels were reported following implementation of variable retention in British Columbia. Bunnell *et al.* (2009) found that mean aggregate size increased over time (although only from 0.8 to 1.0 ha), and that influence levels were well above the 50% minimum (68 - 79%). They noted that failure to meet the influence target was usually due to poor distribution of retention, rather than a lack of retention, which was also the case in this study. Adaptive management proved a useful means of identifying problems with coupe design and providing feedback to District staff, resulting in improvements in outcomes over time (Baker and Read, 2011).

Tasmania has high reservation and retention levels compared to most other temperate regions (Gustafsson *et al.*, 2012). These results show that this is particularly true of areas harvested using aggregated retention, despite that fact that no minimum retention level is currently required. The use of prescribed fire to regenerate ARN coupes and the desire to minimise burn damage to the aggregates for both aesthetic and ecological reasons has led to the use of relatively large aggregates and thus, high retention levels. This is combined with high levels of reservation in the wider 400 ha area around ARN coupes which reflects the current policy of applying VR in areas of old-growth forest. Additional retention in such well-reserved landscapes may have relatively low conservation value compared to additional retention in landscapes lacking in mature forest elements (Bunnell and Dunsworth, 2009). Planning for coupe-level retention within the context of landscape-level reserves may provide the best opportunity to meet conservation and native forest timber production goals into the future. Forestry Tasmania is developing an estate-wide long-term retention target as well as GIS-based landscape metrics to help identify the areas where variable retention silviculture will provide the greatest benefit (Forestry Tasmania, 2011a; Wardlaw *et al.*, 2012).

2.5. Conclusions

Monitoring of variable retention harvesting in Tasmania's old-growth wet eucalypt forests indicates that the two key goals of 1) maintaining forest influence over the majority of the harvested area and 2) retaining old-growth attributes, have largely been met, at least in the short-term. Almost 90% of aggregated retention (ARN) coupes established over a four year period met Forestry Tasmania's target of having at least 50% of the harvested area within one tree height of trees retained for the long-term (i.e., under forest influence). Forest influence was also significantly higher in ARN coupes (71%)

than in comparable clearfells (33%). This should ensure that the harvested areas in variable retention coupes develop under different conditions to those in clearfells, thus distinguishing them ecologically from conventionally harvested areas. On average, 28% of each ARN coupe was retained, making Tasmanian retention levels among the highest in the world. This is complemented by high levels of reservation around ARN coupes, due to the current policy of applying variable retention in old-growth wet eucalypt forests. A multi-scale approach is needed to better plan and quantify retention and reservation at various spatial scales, and coupe-level retention needs to be put into the context of the surrounding landscape if variable retention silviculture is to be applied most effectively.

Chapter 3. Windthrow and harvesting damage

3.1. Introduction

Trees and other stand elements are retained after variable retention harvesting to provide refuges for mature-forest species, increase structural complexity, allow faster re-colonisation of the regenerating stand and improve habitat connectivity (Franklin et al., 1997; Baker and Read, 2011; Gustafsson et al., 2012). The retained trees are intended to provide these benefits throughout the next rotation, but are susceptible to windthrow, harvesting damage and collapse (Neyland, 2004; Scott and Mitchell, 2005; Gibbons et al., 2008; Steventon, 2011; Lavoie et al., 2012). Although some of the objectives of retention can still be met following windthrow or physical damage (e.g., provision of coarse woody debris and wildlife habitat), other functions may be compromised by these disturbance processes (e.g., seedfall, aesthetics, stand health, understorey shading and residual tree growth).

Harvesting damage affects trees around the edges of harvested openings and is caused by machinery or other trees striking standing trees during falling or snigging operations. Wounds that expose the cambium layer allow decay fungi to invade, resulting in increased mortality rates, reduced growth and reduced timber value (Neumann et al., 1997; Vasiliauskas, 2001). Harvesting damage to residual trees has been shown to vary with the harvesting system and equipment used, as well as with tree species, tree size and proximity to snig tracks (Bettinger and Kellogg, 1993; Han and Kellogg, 1997; Vasiliauskas, 2001). Most damage occurs during transport of timber and is located near the base of the tree (Vasiliauskas, 2001). Crown damage is more prevalent after cable or helicopter logging (Han and Kellogg, 1997) but may also occur due to tree strikes during falling. Damage and scarring to the stem occurs when standing stems are struck by felled trees or by harvesting or snigging machinery. Damage rates can be high where dispersed trees are retained (Neyland, 2004) or following thinning operations in regrowth forests or plantations (White and Kile, 1991). Harvesting damage to trees around the edges of retained patches (aggregates) tends to be lower than when trees are dispersed (Moore et al., 2002), but few studies have directly compared damage following aggregated retention harvesting to that after clearfelling. The increased length of forest edge created in aggregated retention harvesting (Chapter 2) is likely to increase the number of trees that are exposed to harvesting damage, while the constrained harvesting patterns and the need to fall trees and manoeuvre machinery around aggregates may likewise increase damage rates.

Residual trees and edges created during harvesting are also susceptible to windthrow, defined as the snapping or uprooting of trees by wind (Stathers *et al.*, 1994). Windthrow has been shown to vary regionally, and to be affected by stand, neighbourhood and individual tree variables (Mitchell *et al.*, 2001; Scott, 2005; Lavoie *et al.*, 2012). In general, post-harvest mortality (including windthrow) tends to increase with increasing harvesting intensity and with greater dispersion of the residual trees (Maguire *et al.*, 2006; Thorpe and Thomas, 2007; Bladon *et al.*, 2008). Trees in aggregated retention coupes are less susceptible to windthrow than those in dispersed retention coupes, at least at retention levels below ~40% (Beese, 2001; Scott, 2005; Maguire *et al.*, 2006). The size, shape and location of aggregates can also affect windthrow risk. Smaller aggregates, riparian strips and aggregates in exposed topographic locations may be at greater risk of being windthrown (Burton, 2001; DeLong *et al.*, 2001; Rollerson *et al.*, 2009). Variable retention harvesting has been shown to increase windthrow levels over those in intact natural stands (Bladon *et al.*, 2008; Lavoie *et al.*, 2012) but may either decrease or increase windthrow when compared to clearfelling (Beese, 2001; Rollerson *et al.*, 2002). Where aggregated retention is used, the risk of windthrow relative to clearfelling may depend largely on differences in average opening size and fetch distance, as well as stand characteristics and site-specific environmental variables.

Variable retention harvesting using aggregated retention (ARN) has been used in Tasmania to harvest old-growth wet eucalypt forests since the mid-2000s. Neyland (2004; 2010) reported windthrow and damage levels in dispersed and aggregated treatments at the Warra Silvicultural Systems trial, but did not compare these to each other or to outcomes after clearfelling. In operational variable retention in Tasmania, relatively large aggregates (most > 1 ha) are retained within the harvested area over the next rotation to provide at least 50% forest influence (Scott *et al.*, 2011). Wood *et al.* (2008) reported that wind damage to merchantable eucalypts in ten early ARN coupes was generally low (< 1 stem windthrown per hectare felled), while the understorey was at greater risk of windthrow. Elsewhere in Australia, studies of post-harvest mortality among residual eucalypts have been limited to trees retained to provide habitat for hollow-dependent species (Whitford and Williams, 2001; Gibbons *et al.*, 2008; Parnaby *et al.*, 2010). These studies reported higher rates of fall in wet forests compared to dry forests, and that isolated trees, larger diameter trees and trees with fire-scarring were at greater risk of collapse.

In this study, all harvested stands were burnt following logging to reduce fuel loads and prepare a seedbed for aerially sown seed. Before burning, a mineral-earth firebreak was constructed around the perimeter of the harvested area using either a bulldozer or an excavator (Chapter 4). In forests regenerated via high-intensity fires, damage to and mortality of retained trees due to the regeneration burn can be significant (Neyland, 2010). When post-fire studies are undertaken it may be difficult to distinguish trees that have collapsed due to fire damage from those that have been windthrown, and fire damage may mask physical damage caused by harvesting. In this study, windthrow and harvesting damage (including damage due to firebreak construction) were examined before the regeneration burn. Damage due to burning was examined separately and is reported in Chapter 4.

The following questions were examined:

1. Does ARN silviculture lead to more windthrow than conventional clearfell, burn and sow (CBS) silviculture? (H0:Windthrow is independent of silvicultural system)
2. Does ARN silviculture increase harvesting damage compared to CBS? (H0: Harvesting damage is independent of silvicultural system)
3. Where on the tree does most damage occur?
4. Within ARN coupes, is there more windthrow in island aggregates compared to edge aggregates? Does windthrow in islands increase as patch size decreases? (H0: Windthrow risk within aggregates is independent of aggregate type and size)

3.2. Methods

3.2.1. Study area and sampling methods

Windthrow and harvesting damage were assessed in 54 harvested wet eucalypt stands (hereafter coupes) located in Tasmania, Australia. Of these, one aggregated retention (ARN) coupe and five clearfell, burn and sow (CBS) coupes were completely or partially cable-harvested, while all remaining coupes were harvested using ground-based machinery. Following harvesting, an excavator or bulldozer was used to clear a mineral-earth firebreak around the perimeter of the harvested area in most coupes. Coupes were sampled following harvesting and firebreak construction, but before the regeneration burn. A total of 36 ARN coupes were sampled, along with 18 paired CBS coupes (Table 3-1). This represents a subset of the full number of coupes available for sampling as windthrow and damage were only assessed in coupes that had firebreaks, and CBS coupes were not assessed in 2007 as CBS pairs had not yet been identified (Table 3-1). Windthrow and damage were assessed along all boundary edges within the coupe that had been tracked (i.e., those with firebreaks). In ARN coupes this included the edges of 93 retained island aggregates ranging in size from 0.2 to 7.5 ha (mean = 1.5, SD = 1.3). Boundary edges immediately adjacent to roads were not assessed to avoid the confounding effects of road-building. Coupes had been harvested (and therefore were exposed to wind) for an average of 7 months prior to sampling (min = 0.5 months, max = 36 months).

Table 3-1. Number of coupes sampled out of those available by year and silvicultural system (ARN – aggregated retention, CBS – clearfell, burn and sow).

	Silvicultural system		
Year	ARN	CBS	Total
2007	8/8	0/8	8/16
2008	9/9	5/7	13/16
2009	6/7	5/6	11/13
2010	13/14	8/10	21/24
Total	**36/38**	**18/31**	**54/69**

Due to the prohibitively large number of understorey trees, harvesting damage was assessed for eucalypts only. All eucalypts > 10 cm dbh within 3 m of the harvest edge in each island aggregate and around the coupe edges ('susceptible' trees) were assessed for damage caused by either logging or subsequent firebreak construction. It was not possible to distinguish between damage due to harvesting and damage due to firebreak construction, but it was possible in some instances to distinguish damage due to windthrow or from other causes which had occurred prior to harvesting. Harvesting damage included any physical damage to the tree that resulted in the cambium being exposed to the air (i.e., bark removal, wounding, broken branches or tops). Each susceptible tree was classed as either old-growth or regrowth, and damaged or undamaged. The location of damage to each tree was noted (roots, stem, or crown). Damage to the roots included damage to visible roots or to the root-collar. Stem damage included damage above the root-collar, and up to the first live branch. Crown damage included wounded or broken branches, and any damage to the stem above the first live branch. If a tree was damaged in more than one location, only the location of the largest or most significant wound was noted. The total number of damaged and undamaged edge trees was tallied for each island aggregate separately, and for each 100 m section of edge. The proportion of susceptible eucalypts that were damaged, the mean number of damaged eucalypts per 100 m of edge and the mean number of damaged eucalypts per hectare felled were calculated.

Windthrow assessments included all windthrown eucalypts and understorey trees > 10 cm dbh, and extended into the edge as far as did the windthrown trees. Standing trees were not assessed. The number of windthrown trees was tallied separately for each island aggregate and around the coupe boundary. Windthrown trees were tallied by tree class (old-growth eucalypt, regrowth eucalypt or understorey species). For each windthrown area or individual windthrown tree, the average direction of tree fall (degrees), length of edge affected, and average and maximum depths of penetration (m) of windthrow into the edge were noted. The area of each windthrow event was estimated by multiplying the length of edge affected by the average depth of penetration. These areas were summed across each coupe to obtain total area windthrown for the coupe. To allow comparisons between silvicultural systems, the mean number of windthrown stems per 100 m of edge, the mean number of windthrown stems per hectare felled and the ratio of area windthrown to area harvested were calculated. Direction of fall data were classed into the eight cardinal directions (N = 337.6-22.5°, NE = 22.6-67.5°, etc.) and the number of windthrown stems that fell in each direction was summed across all coupes.

A number of environmental variables which can contribute to windthrow risk were determined for each coupe from available map layers. These included time since harvest (months), mean opening size (ha), perimeter length (m), annual rainfall (mm), elevation (m) and slope (%). A mean annual windspeed class (very low, low, medium, high and very high), was obtained for each coupe from a windspeed map of Tasmania based on Bureau of Meteorology data (Bureau of Meteorology, 2001; Wood *et al.*, 2008). Topographic exposure in each coupe was determined based on the TOPEX_1500 map layer, and classed as either very sheltered, sheltered, intermediate, exposed or very exposed (Wood *et al.*, 2008).

3.2.2. Data analysis

Data were examined graphically to identify outliers and non-normal distributions. Tests for differences between silvicultural systems were based on 18 paired ARN and CBS coupes and used paired t-tests for normally distributed response variables, while the non-parametric Wilcoxon paired ranks test was used for variables with strongly non-normal distributions. Fisher's exact test was used to determine whether coupes harvested with different silvicultural systems were distributed independently of windspeed and topographic exposure classes. A chi-squared test was used to determine whether the location of damage on damaged trees was distributed independently of tree class, using data from all 54 sampled coupes. Differences between island aggregates and edges within the 38 ARN coupes were tested using paired t-tests for normally distributed variables, and the Wilcoxon paired ranks test for non-normally distributed variables. All analyses were conducted using R software (R Development Core Team, 2012), and statistical significance was accepted at $\alpha = 0.05$.

3.3. Results

3.3.1. Harvesting damage

A total of 6383 eucalypts were assessed for harvesting damage over 177 km of aggregate and coupe edges in 54 coupes. Overall, 30% of susceptible trees were damaged and this did not vary with silvicultural system (Table 3-2). Fewer eucalypts were damaged per 100 m of edge in ARN coupes (although the difference is not significant), resulting in the number of eucalypts damaged per felled hectare also being similar between ARN and CBS coupes (Table 3-2). Similar numbers of trees were assessed in ARN and CBS coupes, but more old-growth eucalypts were present in ARN coupes (50% of assessed trees) than in CBS coupes (30% of assessed trees). A similar proportion of trees were damaged regardless of tree class (old-growth mean = 32%, regrowth mean = 28%).

The location of damage differed between regrowth and old-growth eucalypts (Figure 3-1, $\chi^2 = 370$, df = 2, $p < 0.0001$). Damage to regrowth eucalypts occurred largely to the stem, while old-growth eucalypts were more likely to be damaged near the roots. In both cases, fewer than 10% of damaged trees suffered from crown damage. There was a strong negative correlation between the proportion of eucalypts damaged and felled area for

CBS coupes (Spearman r = -0.52, $p = 0.03$), but not for ARN coupes. Within ARN coupes, island aggregates had similar damage levels when compared to edges in the same coupe (Table 3-4).

Table 3-2. Results of paired tests for differences in harvesting damage variables by silvicultural system. Means for each silvicultural system are shown (standard deviation in brackets), as well as the mean difference between the paired coupes (ARN – CBS). Tests used, test statistics, n and p-values are shown. Significant differences are indicated in bold ($p \leq 0.05$).

Variable	**ARN mean (SD)**	**CBS mean (SD)**	**Mean difference (SD)**	**Test used**	**Test-statistic**	**n**	**p-value**
Susceptible eucalypts per coupe	140 (87)	130 (84)	10 (92)	Paired t	0.46	18	0.682
Proportion of susceptible eucalypts damaged	0.29 (0.14)	0.31 (0.10)	-0.01 (0.17)	Paired t	-0.19	18	0.850
Eucalypts damaged per 100 m	0.88 (0.58)	1.33 (0.86)	-0.44 (1.00)	Paired t	-1.89	18	0.075
Eucalypts damaged per hectare	1.95 (1.33)	1.42 (0.94)	0.52 (1.37)	Paired t	1.62	18	0.124

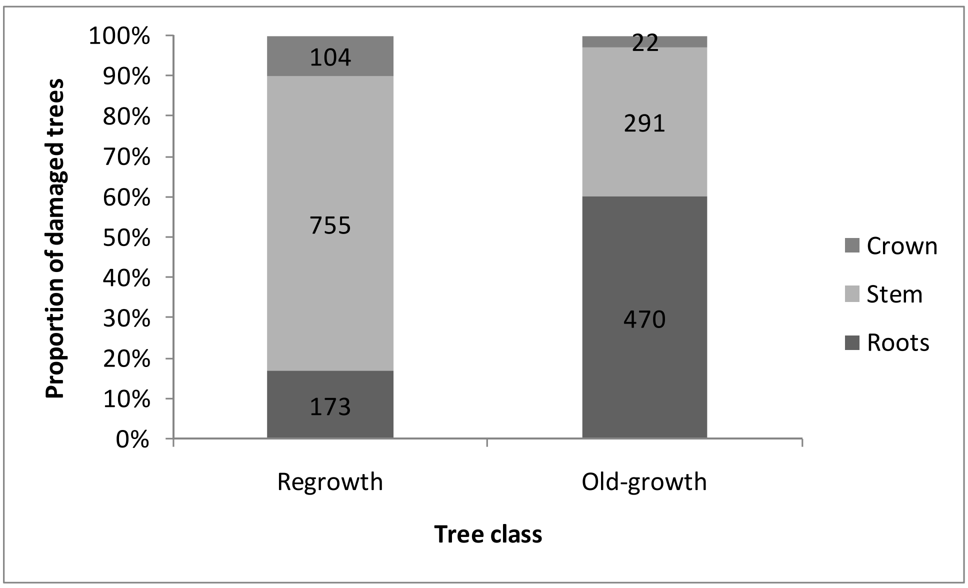


Figure 3-1. Damage location by tree class. The number of damaged trees for each location is shown. Includes data from all 54 sampled coupes.

3.3.2. Windthrow

A total of 8219 windthrown trees were observed in 54 coupes. Most of the windthrown stems consisted of understorey species (94%), while 4% were regrowth eucalypts, and 2% were old-growth eucalypts. Windthrow levels varied widely from coupe to coupe. Five coupes had no observed windthrow, while a single ARN coupe accounted for 41% of all windthrown stems. The four coupes with the most windthrow accounted for over 60% of all windthrown stems.

ARN coupes had greater perimeter lengths and smaller opening sizes than comparable CBS coupes, but did not differ in time since harvest, elevation, rainfall or slope (Table 3-2). Mean annual windspeed and topographic exposure classes were also distributed independently of silvicultural system (Windspeed, Fisher's exact test $p = 0.495$; Topographic exposure, Fisher's exact test $p = 0.228$).

There were no significant differences due to silvicultural system for any of the measured windthrow variables (Table 3-3). Windthrow levels were generally low, with an overall average of 10 understorey stems windthrown per ha felled and 0.4 eucalypt stems windthrown per ha felled. The ratio of area windthrown to area harvested was 0.015, while the average and maximum distances that windthrow penetrated into the edge were 2.7 m and 4.7 m, respectively. Most windthrown trees fell in a northerly to easterly direction (Figure 3-2).

Table 3-2. Results of paired tests for differences in environmental variables by silvicultural system. Means for each silvicultural system are shown (standard deviation in brackets), as well as the mean difference between the paired coupes (ARN – CBS). Tests used, test statistics, n and p-values are shown. Significant differences are indicated in bold ($p \leq 0.05$).

Variable	**ARN mean (SD)**	**CBS mean (SD)**	**Mean difference (SD)**	**Test used**	**Test-statistic**	**n**	**p-value**
Time since harvest (months)	5.8 (5.3)	8.5 (7.2)	-2.6 (6.1)	Paired t	-1.8	18	0.080
Perimeter length (m)	4340 (1920)	2846 (854)	1494 (1860)	Paired t	3.4	18	**0.003**
Mean opening size (ha)	13.9 (6.0)	28.1 (17.4)	-14.2 (17.5)	Paired t	3.4	18	**0.003**
Annual rainfall (mm)	1350 (153)	1304 (185)	46 (162)	Paired t	1.2	18	0.240
Slope (%)	11.6 (7.6)	14.9 (8.8)	-3.3 (9.5)	Paired t	-1.5	18	0.154
Elevation (m)	431 (223)	450 (274)	-19 (174)	Paired t	-0.5	18	0.648

Table 3-3. Results of paired tests for differences in windthrow variables by silvicultural system. Means for each silvicultural system are shown (standard deviation in brackets), as well as the mean difference between the paired coupes (ARN – CBS). Tests used, test statistics, n and p-values are shown. Significant differences are indicated in bold ($p \leq 0.05$).

Variable	**ARN mean (SD)**	**CBS mean (SD)**	**Mean difference (SD)**	**Test used**	**Test-statistic**	**n**	**p-value**
Area windthrown/area harvested	0.011 (0.039)	0.004 (0.007)	0.008 (0.037)	Wilcoxon	67	18	0.670
Understorey trees windthrown per 100 m	5.8 (20.9)	2.5 (4.5)	3.4 (20.9)	Wilcoxon	64	18	0.570
Understorey trees windthrown per hectare	18.2 (68.7)	2.6 (3.8)	15.6 (67.6)	Wilcoxon	83	18	0.776
Eucalypts windthrown per 100 m	0.07 (0.09)	0.21 (0.35)	-0.13 (0.32)	Wilcoxon	17	18	0.168
Eucalypts windthrown per hectare	0.18 (0.25)	0.20 (0.32)	-0.020 (0.31)	Wilcoxon	32	18	0.965
Mean penetration distance (m)[1]	2.5 (2.6)	2.6 (2.1)	-0.10 (3.1)	Paired t	-0.12	14	0.904
Maximum penetration distance (m)[1]	4.2 (3.9)	5.1 (3.9)	-0.9 (4.9)	Paired t	-0.68	14	0.506

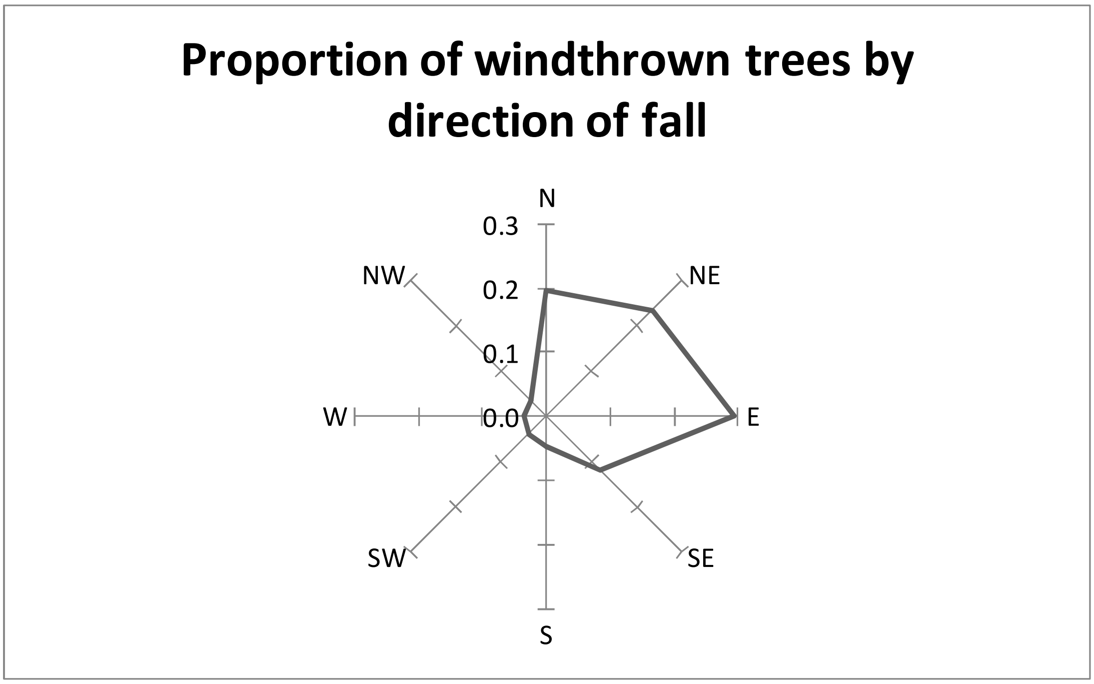


Figure 3-2. Distribution of average direction of fall of all windthrown trees (n = 7463 trees).

Although most measures of windthrow were greater in island aggregates, there were few significant differences in windthrow levels or penetration distance between island aggregates and edges (Table 3-4). Although understorey windthrow per 100 m was greater in island aggregates than on edges, this difference became non-significant when a single outlier was removed (Table 3-4). On average, 8% (SD = 17%, n = 93) of the area of island aggregates contained windthrown trees. The proportion of island area windthrown decreased as the size of island aggregates increased, with aggregates larger than 1.5 ha appearing relatively resistant to windthrow (Figure 3-3).

Table 3-4. Results of paired tests for differences in windthrow and damage variables by aggregate type within ARN coupes. Means for each aggregate type are shown (standard deviation in brackets), as well as the mean difference between the types (Island - Edges). Tests used, test statistics, n and p-values are shown. Significant differences are indicated in bold ($p \leq 0.05$).

Variable	**Island mean (SD)**	**Edges mean (SD)**	**Mean difference (SD)**	**Test used**	**Test-statistic**	**n**	**p-value**
Proportion of susceptible eucalypts damaged	0.33 (0.24)	0.33 (0.13)	0.003 (0.24)	Paired t	0.06	26	0.953
Proportion of sampled length affected by windthrow	0.08 (0.15)	0.04 (0.06)	0.04 (0.11)	Wilcoxon	113	18	0.246
Understorey trees windthrown per 100 m	10.3 (32.6)	4.0 (6.4)	6.3 (28.4)	Wilcoxon	259	26	**0.033**
Understorey trees windthrown per 100 m minus one outlier	4.0 (4.9)	3.2 (4,2)	0.8 (4.8)	Wilcoxon	233	25	0.058
Eucalypts windthrown per 100 m	0.37 (0.60)	0.28 (0.45)	0.09 (0.67)	Wilcoxon	125	26	0.467
Mean penetration distance (m)	3.4 (2.9)	3.0 (1.8)	0.4 (2.7)	Wilcoxon	155	26	0.851
Maximum penetration distance (m)	5.5 (5.5)	5.4 (3.4)	0.1 (4.9)	Paired t	0.07	17	0.947

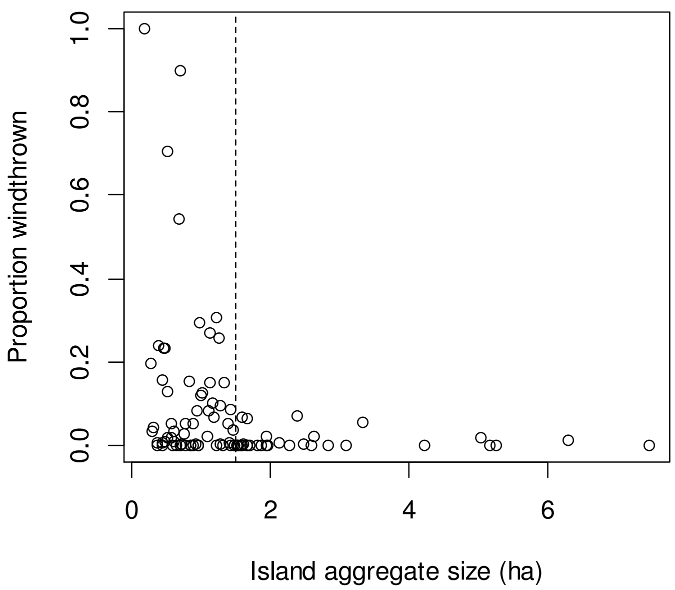


Figure 3-3. Scatterplot of proportion of area windthrown by island aggregate size. Dashed vertical line at 1.5 ha.

3.4. Discussion

Windthrow and harvesting damage were compared in coupes harvested using aggregated retention (ARN) and conventional clearfell, burn and sow (CBS) silviculture. Contrary to expectations, the increased amount of edge in ARN coupes did not result in greater rates of harvesting damage or windthrow on the basis of hectares felled. Similarly, there was no difference in harvesting damage or eucalypt windthrow when edges and island aggregates within ARN coupes were compared. However, the proportion of aggregate area windthrown was greater in smaller island aggregates when compared to larger ones.

3.4.1. Harvesting damage

Harvesting damage to eucalypts did not vary with silvicultural system, despite the greater length of edge in ARN coupes. The number of damaged trees per 100 m of edge was slightly lower in ARN coupes, with the result that the number of damaged trees per ha was only slightly higher in ARN coupes, and neither of these differences were significant. This may be due to part to the relatively small sample size for damage variables (n=18), which reduces the paired t-test's ability to detect differences. Although numerous studies have examined residual stand damage following dispersed retention or thinning, fewer have quantified damage after aggregated retention harvesting, or have compared harvesting damage following aggregated retention with that after clearfelling. Moore et al. (2002) found that damage in 15% and 40% aggregated retention treatments was similar to natural levels of damage in an unharvested control (< 2.5% of trees damaged), but plots were located away from the aggregate edges, where the majority of harvesting damage would be expected to occur. Almost 50% of retained trees were damaged in the aggregated retention treatment at one of the STEMS study sites on Vancouver Island in British Columbia (deMontigny and Nigh, 2009), while only 3% of retained trees were damaged in the same treatment at a different site (deMontigny, 2004). At the Warra Silvicultural Systems Trial in Tasmania, 10% of retained stems were damaged in two aggregated retention coupes (Neyland, 2010). In this study, the proportion of susceptible trees damaged seems high, at around 30%; however, this includes only eucalypts within 3 m of the edge.

The highest damage levels in this study (59% of susceptible trees damaged) were found in an ARN coupe consisting of many small openings. There may be a threshold opening size below which damage levels increase significantly. Given the mean tree height in many of these stands is greater than 50 m, any opening less than 60 m across would be likely to result in higher damage levels to the surrounding trees as trees are felled, or snigged.

Damaged bark at the base of standing trees or on the roots was the most common type of damage observed, which is consistent with other studies (Vasiliauskas, 2001). Much of the damage reported here likely occurred during firebreak construction rather than during harvesting (Neyland, 2010). Damage levels were also similar for old-growth and regrowth trees, although the location of damage differed by tree class.

Damage to retained eucalypts during harvesting can lead to increased incidence of disease and decay and reduced wood quality (Neumann *et al.*, 1997). If damage rates to understorey stems are similar to those observed for eucalypts, then myrtle wilt may become a problem in stands where *Nothofagus cunninghamii* is present (Packham, 1991). Effects on wood quality may not be a major consideration after variable retention harvesting in these forests, given that the aggregates are retained mainly to provide benefits for biodiversity. Retained trees are currently excluded from available wood volume calculations, so harvesting damage and loss of these trees is not critical from a wood-flow perspective. Damage to retained trees may actually help to accelerate the development of structures associated with older trees (such as hollows), but may also reduce stability and increase the risk of mortality (Gibbons *et al.*, 2010). Good silvicultural practice should aim to maintain the health of the forest stand, and thus harvesting contractors should be encouraged to avoid damage to retained trees during forest operations, with particular attention paid to large, old trees. Coupe designs with reduced perimeter-to-area ratios which incorporate larger aggregates and wider openings may help to minimise damage.

3.4.2. Windthrow

In this study, windthrow levels were generally low, and aggregated retention harvesting did not significantly increase windthrow levels when compared to clearfelling. Beese (2001) found that windthrow levels around small 1.5 ha patchfells were lower than those in an adjacent 69 ha clearfell, while Rollerson et al. (2002) found that variable retention harvesting (including dispersed retention) increased windthrow by 33% when compared to clearfelling. The lack of a difference found in this study is due in part to the small sample size (n = 18 ARN/CBS pairs) and the high variability in the data. The large average size of the retained aggregates (1.5 ha) and the smaller average opening size in ARN coupes compared to clearfells may also have helped to moderate windthrow risk. Larger retained patches have been shown to experience less windthrow in a number of studies (Burton, 2001; DeLong *et al.*, 2001; Steventon, 2011), while reduced opening sizes would likely result in lower mean windspeeds in ARN coupes (Gardiner *et al.*, 1997; Novak *et al.*, 2000). Rollerson et al. (2009) and Steventon (2011) suggest that patches greater than 1 ha in size should be relatively windfirm, which this study seems to confirm.

The direction of fall of most windthrown stems was towards north, northeast and east, consistent with prevailing westerly winds and SW storm winds in Tasmania (Bureau of Meteorology, 2009). There was high variability in windthrow between coupes, which may indicate that certain coupes are at higher risk of windthrow due to their location, exposure or soil types (Ruel, 1995). Of the four coupes with the greatest number of windthrow stems, three were located in the northwest of Tasmania in relatively flat terrain and on clayey soils derived from Precambrian mudstone. In one coupe, much of the windthrow was associated with stream gullies (R. Scott, pers. obs). High soil moisture levels or limited rooting depth due to a high water table have been associated with windthrow in other studies, but the relationships are variable (Stathers *et al.*, 1994; Scott, 2005).

Eucalypt windthrow levels were generally low with an average of < 0.25 eucalypt stems windthrown per ha felled, or 0.01 ha windthrown per ha felled. This contrasts with windthrow of 6 stems per ha felled around small patch-cuts reported after variable retention harvesting in British Columbia, and 9 stems per ha felled in clearfells (Beese, 2001). Rollerson et al. (2002) found that 0.06 ha were windthrown per ha felled after variable retention harvesting on Vancouver Island and in the Queen Charlotte Islands. In the mature wet eucalypt forests examined in this study, the eucalypts are often relatively sparse, and emergent over a dense layer of understorey species. As such, they are likely to have developed under and be well adapted to the prevailing wind regime (Jacobs, 1955).

Much greater numbers of understorey stems were windthrown in this study (~10 sph), and approximately 8% of the area of island aggregates was windthrown when measured prior to the regeneration burn. Neyland (2010) found that > 25% of the understorey stems had fallen in island aggregates at the Warra Silvicultural Systems Trial, but this was measured

3 years after the regeneration burn. Windthrow that occurs prior to burning may increase the risk of fire damage and escapes, since windthrown trees often fall into the aggregates and may provide bridging fuel for fires. Likewise, damage to roots and stems sustained during the regeneration burn may increase future windthrow rates and loss of residual trees (Neyland, 2010). The interactive effects of these different types of damage will have implications for the persistence of aggregates and whether they meet the objectives of variable retention. Longer-term research is needed examining the persistence of aggregates in wet eucalypt forests and the links between damage caused by wind, harvesting and the regeneration burn.

3.5. Conclusions and recommendations

Aggregated retention harvesting in Tasmanian wet eucalypt forests did not significantly increase windthrow or harvesting damage compared to conventional clearfell, burn and sow silviculture. Harvesting damage affected a large proportion of susceptible eucalypts (~30% of trees within 3 m of the edge) in both ARN and CBS coupes. This may result in increased rates of decay and mortality in these edge trees, with implications for overall forest health. Windthrow rates were generally low, with an area of ~ 0.01 ha windthrown per ha harvested. Most of the observed windthrow consisted of understorey stems. Windthrow affected 8% of island aggregate area, and decreased as aggregate size increased. Island aggregates greater than 1 ha in size appear to be relatively windfirm and are recommended. Further research is needed to assess the long-term persistence of aggregates in wet eucalypt forests, to quantify short- and long-term mortality due to windthrow, harvesting damage, and the regeneration burn and to examine the relative importance of these processes and any interactions among them. Information on mortality levels in natural stands is also lacking, and will be needed to help quantify any changes due to variable retention silviculture.

Chapter 4 - Burning and site preparation

4.1. Introduction

Since the 1960s, managed wet eucalypt forests in south-eastern Australia have primarily been clearfelled, followed by a high-intensity regeneration burn and aerial sowing (Hickey and Wilkinson, 1999). The clearfell, burn and sow (CBS) silvicultural system has been shown to be safe, efficient, and cost-effective (Dignan, 1993; Mitchell, 1993). It reduces the high fuel loads that exist following harvesting in wet eucalypt forests (Marsden-Smedley and Slijepcevic, 2001), creates receptive seedbed over most of the harvested area (Gilbert, 1959; Cunningham, 1960), and usually results in abundant and fast-growing eucalypt regeneration (Lockett and Candy, 1984; King *et al.*, 1993b; Neyland *et al.*, 2009b). However, clearfelling has increasingly come under public scrutiny when used in old-growth forests due to concerns about aesthetics, biodiversity, and loss of old-growth species and structures, particularly hollow-bearing trees (Lindenmayer *et al.*, 1990; Lindenmayer and Franklin, 1997). This increased social pressure has led to a search for alternative silvicultural systems.

Retention forestry (green-tree retention, variable retention, clearfelling with reserves) is increasingly being used around the world to manage temperate and boreal native forests (Rosenvald and Lõhmus, 2008; Gustafsson *et al.*, 2012). Retention forestry aims to maintain or restore biodiversity and ecosystem function at the site level by more closely emulating natural disturbance and retaining important structural features from the unlogged forest into the regenerating stand (Franklin *et al.*, 1997; Mitchell and Beese, 2002). These ‘biological legacies’ are retained for the long-term, and are intended to provide continuity in forest structure and function between the old and new forest stands.

This approach is informed by a large body of research conducted in experimental sites around the world (Gustafsson *et al.*, 2012). In Tasmania, the Warra Silvicultural Systems Trial was established in 1997 to test alternatives to clearfelling in old-growth wet eucalypt forests (Hickey *et al.*, 2001). Of the systems tested at the Warra Silvicultural Systems Trial, aggregated retention was found to be the most suitable alternative for routine use in wet eucalypt forests (Forestry Tasmania, 2009a; Neyland *et al.*, 2012).

Aggregated retention (ARN), as practised in Tasmania, aims to retain late-successional species and structures important for biodiversity, and maintain a forest influence over the majority of the harvested area for the next rotation (Baker and Read, 2011; Scott *et al.*, 2011). Forest influence refers to the biophysical effects of standing trees on the environment surrounding them, and is generally considered to extend a distance of at least one tree length (Keenan and Kimmins, 1993). Requiring at least half of the harvested area to be within one tree length of standing forest helps to ensure that retained trees are well-dispersed. This forest influence target distinguishes ARN harvesting ecologically from clearfelling, and may assist in recolonisation of the harvested area (Keenan and Kimmins, 1993; Mitchell and Beese, 2002; Baker and Read, 2011). In Tasmania, the goals of ARN harvesting are achieved by retaining relatively large patches (most > 1 ha) of the original forest within the coupe boundary and ensuring that most openings are less than four tree lengths wide. Levels of forest reservation in Tasmania are among the highest in the world (47% of native forests are reserved), and informal reserves (where harvesting will not occur due to topographic, economic or other constraints) generally account for an additional 25% of the production landbase in wet eucalypt forests (Forestry Tasmania, 2009a). In some cases the forest influence and structural retention requirements of ARN can be met via these reserves, and little or no additional retention is required (Scott *et al.*, 2011). Where additional retention is used, it may include both island aggregates (free-standing patches), or edge aggregates, which are adjacent to standing forest outside of the coupe. ARN is expected to lead to better biodiversity outcomes (Baker *et al.*, 2009; Baker and Read, 2011) and has been shown to be more socially acceptable than clearfelling so long as information is provided to the public about the benefits of this type of harvesting (Ford *et al.*, 2009a). However, regenerating ARN coupes may be difficult, and the long-term impacts of the ARN system on eucalypt productivity are not known (Forestry Tasmania, 2009a; Neyland *et al.*, 2009b).

Fire is a key ecological process and an essential management tool in wet eucalypt forests (Gilbert, 1959; Ashton, 1976; Attiwill, 1994). Elsewhere in fire-dominated forests burning for regeneration has largely been replaced by mechanical disturbance and planting of seedlings; however, there has been renewed interest in the use of prescribed burning to assist natural regeneration in boreal forests in Ontario, Canada (Ontario Ministry of Natural Resources, 2002), to provide habitat for red-listed species in Fennoscandian boreal forests (Hyvärinen *et al.*, 2005; Olsson and Jonsson, 2010), and for ecological restoration and fuel management following decades of fire suppression in the forests of the western United States (Schoennagel and Nelson, 2011). High-intensity burning remains the most effective means of removing harvesting debris and preparing a seedbed in Australian wet eucalypt forest coupes (Attiwill, 1994; Forestry Tasmania, 2009b).

Recent research has confirmed that well-burnt seedbed is important for the establishment and early growth of eucalypt seedlings (Neyland *et al.*, 2009b)(Neyland *et al.*, 2009), and that burnt seedbeds result in greater species richness of vascular plants than disturbed seedbeds (Hindrum, 2009; Hindrum *et al.*, 2012). Developing effective burning methods for ARN coupes has been one of the key challenges in implementing the variable retention program in Tasmania (Forestry Tasmania, 2009a).

The objective of the regeneration burn is to create receptive seedbed while reducing fuel loads and fire risk (Forestry Commission, 1993). In a conventional clearfell, a mineral earth firebreak is cleared around the edges of the coupe, and a helicopter-mounted drip-torch is used to light the central portions of the coupe first, followed by the edges. The convection column thus formed helps to draw the fire away from the forested edges, reducing the risk of escapes (Forestry Tasmania, 2005a). Coupe shapes with regular edges and low perimeter-to-area ratios are preferred for this type of burning (Forest Practices Board, 2000; Forestry Tasmania, 2005a). In ARN coupes, which are likely to have irregular shapes and usually include retained aggregates, conventional high-intensity burning cannot be used because the risk of damage to the retained aggregates and adjacent unlogged forest is too great (Chuter, 2007; Neyland *et al.*, 2009b). The first attempts at burning in ARN coupes used low-intensity fires that left the aggregates unburnt but failed to create sufficient receptive seedbed for good regeneration. In two experimental ARN coupes at the Warra Silvicultural Systems Trial, burnt seedbed was created over only half of the harvested area, contributing to marginal seedling densities (<1800 stems per hectare) at age three (Neyland *et al.*, 2009b). The first operational ARN coupes in Tasmania were harvested in 2004, and in 2007 a new burning prescription was developed specifically for aggregated retention coupes (Chuter, 2007) (Scott *et al.*, 2011). ‘Slow burning’ aims to minimise convection while ensuring that most fine fuels are still consumed (Chuter, 2007). Slow burning is a higher-risk burning strategy than conventional high-intensity burning, due to the lack of a strong convection column and reliance on fires self-extinguishing along the edges of the coupe (Chuter, 2007).

Differences in the prescribed burning conditions for slow burns (sparse ignition late in the day) are likely to result in different fire behaviour and outcomes, compared to conventional high-intensity burns. ARN slow burns are expected to burn less evenly and produce less burnt seedbed. Fuels on these coupes are likely to burn less completely, but for longer, which may increase the risk of escape into the surrounding forest (Forestry Tasmania, 2009a). The complex openings and retained aggregates required to meet the ecological objectives of ARN harvesting may result in higher perimeter-to-area ratios in ARN coupes, which may also contribute to a greater risk of escapes and burn impact on the unharvested forest. Aggregates retained within ARN coupes, and in particular small island aggregates, may be more prone to burning, due to their location within the coupe and drying edge effects. Higher perimeter-to-area ratios are also likely to increase the area disturbed by mineral-earth firebreaks, with negative consequences for regeneration of both eucalypts and other vascular plant species (Hindrum, 2009; Hindrum *et al.*, 2012).

As of December 2011, over 50 ARN coupes had been harvested and regenerated in wet eucalypt forest across Tasmania. A monitoring program was established in a number of these coupes and a set of paired CBS coupes to evaluate silvicultural outcomes including retention level, coupe size and shape, burning conditions, the extent of firebreaks, the type and amount of post-burn seedbed and the impact of escaped burns on retained areas. When compared to similar clearfells, it was expected that:

1. Perimeter lengths and perimeter-to-area ratios would be higher in ARN coupes,
2. Firebreaks would affect a greater proportion of the harvested area in ARN coupes,
3. ARN coupes would have less burnt seedbed overall,

4. ARN coupes would have less well-burnt seedbed (ashbed),
5. Burn impact on unharvested forest would be greater in ARN coupes (due to retained aggregates), and
6. The likelihood of a burn escaping would be greater in ARN coupes.

4.2. Methods

4.2.1. Study design

To allow comparisons between the two silvicultural systems, a CBS coupe was chosen to pair with each operational ARN coupe (Figure 4-1). Where possible, the CBS pair was a nearby coupe of similar size, soils, aspect, and forest type, although some variation in all of these variables did occur. All paired coupes were burnt in the same year. All 38 ARN coupes harvested and regenerated from 2007-2010 were monitored; however, paired data were available for only 31 of these coupes due to an insufficient number of CBS comparison coupes.

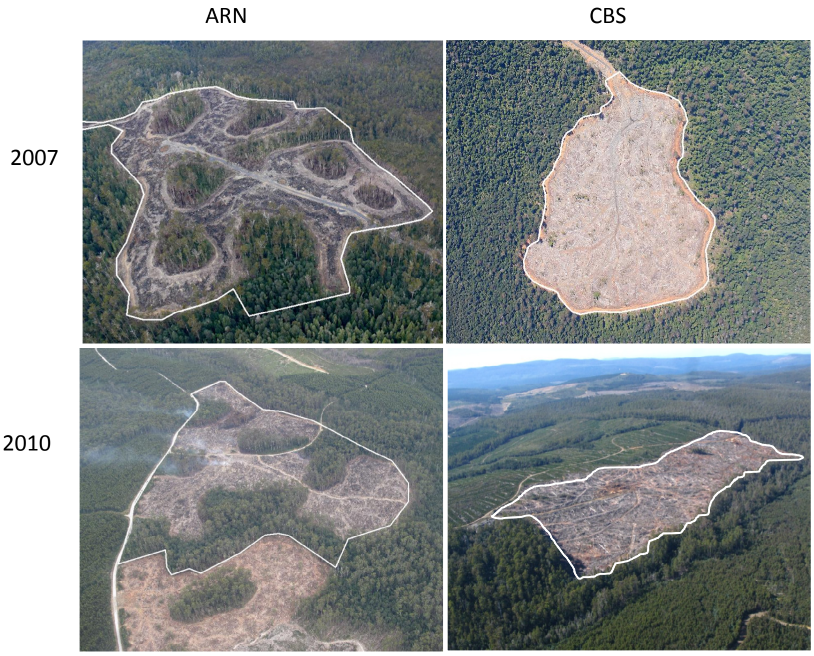


Figure 4-1. Two sets of paired ARN-CBS coupes from 2007 and 2010. Coupe boundaries shown in white. Not to scale. Note changes in ARN coupe design from 2007 to 2010, the use of both island and edge aggregates, and burnt areas visible in some aggregates.

4.2.2. Study sites

Coupes were distributed across Tasmania (Figure 4-2), and were located in mature wet eucalypt forest, although a regrowth component was sometimes also present. Average rainfall across the coupes ranged from 870 to 1800 mm annually (Bureau of Meteorology, 2001). Slopes were generally moderate (< 20%) but ranged up to 40%, and aspect varied. Dominant tree species were *Eucalyptus obliqua* L'Herit., *E. regnans* F. Muell, *E. delegatensis* R. Baker, and *E. nitida* Hook. f. Soil type varied, but soils were mainly loamy over clayey or mottled yellowish, red or brown clayey and derived from Jurassic dolerite, Permian mudstone or Precambrian mudstone (Grant *et al.*, 1995). Site characteristics for individual coupes can be found in Appendix 2. Two ARN coupes and eight CBS coupes were completely or partially cable-harvested, while all remaining coupes were harvested using ground-based machinery. Following harvesting, an excavator or bulldozer was used to clear a mineral-earth firebreak around the perimeter of the harvested area in most coupes, a process called tracking. Firebreaks are required to be at least 5 m wide and trafficable by four-wheel drive vehicle (Forest Practices Board, 2000; Forestry Tasmania, 2005a). All fine and large fuels are removed from the firebreak and piled in a windrow along its inside edge (Figure 4-3). Regeneration burns were undertaken by Forestry Tasmania District staff in autumn each year (from mid-March to June). Three ARN coupes and two CBS coupes were lit using handheld drip-torches, while the remaining 57 coupes were lit using an aerial drip-torch suspended from a helicopter.

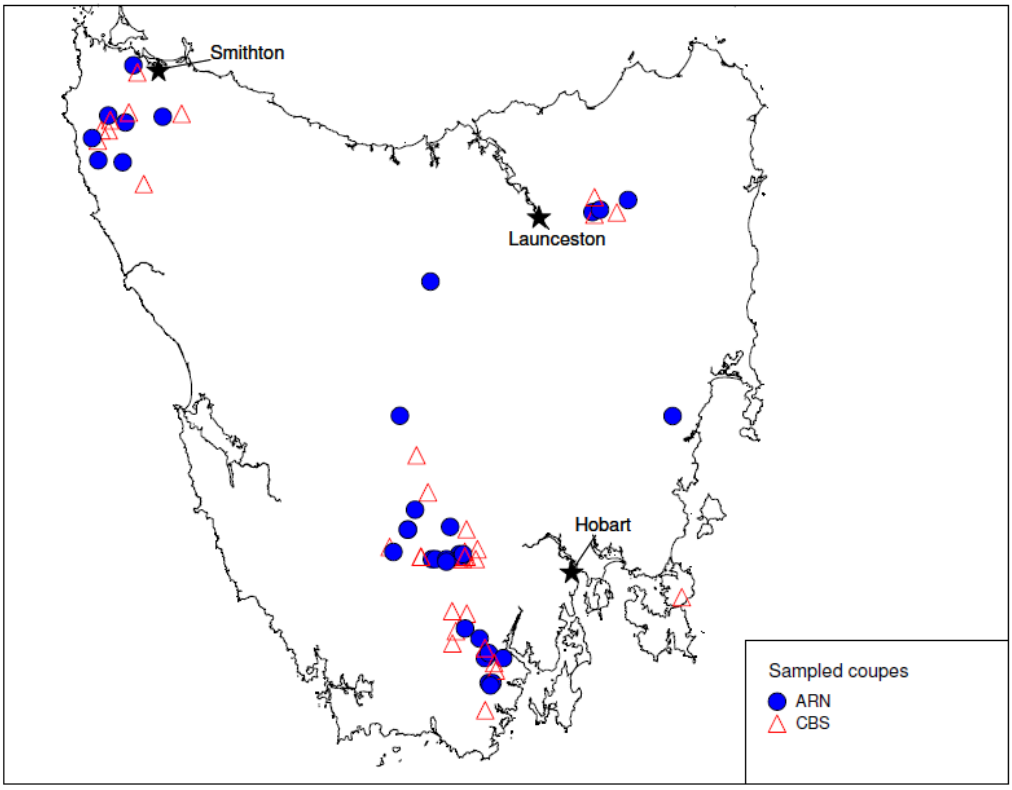


Figure 4-2. Map of Tasmania showing coupe locations by silvicultural system.

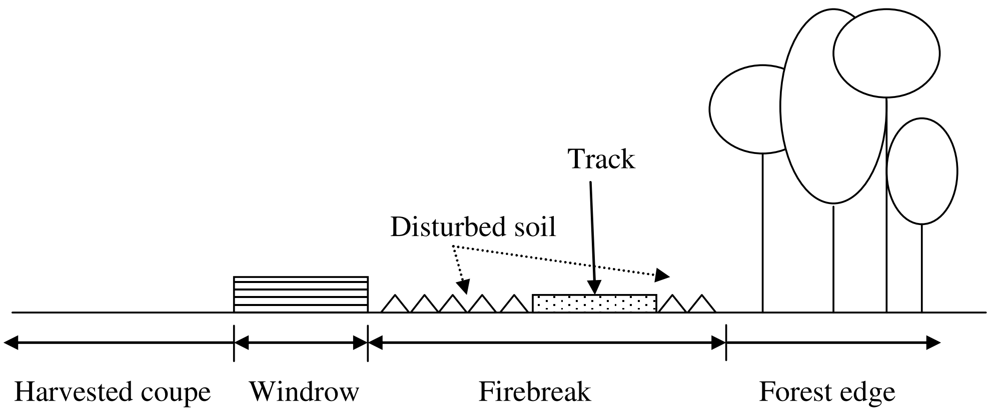


Figure 4-3. Schematic illustration of firebreak configuration.

4.2.3. Sampling methods

Sampling occurred each year from 2007-2010. Firebreaks were sampled following harvesting and site preparation but before burning (January-March), while all other sampling occurred after the autumn regeneration burn (May-July).

4.2.3.1. Coupe shape and size

All coupes were mapped to a Geographic Information System (GIS) using Global Positioning Systems or from ortho-rectified aerial photos following harvest. Perimeter length (m), harvested area (ha), the number of aggregates in each coupe, and individual aggregate areas (ha) were obtained from the GIS. Retention level (%) was calculated for each coupe as:

$$\Sigma(\text{aggregate area}) / (\text{harvested area} + \Sigma(\text{aggregate area}))*100$$

Perimeter-to-area ratios were calculated for each coupe by dividing the perimeter length by the harvested area.

4.2.3.2. Firebreaks

Two ARN coupes and seven CBS coupes were burnt without firebreaks or had firebreaks built around less than 50% of their perimeter, and were excluded from the firebreak width analysis. In 2007, firebreak width (from disturbed outer edge to edge of windrow, Figure 4-3) was measured at 50 m intervals for a random sample of aggregates and edge sections in ARN coupes only. From 2008-2010, firebreaks in both ARN and CBS coupes were sampled and all boundary edges and aggregates were surveyed, except for edges adjacent to roads. Both firebreak width and track width (where the ground had been compacted by multiple machinery passes) were measured at 100 m intervals (Figure 4-3), and the height of the windrow was estimated to the nearest 0.5 m. The firebreaks on each coupe were mapped to a GIS from ground measurements and aerial photos, and the total length of the firebreaks for each coupe was determined. The proportion of the perimeter with firebreaks was calculated by dividing the total firebreak length by the coupe perimeter length. The proportion of the harvested area of each coupe covered by firebreaks (firebreak cover) was calculated by multiplying average firebreak width by total firebreak length, then dividing by the harvested area. In the 2007 CBS coupes (in which firebreak width was not measured), the mean firebreak width measured in each CBS coupes' ARN pair was used to calculate the proportion of the coupe covered by firebreaks. This approximation was considered acceptable given that measured firebreak widths did not vary between silvicultural systems or between years ($p > 0.14$) but did vary between regions within Tasmania ($F_{(3,41)} = 10.55$, $p < 0.0001$).

4.2.3.3. Burning conditions

Air temperature (°C), relative humidity (%), wind direction and wind speed (km/hr) were measured prior to the regeneration burn in each coupe. Fine fuel moisture content

(FFMC) was measured for fuels in the logged coupe and fuels in the adjacent unlogged forest using hazard sticks (Forestry Tasmania, 2005a). These are a standardised set of three pine rods weighing 100 g when dried to 0% moisture content. These are placed in the field and weighed at intervals to determine the approximate moisture content of the fine fuels on the coupe and in the surrounding forest. Soil Dryness Index (SDI) data were obtained for the day of the burn from the Tasmanian Bureau of Meteorology for the weather stations nearest each coupe, and a mean SDI calculated. SDI is a measure of the amount of rain required to bring the soil back to field capacity (Mount, 1972). It is related to dryness of large forest fuels (the higher the SDI, the dryer the large fuels) and is used to forecast fire behaviour (Forestry Tasmania, 2005a).

4.2.3.4. Seedbed

A systematic survey with random starting point was used to assess seedbed in each coupe following the regeneration burn. Burn intensity and soil disturbance were assessed visually at points located every 20 m along lines 100 m apart, and seedbed at each point was classified into one of six seedbed classes, modified slightly from Neyland *et al.* (2009; Table 4-1). In smaller coupes, additional lines (50 m apart) or additional points (10 m apart) were established to ensure a minimum sample size of 50 points in each coupe. In most coupes, seedbed was assessed during the period from May-July in the same year that the coupe was burnt. In some coupes, seedbed was not assessed immediately following the burn, in which case it was assessed during the age 1 regeneration survey. The proportion of the sample points falling into each seedbed class was calculated for each coupe. In wet eucalypt forests, both burnt and uncompacted disturbed seedbeds are considered to be receptive, while unburnt-and-undisturbed and compacted seedbeds are not (King and Cook, 1992; Neyland *et al.*, 2009b). To assess the success of the regeneration burn and more broadly, of the silvicultural system, the proportion of burnt seedbed (classes 4+5, 6 and 7) and receptive seedbed (classes 2, 4+5, 6, and 7) in each coupe was also determined. In wet eucalypt forests, Forestry Tasmania aims to achieve at least 66% receptive seedbed during site preparation to assure good regeneration (Forestry Tasmania, 2011b).

Table 4-1. Burn intensity, soil disturbance and combined seedbed classes. Seedbed classes shown in bold are burnt, those shown on a grey background are considered to be receptive for eucalypt seed. Seedbed classes follow Neyland *et al.* (2009).

Seedbed class	**Description**
1	Unburnt and undisturbed
2	Unburnt and disturbed
3	Unburnt and compacted
4+5[1]	Burnt to litter
6	Burnt to mineral soil
7	Ashbed

[1] Burnt to litter/disturbed and burnt to litter/undisturbed seedbed classes from Neyland *et al.* (2009) have been combined, based on their similar effects on eucalypt regeneration.

4.2.3.5. Burn impact on unharvested forest

The impact of escaped regeneration burns on island aggregates and along coupe edges was surveyed in ARN and CBS coupes. The methods used to quantify burn impact varied by year. In 2007 and 2010, all coupes were assessed for burn impact via ground-based visual surveys. All aggregates and edges were examined from the ground and the length and width of burnt areas (ground, understorey or overstorey burnt or scorched) was estimated and sketched onto a 1:5000 scale map of the coupe. In 2008 and 2009, an aerial helicopter survey was made of each coupe, and aerial photographs and sketch maps were used to map burnt areas in and around each coupe (McElwee and Baker, 2009). 1:5000 maps of each coupe were scanned and burnt areas copied to a GIS which enabled calculation of the estimated burnt area. Ground-based surveys tended to underestimate the burn impact compared to the aerial surveys (McElwee and Baker, 2009), and the two methods produce different estimates of overall burnt area. For this reason, no comparisons of burn impact were made between years, and estimates of total burnt area given here may be conservative.

It is difficult to compare burn impact across silvicultural systems, since CBS coupes do not contain aggregates. To allow more meaningful comparisons between ARN and CBS coupes, the means of the total area burnt per coupe, the area burnt outside of the coupe, the ratio of area burnt to area harvested, and the proportion of the coupe perimeter burnt are all reported. Forestry Tasmania considers a significant escape to have occurred if the area of surrounding forest burnt is greater than 10% of the harvested area of the coupe. The number of burns resulting in significant escapes was determined for each silvicultural system.

4.2.4. Statistical analyses

Relationships between variables were examined using Spearman rank correlations. Hypotheses regarding differences between silvicultural systems were tested using paired t-tests for normally distributed response variables, and the Wilcoxon paired signed-ranks test for variables with strongly non-normal distributions. Where a stated hypothesis was being tested, a one-tailed test was used; otherwise a two-tailed test was used to test the null hypothesis of no difference between silvicultural systems. Statistical significance was accepted at a level of $\alpha = 0.05$. Differences between years were tested using one-way analysis of variance. Response variables were transformed as necessary to equalise variances and normalise residuals. Where a significant difference was indicated, Fisher's Least Squares Difference was used to distinguish between years. Fisher's exact test was used to test whether the proportion of escaped burns differed between silvicultural systems. All analyses were conducted using ‘R’ software (R Development Core Team, 2012).

4.3. Results

4.3.1. Coupe shape and size

ARN coupes contained on average 1806 m more edge (perimeter length) and were 7.7 ha smaller than paired CBS coupes and, as a result, perimeter-to-area ratios were nearly twice as high in ARN coupes compared to CBS coupes (Table 4-2). The differences in perimeter length and perimeter-to-area ratio decreased with year burnt, and perimeter length was significantly less for coupes burnt in 2010 compared to coupes burnt in 2007 (Figure 4-4a).

Table 4-2. Mean difference in coupe shape and firebreak variables for paired ARN and CBS coupes. Means for each silvicultural system are shown (standard deviation in brackets), as well as the mean difference between the paired coupes (ARN-CBS). Tests used, test statistics, n and p-values are shown. Significant differences between the silvicultural systems are indicated in bold ($p \leq 0.05$).

Variable	**ARN mean (SD)**	**CBS mean (SD)**	**Mean difference (SD)**	**Test used**	**Test statistic**	**n**	***p*-value**
Perimeter (m)	4642 (2257)	2836 (945)	1806 (1965)	Paired t	5.12	31	**<0.0001**
Harvested area (ha)	20.7 (10.1)	28.5 (17.6)	-7.7 (17.1)	Paired t	-2.51	31	**0.0175**
Perimeter-to-area ratio	224 (59)	127 (60)	98 (86)	Wilcoxon	465	31	**<0.0001**
Firebreak width (m)	10.1 (2.8)	11.5 (2.4)	-0.82 (2.0)	Paired t	-1.56	15	0.1416
Track width (m)	4.02 (0.51)	3.79 (0.93)	0.35 (0.92)	Wilcoxon	92	15	0.0730
Windrow height (m)	1.73 (0.48)	1.73 (0.48)	-0.11 (0.34)	Paired t	-1.16	14	0.2664
Proportion of harvested area covered by firebreaks	0.20 (0.06)	0.12 (0.07)	0.08 (0.09)	Paired t	4.55	23	**<0.0001**
Proportion of harvested area covered by tracks	0.07 (0.02)	0.04 (0.02)	0.03 (0.03)	Paired t	3.57	15	**0.0031**
Proportion of perimeter with firebreaks	0.85 (0.21)	0.75 (0.32)	0.09 (0.33)	Wilcoxon	281	31	0.1618

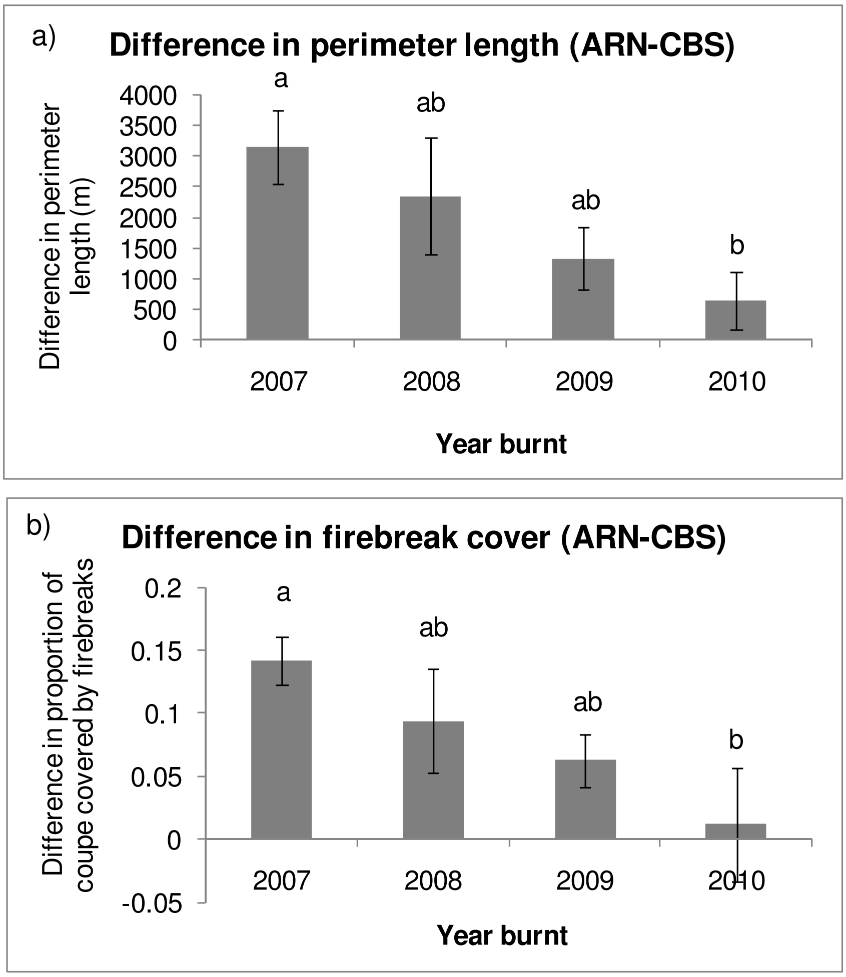


Figure 4-4. Mean difference (±SE) in a) perimeter length and b) firebreak cover between paired ARN and CBS coupes by year. Bars labelled with different letters are significantly different at $p \leq 0.05$.

The retention level in ARN coupes ranged from 0 to 56% (mean = 27.6, SE = 2.8, n = 38). Overall, ARN coupes contained from 0 to 12 aggregates (mean = 5.05, SE = 0.58), with a total of 193 aggregates retained in 38 ARN coupes. Five ARN coupes were harvested with no additional retained aggregates, due to high levels of reservation surrounding the harvested area. These five coupes differed from their CBS pairs in having more than 50% of the harvested area under forest influence, and also met the other ecological criteria that define ARN (Scott *et al.*, 2011; Baker and Read 2011). Island aggregates averaged 1.4 ha in size, while edge aggregates were more than twice as large (mean = 3.0 ha; t = 3.92, df = 87.77, p = 0.0002). Over time there was a shift in coupe design towards fewer and larger aggregates (Figure 4-1, Figure 4-5).

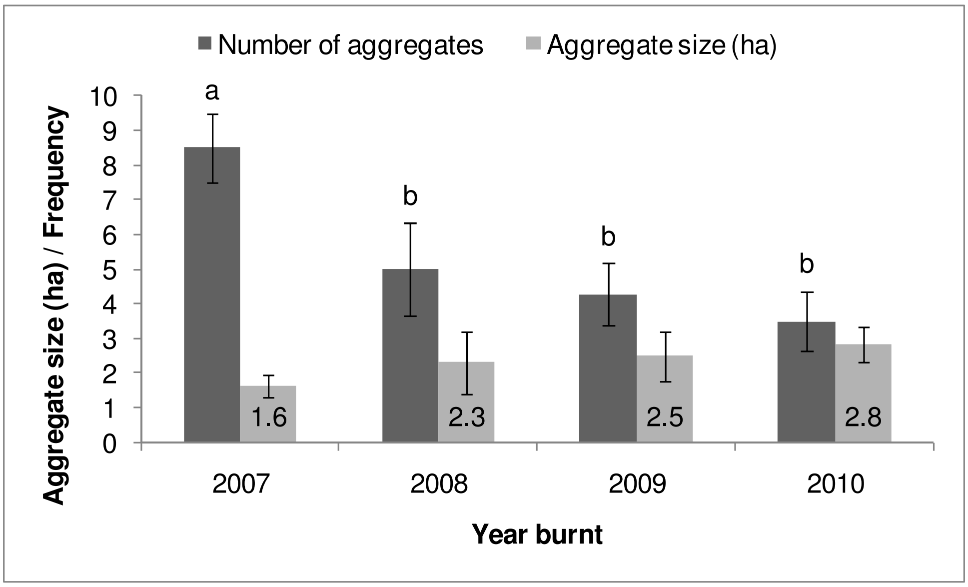


Figure 4-5. Mean aggregate size and frequency (±SE) by year. Bars labelled with different letters are significantly different at $p \leq 0.05$.

4.3.2. Firebreaks

Firebreak width, track width and windrow height were similar between the paired ARN and CBS coupes (Table 4-2). Similarly, the proportion of the perimeter with firebreaks was the same across silvicultural systems (Table 4-2). Across all coupes the mean firebreak width was 10.6 m (SE = 0.4, n = 45), while the mean track width was 3.9 m (SE = 0.1, n = 37). The percentage of the harvested area covered by firebreaks ranged from 4% to 32%, and was 8% higher in ARN coupes (p <0.0001, Table 4-2). The difference in firebreak cover between ARN and CBS coupes decreased significantly over time (4-4b).

4.3.3. Burning conditions

There were no significant differences in burning conditions between ARN and CBS coupes with the exception of Soil Dryness Index, which was slightly higher in ARN coupes (Table 4-3). Although ARN coupes were ignited an average of 25 minutes later than their comparable CBS pairs, this difference was not significant (Table 4-3).

Table 4-3. Mean difference in burn weather conditions for paired ARN and CBS coupes. Means for each silvicultural system are shown (standard deviation in brackets), as well as the mean difference between the paired coupes (ARN-CBS). Tests used, test statistics, n and p-values are shown. Significant differences between the silvicultural systems are indicated in bold ($p \leq 0.05$).

Variable	ARN mean (SD)	CBS mean (SD)	Mean difference (SD)	Test used	Test-statistic	n	*p*-value
Burn start date (date/days)	5 April (13)	6 April (14)	-1.03 (13)	Wilcoxon	126	31	0.9870
Ignition time	2:43 PM (1h20m)	2:18 PM (1h04m)	0h29m (1h40m)	Paired t	1.38	31	0.1772
Temperature (°C)	18 (3.1)	19 (2.8)	-1.03 (3.6)	Paired t	-1.61	31	0.1182
Relative humidity (%)	63 (11)	61 (12)	2.42 (13)	Paired t	1.05	31	0.3035
FFMC - unlogged forest (%)	23 (3.5)	24 (3.9)	-1.35 (4.6)	Paired t	-1.63	31	0.1132
FFMC - logged coupe (%)	14 (2.3)	14 (2.2)	-0.23 (3.1)	Paired t	-0.40	31	0.6920
Soil Dryness Index	92 (27)	87 (23)	5.23 (15)	Wilcoxon	166	31	**0.0236**

FFMC = Fine fuel moisture content.

4.3.4. Seedbed

The proportion of the harvested area falling into the different seedbed classes was similar between silvicultural systems, with the exception of compacted seedbed, of which there was 2% more in ARN coupes (Table 4-4). Although there was no significant difference between burnt seedbed classes (ashbed, burnt to mineral soil, and burnt to litter) when compared individually, when the three classes were combined, significantly less burnt seedbed was created in ARN coupes compared to CBS coupes (Table 4-4). Similarly, there was 4% less receptive seedbed in ARN coupes compared to CBS coupes (Table 4-

4). Seven ARN coupes and four CBS coupes did not reach the target of 66% receptive seedbed, but mean levels of receptive seedbed were 79% and 83% for ARN and CBS coupes, respectively. When all coupes were combined, most seedbed fell within the burnt to litter class (mean = 28%), followed by burnt to mineral soil (mean = 25%), disturbed (mean = 15%) and ashbed (mean = 13%). Just 11% of seedbed was unburnt-and-undisturbed and 8% was compacted. Combining the disturbed and compacted seedbed classes provides an estimate of the total soil disturbance due to harvesting. The proportion of soil disturbed by harvesting averaged 32% (SE = 1.6%) and did not differ between silvicultural systems (Paired t = 1.62, df = 30, $p = 0.115$).

Table 4-4. Mean difference in proportion of the harvested area falling within each seedbed class, proportion of burnt seedbed and proportion of receptive seedbed for paired ARN and CBS coupes. Means for each silvicultural system are shown (standard deviation in brackets), as well as the mean difference between the paired coupes (ARN-CBS). Tests used, test statistics, n and p-values are shown. Significant differences between the silvicultural systems are indicated in bold ($p \leq 0.05$).

Variable	**ARN mean (SD)**	**CBS mean (SD)**	**Mean difference (SD)**	**Test used**	**Test-statistic**	**n**	***p*-value**
1 - Unburnt and undisturbed	0.12 (0.12)	0.10 (0.11)	0.02 (0.10)	Wilcoxon	246.5	31	0.5371
2 - Disturbed	0.16 (0.08)	0.15 (0.08)	0.02 (0.11)	Paired t	0.8356	31	0.4100
3 - Compacted	0.09 (0.06)	0.07 (0.07)	0.02 (0.08)	Wilcoxon	340	31	**0.0278**
4+5 - Burnt to litter	0.26 (0.11)	0.27 (0.11)	-0.01 (0.13)	Paired t	-0.4207	31	0.6770
6 - Burnt to mineral soil	0.24 (0.14)	0.27 (0.12)	-0.03 (0.12)	Paired t	-1.4815	31	0.1489
7 - Ashbed	0.13 (0.09)	0.14 (0.08)	-0.02 (0.09)	Paired t	-1.0791	31	0.1635*
Burnt seedbed (4+5+6+7)	0.63 (0.19)	0.68 (0.19)	-0.06 (0.16)	Paired t	-2.0352	31	**0.0254***
Receptive seedbed (2+4+5+6+7)	0.79 (0.13)	0.83 (0.14)	-0.04 (0.11)	Paired t	-2.0794	31	**0.0462**

* One-tailed *p*

4.3.5. Burn impact on unharvested forest

In total, 109 ha of unharvested forest was burnt in the regeneration burns in ARN and CBS coupes from 2007 to 2010, an amount equal to approximately 7% of the area harvested during that time. The area of unharvested forest burnt followed a negative exponential distribution, indicating that much of the damage was due to a few large escapes. For example, a single escape from an ARN coupe in 2009 burnt 19.3 ha of buttongrass plains outside of the coupe. The mean area of unharvested forest burnt in the regeneration burn was higher in ARN coupes than CBS coupes (2.6 ha vs. 0.9 ha, Table

4-5). This difference was still significant when the burnt area was divided by the area harvested, and the proportion of the perimeter burnt was likewise higher in ARN coupes (Table 4-5). However, there was no significant difference between the silvicultural systems when only burnt area outside of the coupes was considered (Table 4-5). The proportion of burns that escaped was the same in ARN and CBS coupes (13% vs. 10%, Fisher's exact test odds ratio = 0.727, $p = 0.9999$). All measures of burn impact were strongly and positively correlated (Spearman r > 0.62, $p < 0.0001$, n = 62), but there were no significant correlations between firebreak width and any of the measures of burn impact (Spearman r < 0.26, $p > 0.07$, n = 45).

Over four years, 11% of retained aggregate area was burnt in the regeneration burns in ARN coupes (44 ha burnt out of 399 ha retained). Island aggregates were much more susceptible to burning than edge aggregates when both were present within the same coupe: 28% of island aggregate area was burnt compared to 5% of edge aggregate area (Wilcoxon signed-rank W = 132, $p = 0.001$, n = 20). Small island aggregates were also more susceptible to burning than larger islands (Figure 4- 6).

Table 4-5. Mean difference in burn impact for paired ARN and CBS coupes. Means for each silvicultural system are shown (standard deviation in brackets), as well as the mean difference between the paired coupes (ARN-CBS). Tests used, test statistics, n and p-values are shown. Significant differences between the silvicultural systems are indicated in bold ($p \leq 0.05$).

Variable	ARN mean (SD)	CBS mean (SD)	Mean difference (SD)	Test used	Test-statistic	n	*p*-value
Area of unharvested forest burnt (ha)	2.58 (3.90)	0.95 (1.58)	1.63 (2.78)	Wilcox	377	31	**0.0002**
Area of unharvested forest burnt /Harvested area	0.13 (0.24)	0.04 (0.05)	0.09 (0.21)	Wilcox	410	31	**0.0001**
Area of unharvested forest burnt outside coupe (ha)	1.19 (3.45)	0.95 (1.58)	0.24 (2.22)	Wilcox	206	31	0.7107
Proportion of perimeter burnt	0.20 (0.12)	0.14 (0.13)	0.06 (0.14)	Wilcox	329	31	**0.0242**

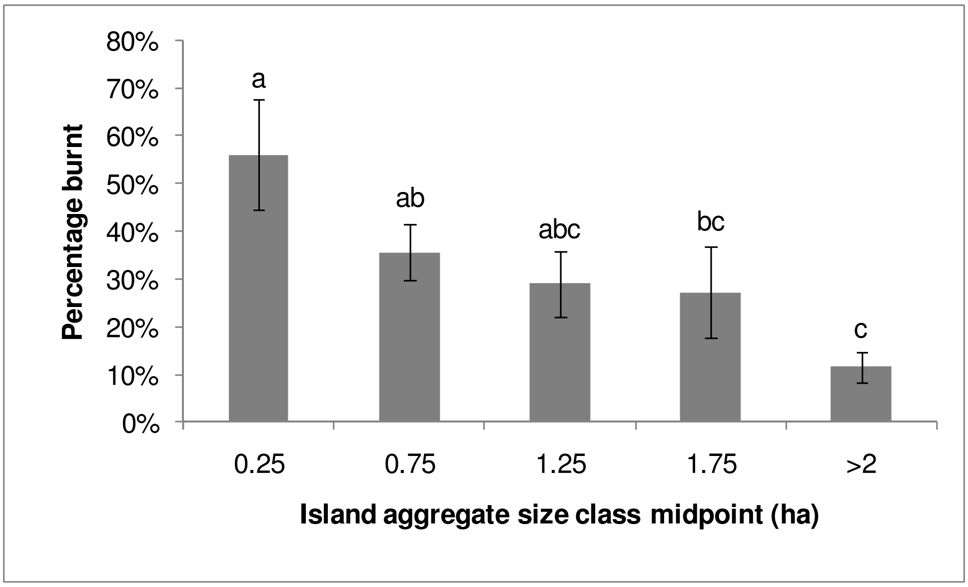


Figure 4-6. Percentage of island aggregates burnt (±SE) by aggregate size. Bars labelled with different letters are significantly different at $p \leq 0.05$.

4.4. Discussion

Regeneration burning and its associated site preparation produced different outcomes in aggregated retention (ARN) coupes in wet eucalypt forest compared to conventional clearfell, burn and sow (CBS) coupes in the same forest type. As predicted, ARN coupes had higher perimeter-to-area ratios, a greater area affected by firebreaks, less burnt seedbed and a greater area of unharvested forest burnt or scorched in the regeneration burn than paired CBS coupes. Contrary to expectations, there was no difference in the proportion of ashbed produced in ARN and CBS coupes, and the risk of the regeneration burn escaping was similar across the two silvicultural systems.

As expected, ARN coupes were more complex in shape than CBS coupes, with greater perimeter lengths and perimeter-to-area ratios. Because of this, firebreaks affected a greater proportion of the harvested area in ARN coupes than in clearfelled coupes (8% more, on average), although this difference decreased over time. Firebreaks continue to affect a substantial area in both ARN and CBS coupes, and may negatively impact regeneration in these coupes. Disturbed and compacted seedbeds have been shown to grow fewer and smaller eucalypt seedlings (King *et al.*, 1993b; King *et al.*, 1993a; Rab, 1994; Pennington *et al.*, 2004; Neyland *et al.*, 2009b). Compacted firebreaks also negatively affect understorey vascular plant biodiversity relative to burnt harvested areas (Hindrum, 2009; Hindrum *et al.*, 2012) and may likewise affect other biodiversity groups such as soil invertebrates and fungi. Firebreak widths did not differ between ARN and CBS coupes, suggesting that the tracking process is similar regardless of silvicultural system. Although the Tasmanian Forest Practices Code requires firebreak widths of at least 5 m (Forest Practices Board, 2000), average widths in this study were double this. This seems excessive, especially as wider breaks do not appear to offer better fire protection, as demonstrated by the non-significant correlations between burn impact and firebreak width. To minimise adverse effects on the soil, the width of firebreaks should be minimised, although it is unlikely that widths can be reduced much below 6 m, due to the size of the machinery used in construction. Therefore, the need for firebreaks and access tracks for browsing control and fire-fighting should also be carefully assessed and planned, and they should only be established where they are absolutely necessary.

Weather conditions at the time of burning were similar across ARN and CBS coupes, although a difference in the mean Soil Dryness Index indicates ARN coupes were burnt with dryer soils and large fuels than CBS coupes. The proportion of burnt seedbed was lower in ARN coupes compared to CBS coupes, as expected, but the difference of 6% is unlikely to be limiting to regeneration, given that the target of 66% receptive seedbed was met, on average, in both ARN and CBS coupes (Forestry Tasmania, 2011b). In addition, there was no difference in the proportion of ashbed created in ARN and CBS coupes, which has been shown to be important for early growth and establishment of eucalypt regeneration (Neyland *et al.*, 2009b). The mean proportion of burnt seedbed found in the operational ARN coupes in this study (63 ± 3%) was considerably higher than was achieved in the two experimental ARN coupes at the Warra Silvicultural Systems Trial (56 and 44%, Neyland *et al.*, 2009). These differences reflect the different burning approaches taken (low-intensity, late-season burns at Warra vs. slow burns in the operational coupes), as well as changes to operational coupe design, including the use of fewer and larger aggregates (Figure 4- 1). In addition to simplifying burning, these changes to coupe design also helped to reduce perimeter-to-area ratios and firebreak cover in ARN coupes. The mean level of soil disturbance due to harvesting (i.e., disturbed and compacted seedbed classes combined) did not differ between silvicultural systems and was relatively steady over time, averaging ~30%. This is within the range reported in other studies (Williamson, 1990; Bassett *et al.*, 2000; Neyland *et al.*, 2009b).

Although several recent silvicultural experiments have included prescribed burning treatments after variable retention harvesting (e.g., Work *et al.*, 2004; Hyvärinen *et al.*, 2005; Lindenmayer *et al.*, 2010), to date few have reported on burn impact (but see Neyland, 2010). In this operational study, burn impact on unharvested forest was considerably greater in ARN coupes than in CBS coupes, but this was largely due to burning in the retained aggregates. When only the area outside of the coupes was considered, there was no difference in burn impact between the two silvicultural systems. It was expected that the lower intensity of the ARN slow burns would lead to longer fire residence times, increasing the risk of escape (Forestry Tasmania, 2009a), but this did not occur. The lack of a difference may be due to greater effort being expended in fire-control efforts after ARN burns (Forestry Tasmania, 2009a).

Approximately 11% of the retained area was burnt or scorched by the regeneration burn in operational ARN coupes. In each of the two ARN coupes at Warra, 11% of the retained aggregate area was also burnt (Neyland, 2010). Although not directly comparable, mortality due to windthrow following aggregated retention harvesting has been widely reported and ranges from 9% to 41% (Rollerson *et al.*, 2002; Hautala *et al.*, 2004; Steventon, 2011; Lavoie *et al.*, 2012). To date, windthrow has not had a large impact following ARN harvesting in Tasmania (Wood *et al.*, 2008).

Within ARN coupes, burn impact was greater in island aggregates than in edge aggregates. This is likely due to increased exposure to the fire in islands, as well as increased drying of the fuels in the smaller islands due to microclimatic edge effects

(Chen *et al.*, 1992). In addition, many edge aggregates are adjacent to streamside reserves, with the result that they are downslope of the harvested area and have higher moisture levels, factors which can reduce the risk of burn impact. Based on the results presented here, edge aggregates are easier to burn around and less susceptible to damage than island aggregates. However, island aggregates help to visually distinguish ARN harvesting from clearfelling. When designing coupe layouts to meet the forest influence target, island aggregates provide more forest influence for a given area retained compared to edge aggregates. For these and other reasons, the current guidelines call for at least one island aggregate to be left in most ARN coupes (Scott *et al.*, 2011).

With average sizes of 1.4 ha and 3.0 ha, respectively, island and edge aggregates in Tasmania are generally much larger than elsewhere (Vanha-Majamaa and Jalonen, 2001; Beese *et al.*, 2003). Island aggregates showed a clear trend of increasing burn impact with decreasing aggregate size, with islands larger than two hectares surviving the burn relatively intact in contrast to more than half the aggregate area being burnt or scorched when islands were less than half a hectare. Lindenmayer (2009) similarly noted that experimental 1.5 ha aggregates were more easily established and maintained through the regeneration burn than 0.5 ha aggregates. It is evident that where prescribed burning is to be used in combination with variable retention, larger aggregates will be better able to withstand the fire. However, some burning of retained aggregates is inevitable and may even be desirable to better emulate the ecological effects of wildfire (Ontario Ministry of Natural Resources, 2002; Hyvärinen *et al.*, 2006; Baker and Read, 2011). Forestry Tasmania currently aims to minimise but not exclude burning in retained aggregates. Burning or scorching more than 30% of the retained area is considered unacceptable (Scott *et al.*, 2011). Based on the data presented here, the existing recommendations for aggregate size (which call for most aggregates to be greater than one hectare) appear to be sufficient to keep burn impact well within this threshold.

4.5. Conclusions and recommendations

Despite having more complex shapes, aggregated retention coupes in wet eucalypt forest can be successfully burnt for regeneration, with adequate levels of receptive seedbed created. Firebreak cover is higher in ARN coupes than in comparable clearfells, but can be reduced by designing coupes with lower perimeter-to-area ratios and using fewer and larger aggregates. To reduce the potential negative impacts of firebreaks in both ARN and CBS coupes in wet forests, firebreak widths should be kept to a minimum and they should only be established where necessary. The area of unharvested forest affected by regeneration burns is greater in ARN coupes compared to CBS coupes, largely due to burning in the retained aggregates. Ensuring that most island aggregates are at least 1 ha should keep burn impact within acceptable levels. To date, there does not appear to be an increased risk of escape associated with ARN burns.

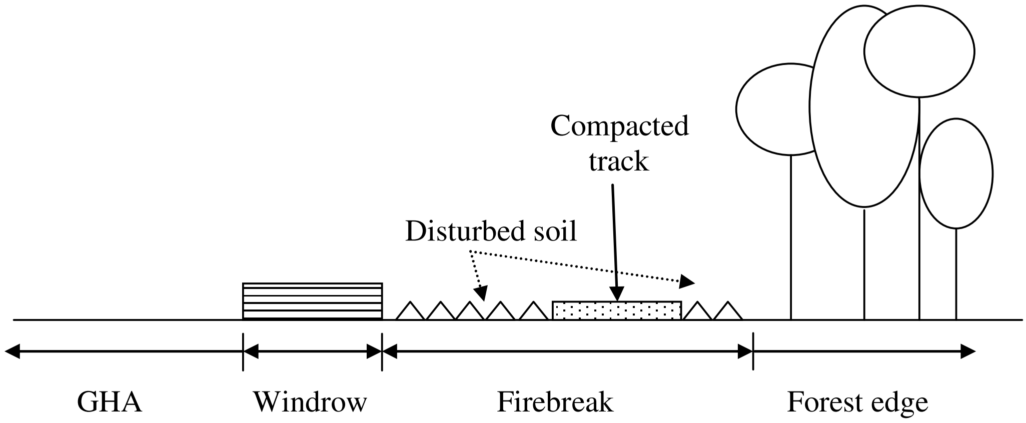
Chapter 5 – Impacts of firebreaks

5.1. Introduction

Wet eucalypt forests are extensive in southeastern Australia, covering over 800,000 ha in Tasmania alone (Forestry Tasmania, 2010a). These productive forests consist of tall eucalypts over a dense understorey of shrubs and small trees; they are significant for biodiversity, carbon storage (Dean and Wardell-Johnson, 2010; Moroni *et al.*, 2010), and wood production (Elliott *et al.*, 2008), and their management has been the subject of intense public scrutiny and debate (e.g., Dargavel, 1995; Public Land Use Commission, 1996). Since the late 1960s, wet eucalypt forests in Tasmania have been harvested and regenerated by clearfelling, followed by a broadcast burn and aerial sowing (Hickey and Wilkinson, 1999). Due to the high fuel loads and intense heat generated by burning operations in wet forest coupes (cutblocks), some protection of the surrounding forest is required to ensure this remains unburnt. Conventional site preparation methods involve the use of an excavator or bulldozer to clear a mineral-earth firebreak at least 5 m wide around the perimeter of the harvested area (Forest Practices Board, 2000; Forestry Tasmania, 2005a). All fine and large fuels are removed from this area, resulting in a strip of disturbed soil and a visibly compacted track, which are bordered by a windrow of displaced debris (Figure 5-1a). Topsoil and organic matter from the firebreak may be displaced onto the windrow, or may be mixed in with lower soil layers.

The introduction of aggregated retention (ARN) harvesting in Tasmanian wet eucalypt forests has led to significant increases in firebreak cover (Chapter 4). Firebreaks in recent ARN and CBS coupes were 10 m wide, on average (double the required width) and firebreak cover ranged from 4-32% (Chapter 4) (Figure 5-1b). Given the large areas affected, soil compaction and soil profile disturbance during firebreak construction could significantly impact productivity at these sites. The effects of firebreak construction are expected to be similar to those observed following harvesting disturbance and snig track (skid trail) construction. These have been studied extensively, and include both short and long-term effects on bulk density, soil strength, nutrient concentrations and eucalypt growth and density. In the short term, bulk density and soil strength increase (Rab, 1996; Williamson and Neilsen, 2000; Croke *et al.*, 2001; Powers *et al.*, 2005); soil nutrient concentrations are decreased (Pennington *et al.*, 2004; Packer *et al.*, 2006); and eucalypt growth and density are reduced on compacted and disturbed areas when compared to control areas (Williamson, 1990; King *et al.*, 1993b; King *et al.*, 1993a; Rab, 1994; Packer *et al.*, 2006). Increases to bulk density and soil strength following soil trafficking have been shown to persist for decades (Greacen and Sands, 1980; Whitford and Mellican, 2011). Long-term reductions in stand volume have also been observed. In eucalypt forests, volumes were reduced by 52-79% on snig tracks 17-23 years after harvest (Pennington *et al.*, 2004). *Pinus radiata* volumes were reduced by 28-38% at 28 years (Murphy *et al.*, 2009), and *Pseudotsuga menziesii* (Douglas-fir) volumes were reduced by 75% at 32 years (Wert and Thomas, 1981). Although these losses are considerable, increased growth on transitional areas adjacent to snig tracks can compensate for reduced growth on the snig tracks themselves, leading to much smaller effects on overall site productivity (estimates of losses range from 0 to 12%) (Wert and Thomas, 1981; Dykstra and Curran, 2000; Whitford *et al.*, 2001a; Pennington *et al.*, 2004). Losses may be more substantial on lower productivity sites (Whitford *et al.*, 2001a), or where disturbance is extensive.

a)



b)

Figure 5-1. a) Diagram showing firebreak configuration and disturbance types and b) aerial view of a recently harvested aggregated retention coupe showing extent of firebreak cover.

The aims of this study were i) to assess the short-term effects of firebreaks on seedling growth and ii) to examine possible reasons for any observed effects. To achieve this, seedling size, foliar nutrient concentrations, soil chemistry and soil strength (penetration resistance) were examined on two disturbance types associated with firebreaks (disturbed soil and the visibly compacted track), on the adjacent burnt windrows and in the general harvest area.

5.2. Methods

5.2.1. Study area

This study took place in eight native forest coupes spread over 50 km in southeastern Tasmania, Australia (Figure 5-2). The coupes were a subset from a larger multi-year monitoring program comparing aggregated retention (ARN) and clearfell, burn and sow (CBS) silvicultural systems (Chapter 2). All coupes were located in tall wet eucalypt forest (Wells and Hickey, 1999), dominated by *Eucalyptus obliqua* L'Herit., *E. regnans* F. Muell, or *E. delegatensis* R. Baker. Average rainfall across the coupes ranged from 1125 to 1800 mm annually (Bureau of Meteorology, 2001). Aspects were varied and elevations ranged from 200 to 670 m (Table 5-1). Soils were either Mottled Brown Kurosols derived from Permian mudstone, or Haplic Red Ferrosols or Mottled Brown Ferrosols derived from Jurassic dolerite (Grant *et al.*, 1995). Slopes were moderate (0-20%) and all coupes were harvested using ground-based machinery except for one, which was partially harvested by cable. Site preparation after harvesting involved clearing a mineral-earth firebreak around the boundary of the coupe using an excavator or bulldozer, in preparation for a high-intensity burn. Total firebreak width ranged from 10.2-16.2 m, while the width of the visibly compacted track within the firebreak varied from 0-7.5 m (Table 5-1). Coupes were broadcast burnt following harvesting to remove slash and prepare the seedbed, and aerially sown with eucalypt seed.

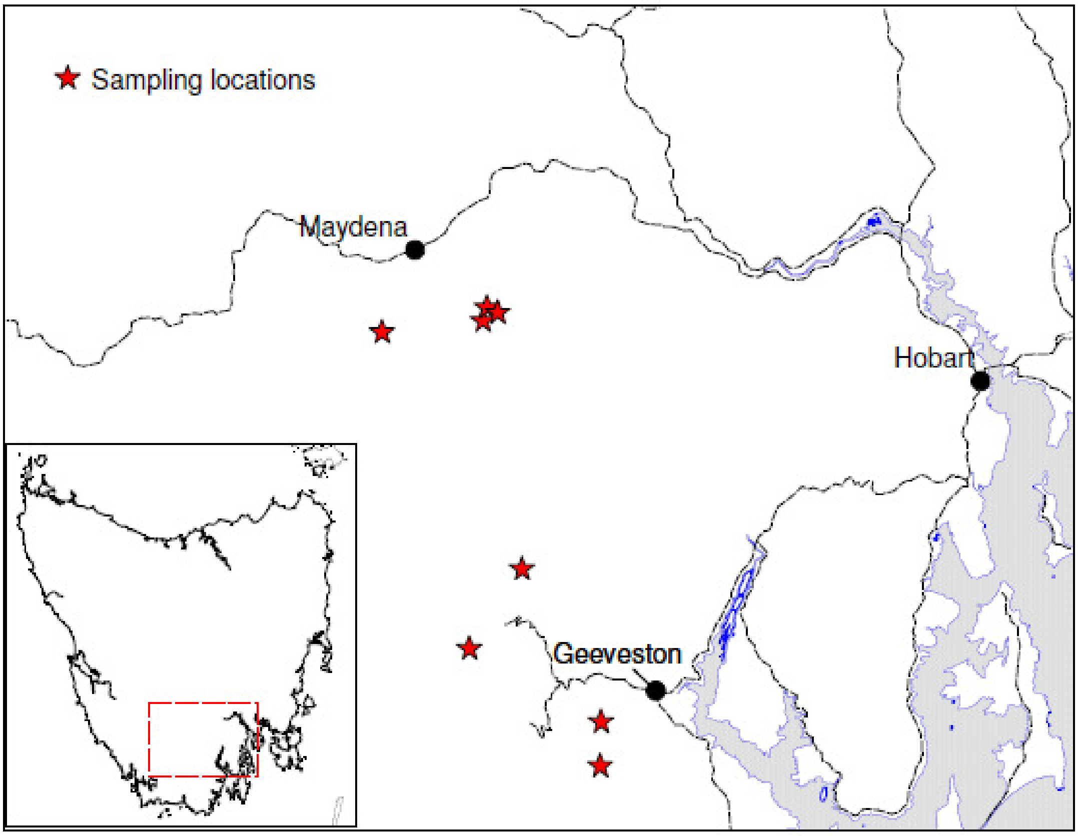


Figure 5-2. The island of Tasmania (inset) and location of sampling sites.

Table 5-1. Site characteristics.

Coupe	District	Year burnt	Silv system	Soil type	Australian Soil classification[1]	Soil texture
SX007A	Derwent	2007	ARN	Permian mudstone	Mottled Brown Kurosol	Clayey
SX018E	Derwent	2007	ARN	Permian mudstone	Mottled Brown Kurosol	Mottled grey and brown clayey
SX018F	Derwent	2007	CBS	Permian mudstone	Mottled Brown Kurosol	Loamy over clayey
SX020A*	Derwent	2008	ARN	Permian mudstone	Mottled Brown Kurosol	Mottled grey and brown clayey
EP081B	Huon	2007	ARN	Jurassic dolerite	Haplic Red Ferrosol	Loamy over clayey
PC023C	Huon	2007	CBS	Jurassic dolerite	Mottled Brown Ferrosol	Yellowish brown mottled clayey
WR013C	Huon	2007	CBS	Jurassic dolerite	Mottled Brown Ferrosol	Mottled grey and brown clayey
KD009E*	Huon	2008	CBS	Jurassic dolerite	Haplic Red Ferrosol	Loamy over clayey

Table 5-1. cont'd

Coupe	Latitude	Longitude	Rainfall (mm yr^{-1})	Aspect	Slope (%)	Elevation (m)	Harvested area (ha)	Total firebreak width (m)	Track width (m)	Windrow width (m)
SX007A	-42°50′09″	146°34′49″	1400	N-NW	12	430-470	19.5	13.3	3.5	9.2
SX018E	-42°48′48″	146°42′41″	1150	NW	7	490-530	21.6	15.0	7.5	5.9
SX018F	-42°49′24″	146°42′21″	1170	SW-W	11	450-560	20.1	10.2	0.0	6.2
SX020A*	-42°48′55″	146°43′30″	1125	NE	11	500-670	37.1	na	na	na
EP081B	-43°13′34″	146°51′02″	1550	SE-SW	20	500-610	40.5	16.2	3.8	9.4
PC023C	-43°07′23″	146°41′11″	1700	SE	11	200-310	44.6	13.7	4.3	15.9
WR013C	-43°03′02″	146°45′14″	1200	E	20	80-200	74.5	10.6	7.4	4.6
KD009E*	-43°11′29″	146°51′09″	1500	E-SE	13	440-520	33.3	na	na	na

*Additional coupes sampled in 2010 for seedling growth and foliar nutrients only
[1] From Grant *et al.* 1995

5.2.2. Sampling design

Soil strength, soil chemistry, seedling size and foliar nutrients were assessed across four replicates of two silvicultural systems on soils derived from two different parent materials (Table 5-1). Six coupes were sampled from January - June 2009, three each on soils derived from Jurassic dolerite and Permian mudstone. Seedling size and foliar nutrients were assessed at two additional coupes in July-August 2010; no soil samples were taken in these coupes. The six initial coupes were burnt in autumn 2007 and the two additional coupes were burnt in autumn 2008. Coupes were sampled from 21-27 months after sowing. The following disturbance categories were considered to be ‘treatments’. The visibly compacted portion of the firebreak (Track) was considered separately from the disturbed portions of the firebreak (DistFB), the adjacent burnt windrow (WR) and the general harvest area (GHA).

From 2-4 sampling locations were established within each coupe. Sampling locations were chosen subjectively based on the presence of all (or most) of the desired treatments and the absence of snig tracks, aggregates or other potentially confounding features. Sampling locations were at least 200 m apart, and were distributed around the coupe to capture different edge aspects. At each sampling location, 20 m long plots were established on each treatment. Plot width varied depending on the width of the firebreak, track and windrow (Table 5-1). Due to the heterogeneous nature of forestry coupes, not all treatments were present at all sampling locations, and for this reason, measurements from all sampling locations were averaged for each treatment and these coupe-level means were used in all analyses. In one coupe (SX018F) no visibly compacted track was observed on the firebreaks, and this treatment was therefore missing for that replicate.

5.2.3. Seedling size

Five well-spaced dominant or co-dominant seedlings were selected for measurement on each plot. Height (cm), basal diameter (mm), and crown width (cm, average of two diameters taken at maximum width and at right angles to the maximum width) were recorded for the selected seedlings on each treatment. Stem volume (cm^3) was calculated according to the following formula:

$$Vol = 1/3(\mathit{pi}) \times (height) \times (diameter/2)^2$$

Species was recorded for each seedling when measured. It is difficult to distinguish between young *Eucalyptus obliqua* and *E. regnans* seedlings in the field, so those species were recorded together. *E. delegatensis* seedlings were recorded at two coupes only (EP081B and SX007A). The *E. delegatensis* seedlings were well-distributed across both treatments and soil types and therefore all species were pooled for analysis.

5.2.4. Foliar nutrients

Foliar samples for nutrient analysis were collected in winter (June-August). Young, fully expanded leaves were sampled from the upper third of the seedling crowns. To obtain a sample of 30 leaves per plot, up to five leaves were collected from the measured seedlings on each plot and additional leaves were collected from nearby seedlings on the same disturbance type. This was done to avoid totally defoliating some of the smaller seedlings. Samples were frozen as soon as possible after collection and kept frozen until analysed. Foliar samples were dried to constant weight at 65°C, then ground for subsequent nutrient analysis. Samples were analysed for Kjedahl nitrogen (N), total phosphorus (P), total potassium (K), total magnesium

(Mg) and total calcium (Ca). Kjedahl N was determined using Buchi digestions and steam distillation. Foliar samples were analysed for K, Ca and Mg concentration by nitric/perchloric acid digest followed by atomic absorption spectrophotometry using a Varian FS220 atomic absorption spectrophotometer. Phosphorus was determined via the Ammonium Molybdate colourimetric determination, using a Cary 1E spectrophotometer.

5.2.5. Soil chemistry

Surface soils were sampled (0-20 cm) to characterise the early growing environment of the establishing seedlings. Three 20 cm soil cores were collected within 1 m of each measured seedling using a hand-held auger with a diameter of 50 mm. Litter was removed prior to sampling but ash was left in place. The three soil cores were broken into small, evenly sized fragments and mixed in a bucket, and a representative sample of approximately 250 g per seedling was sealed in a plastic bag, and stored at 4^{o}C until analysed. Each sample was weighed, then air dried and sieved with a 2 mm mesh. Soil moisture content (%) was calculated as: (wet weight - dry weight)/dry weight x 100. Electrical conductivity and pH were measured according to the method of Rayment and Higginson (1992) in a 1:5 slurry of soil to distilled water using a Wissenschaftlich-Technische Werkstätten (WTW pH 325) meter. Approximately 25 g of each soil sample was sent for nutrient analysis. These sub-samples were analysed for total C and total N concentration on a Perkin Elmer 2400 Series II elemental analyser (Analytical Development Company, Adelaide, Australia; precision of standards ±0.2% for both C and N) after being ground to powder in a Retsch MM200 mixer mill (Retsch GmbH, Haan, Germany). Soil nutrient concentrations for P, K, Ca and Mg were determined following digestion in nitric/hydrochloric acid using the same methods as described above.

5.2.6. Soil strength

An SC900 recording penetrometer (Spectrum Technologies Inc) was used to measure soil penetration resistance (kPa) at 2.5 cm intervals to a maximum depth of 45 cm. Six soil profiles were taken around each measured seedling, and averaged to obtain a mean penetration resistance profile for that seedling. These values were then averaged to obtain means for each treatment (30 -120 profiles per treatment). Soil strength measurements were combined into four depth classes for analysis (0-10 cm, 10-20 cm, 20-30 cm and 30-40 cm).

5.2.7. Data analysis

Coupe-level means were used for all analyses. Relationships between variables were examined using Spearman correlation coefficients. Response variables were analysed for the effect of treatment and soil type using a two-factor nested analysis of variance (ANOVA). Treatment and soil type were fixed effects while coupe nested within soil type was included as a random effect. The model used was of the general form:

$$y_{ijkl} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + x(\beta)_{jk} + \varepsilon_{ijkl},$$

where y_{ijkl} is the ij^{th} observed response in coupe k, μ is the population mean, α and β are fixed effects for treatment and soil type, $\alpha\beta$ is their interaction, $x(\beta)$is a nested term for coupe within soil type, and ε_{ijkl} is the random error.

Variables were transformed where necessary to normalize residuals and equalize variances. Seedling height, diameter, crown width, stem volume, all soil strength variables, EC, Mg, and Ca were log-transformed before analysis, while K was x^{-1} transformed. Wald F-tests were used to assess significance of fixed main effects and their interaction. Where there was a significant treatment effect but no interaction, Fisher's Least Significant Difference was used to assess differences between treatment means. Soil moisture content was initially added as a covariate to all models with soil strength as a response variable, but was not significant in any of the models and was not included in the final models. All analyses were conducted using 'R' software (R Development Core Team, 2012), and an alpha level of 0.05 was used for all tests, unless otherwise noted.

5.3. Results

5.3.1. Seedling size

Seedlings averaged 93 cm in height and 13 mm in basal diameter (Table 5-2). All measures of seedling size were strongly correlated (Spearman r > 0.95, $P < 0.0001$, n = 31), and varied with treatment but not soil type (Table 5-3). Seedling height, basal diameter and crown width were reduced by ~60% on the track and by ~40% on the disturbed firebreak when compared to the general harvest area (Figure 5-3). Stem volumes were even more strongly affected; volumes on the track and the disturbed firebreak were reduced by 95% and 78%, respectively. Seedlings growing on the burnt windrow were similar in size to those on the general harvest area (Figure 5-3). There was significant variability between coupes within soil type for all seedling variables (Table 5-3).

Table 5-2. Summary statistics for seedling size variables and foliar nutrient concentrations.

Variable	**Mean**	**SD**	**Min**	**Max**	**n**
Seedling size					
Height (cm)	93.0	58.1	18.4	239.2	31
Basal diameter (mm)	13.4	7.8	3.6	32.2	31
Crown width (cm)	53.7	26.0	18.3	115.8	31
Stem volume (cm^3)	105.3	151.1	0.7	577.1	31
Foliar nutrient concentrations					
Foliar N (%)	1.54	0.18	1.17	1.88	30
Foliar P (%)	0.102	0.027	0.055	0.157	30
Foliar K (%)	0.357	0.053	0.210	0.485	30
Foliar Mg (%)	0.169	0.026	0.130	0.237	30
Foliar Ca (%)	0.373	0.084	0.210	0.590	30

Table 5-3. Results of ANOVA for effect of treatment and soil type on all response variables. Results shown are p-values from Wald F-tests based on type III sums of squares. Significant effects are shown in bold.

			Source of variation			
Variable type	n	Variable	Treat	Soil type	Treat x Soil type	Coupe (Soil type)
Seedling size	31	Height[1]	**0.000**	0.783	0.978	**0.000**
	31	Diameter[1]	**0.000**	0.797	0.951	**0.015**
	31	Crown width[1]	**0.000**	0.824	0.956	**0.009**
	31	Volume[1]	**0.000**	0.824	0.956	**0.009**
Foliar nutrients	30	Foliar N	**0.009**	0.458	0.788	0.136
	30	Foliar P	**0.000**	0.823	0.784	**0.002**
	30	Foliar K	**0.040**	0.202	0.986	**0.001**
	30	Foliar Mg	0.092	0.247	0.468	0.098
	30	Foliar Ca	0.100	**0.004**	0.887	0.551
Soil chemistry	23	EC[1]	**0.000**	**0.010**	0.647	**0.001**
	23	pH	**0.007**	0.420	0.864	**0.000**
	23	MC	**0.000**	0.352	0.639	0.171
	23	C	**0.021**	0.640	0.964	**0.003**
	23	N	**0.014**	0.653	0.940	**0.002**
	23	P	**0.000**	0.133	0.984	**0.004**
	23	K[2]	**0.000**	**0.023**	0.700	**0.000**
	23	Mg[1]	0.444	0.467	0.960	**0.001**
	23	Ca[1]	**0.000**	0.732	0.929	**0.004**
Soil strength	23	0-10 cm[1]	**0.000**	**0.037**	0.504	**0.038**
	23	10-20 cm[1]	**0.001**	**0.013**	0.573	0.207
	23	20-30 cm[1]	**0.001**	**0.006**	0.844	0.446
	23	30-40 cm[1]	**0.040**	**0.036**	0.506	0.327

[1] Variable was log-transformed before analysis
[2] Variable was 1/x transformed before analysis

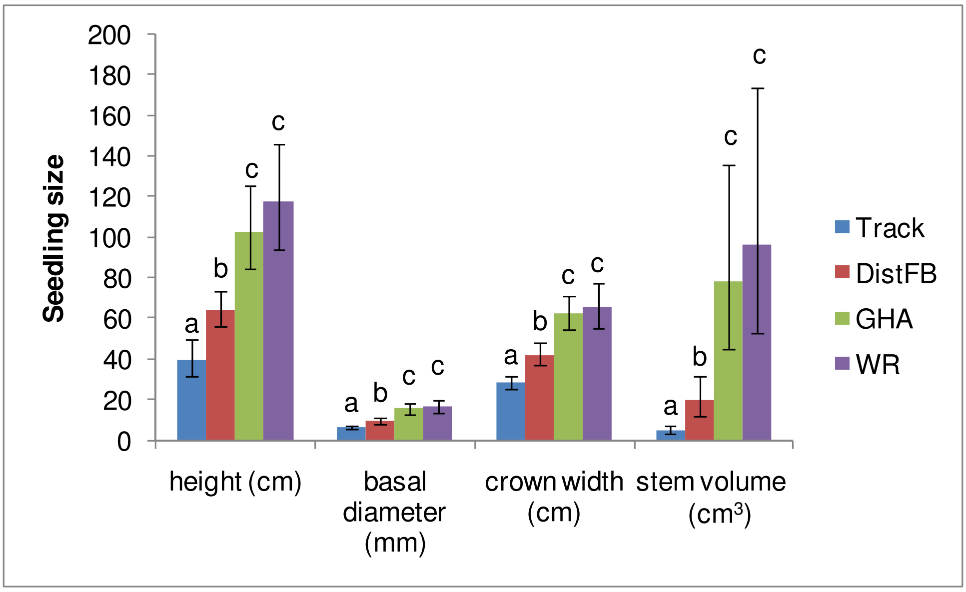


Figure 5-3. Mean (±SE) seedling height, basal diameter, crown width and stem volume on the firebreak track, the disturbed firebreak (DistFB), the general harvest area (GHA) and the burnt windrow (WR). Bars labelled with different letters are significantly different at α=0.05. Values have been back-transformed from transformations used in the analysis.

5.3.2. Foliar nutrients

Foliar N, P, and K varied with treatment but not soil type (Table 5-3), and were lowest in seedlings on the track, followed by the disturbed firebreak, the general harvest area and the windrow. Although all foliar nutrients were at their highest level in seedlings on the burnt windrow, this was not significantly higher than foliar nutrient levels for seedlings on the general harvest area (Figure 5-4). By contrast, foliar N, P and K were reduced by up to 39% in seedlings on the track when compared to the general harvest area and windrow, and foliar P was also reduced in seedlings on the disturbed firebreak compared to the other two treatments.

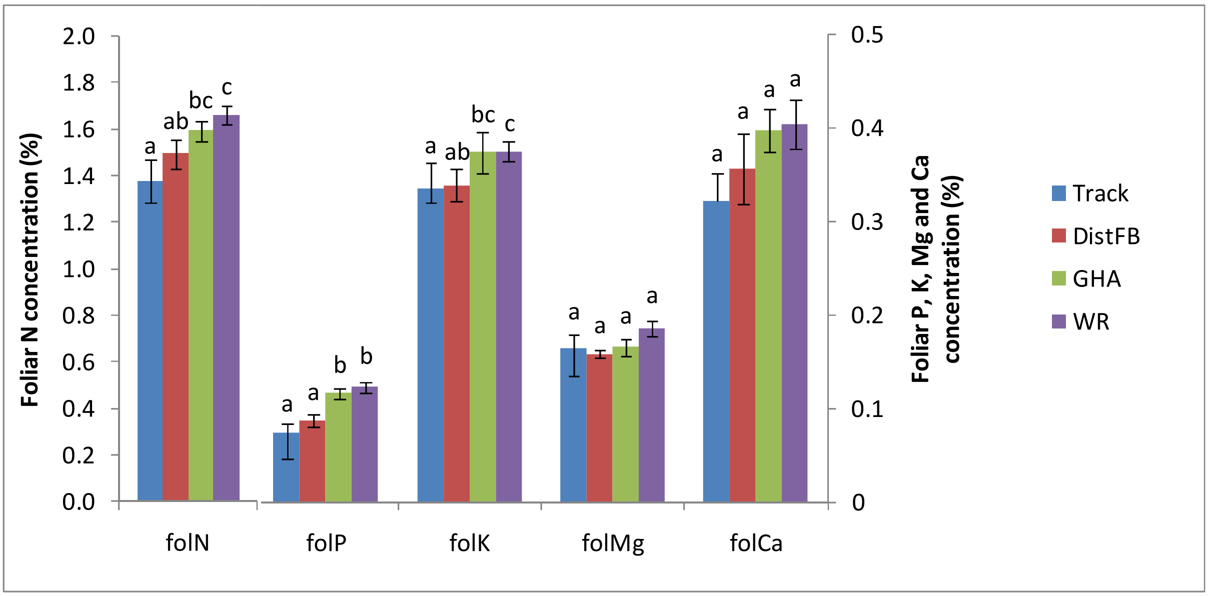


Figure 5-4. Mean (±SE) foliar N, P, K, Mg and Ca concentration on the firebreak track, the disturbed firebreak (DistFB), the general harvest area (GHA) and the burnt windrow (WR). Bars labelled with different letters are significantly different at α=0.05. Values have been back-transformed where necessary.

5.3.3. Soil chemistry

All soils tested were slightly-to-strongly acidic; dolerite soils were less acidic than mudstone soils (Table 5-3, Table 5-4). All soil chemistry variables except for Mg varied with treatment and were lowest in the track and highest in the windrow (Table 5-3, Figures 5-5 and 5-6). C and N concentrations in the track were 24% and 33% lower than in the general harvest area, respectively. Electrical conductivity and pH were 40% and 5% lower in the two firebreak treatments compared to the general harvest area, while P and Ca were reduced by 23% and 70%, respectively. By contrast, soils in the windrow contained 31% more P, 53% more K and had significantly higher pH than soils in the general harvest area. There was significant variability between coupes within soil type for all soil chemistry variables (Table 5-3).

Table 5-4. Summary statistics for soil chemistry and soil strength variables (n=23).

Variables	Mean	SD	Min	Max
Soil chemistry				
MC (%)	62	16	39	95
pH	4.5	0.6	3.7	5.7
EC (dS m^{-1})	0.047	0.020	0.023	0.097
C (%)	7.18	2.13	4.35	11.72
N (%)	0.257	0.090	0.125	0.433
P (%)	0.021	0.007	0.010	0.041
K (%)	0.106	0.065	0.036	0.234
Mg (%)	0.071	0.027	0.032	0.139
Ca (%)	0.050	0.044	0.005	0.177
Soil strength				
0-10 cm (kPA)	528	272	242	1283
10-20 cm (kPA)	1107	335	626	1927
20-30 cm (kPA)	1435	347	788	2099
30-40 cm (kPA)	1606	369	644	2335

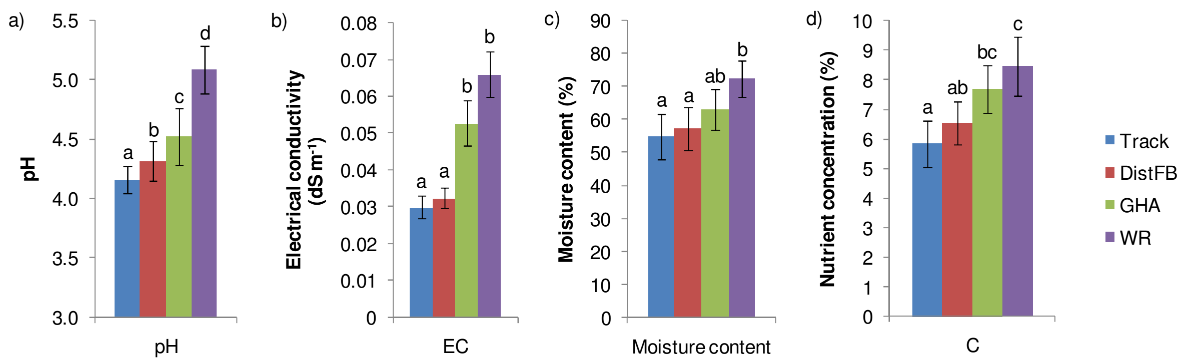


Figure 5-5. Mean (±SE) pH, electrical conductivity, moisture content, and C in the firebreak track, the disturbed firebreak (DistFB), the general harvest area (GHA) and the burnt windrow (WR). Bars labelled with different letters are significantly different at α=0.05. All values except pH have been back-transformed.

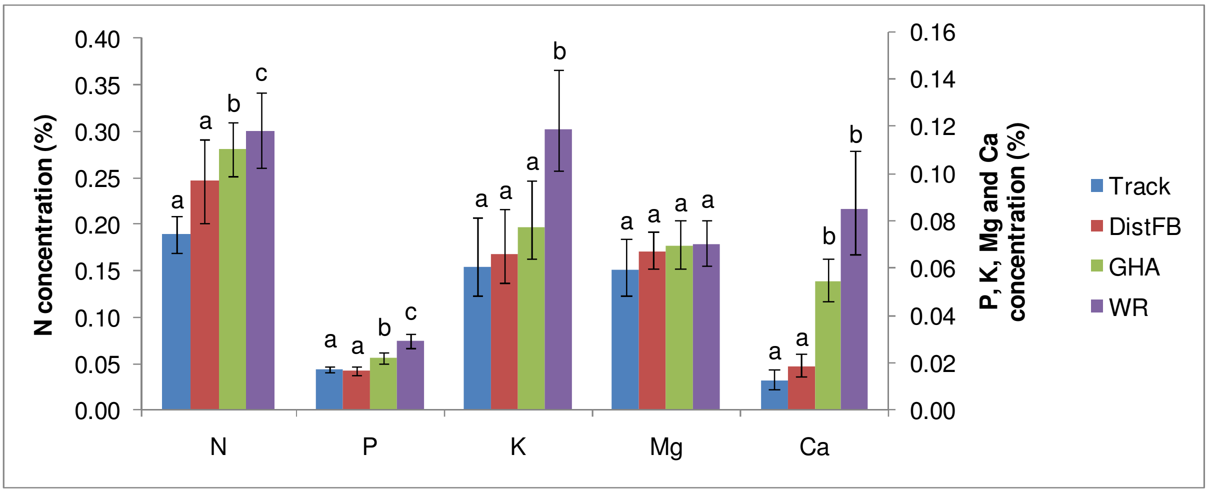


Figure 5-6. Mean (±SE) N, P, K, Mg and Ca concentration in the firebreak track, the disturbed firebreak (DistFB), the general harvest area (GHA) and the burnt windrow (WR). Bars labelled with different letters are significantly different at α=0.05. Values have been back-transformed.

5.3.4. Soil strength

Soil strength increased with soil depth and averaged 528 kPa in the top 10 cm (Table 5-4). Soil strength varied significantly with both treatment and soil type at depths up to 40 cm (Figure 5-7, Table 5-3). Although soil strengths were consistently higher in mudstone soils than in dolerite soils, the treatment response was the same across both soil types (Table 5-3). Penetration resistance was greatest in the track, followed by the general harvest area, the disturbed firebreak and the windrow. Soil strengths were 24-52% higher in the track compared to the general harvest area. The impact was greatest in the 0-10 cm depth class, but extended through the soil profile right to the 30-40 cm depth (Figure 5-7). Soil strengths in the disturbed firebreak were in all cases less than those in the track, and could not be distinguished from either the general harvest area or the windrow. For the 0-10 cm and 10-20 cm depth classes, soil strength in the windrow was significantly less than in the general harvest area (Figure 5-7). All soil strength variables were strongly positively correlated (Spearman r > 0.64, $p < 0.001$, n = 23).

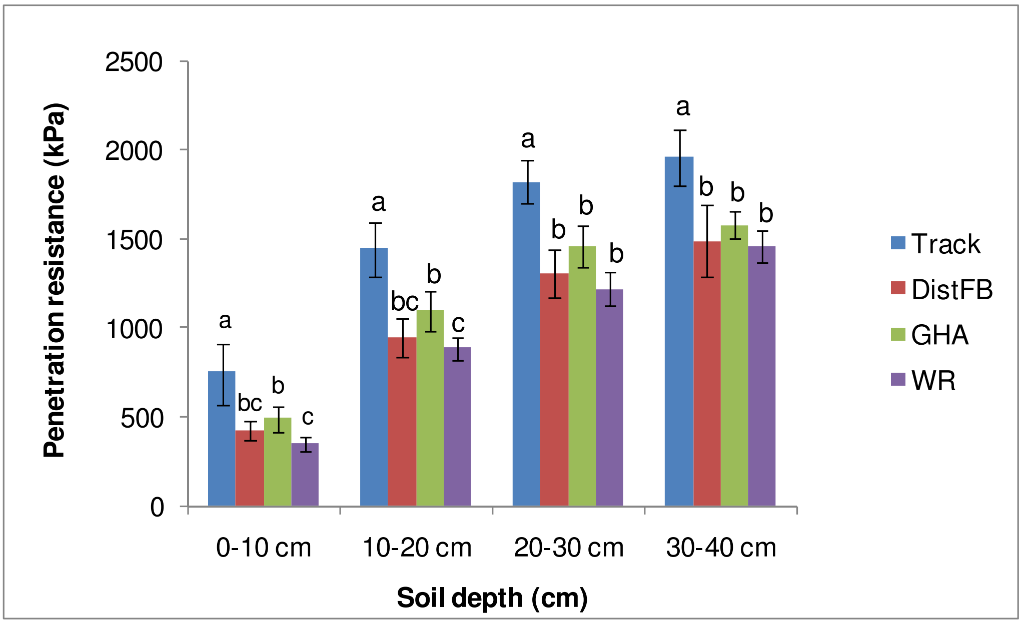


Figure 5-7. Mean soil strength at different soil depths on the firebreak track, the disturbed firebreak (DistFB), the general harvest area (GHA) and the burnt windrow (WR). Within each soil depth class, bars labelled with different letters are significantly different at α=0.05. Values have been back-transformed

5.4. Discussion

This study aimed to quantify the short-term impacts of firebreak construction on seedling size and examine possible reasons for any effects. Substantial and consistent reductions in eucalypt seedling height, basal diameter, crown width and stem volume were observed on firebreaks at age two. The magnitude of these effects varied across the different disturbance types observed on the firebreak. Seedlings on the tracked portion of the firebreak were ~60% smaller than seedlings growing in the general harvest area, while growth on the disturbed portion of the firebreaks was reduced by ~40%.

The reductions in growth observed on the firebreaks can be attributed in part to reduced nutrient supply. Soil C, N, P and Ca concentrations were reduced by 24 – 73% on the firebreaks when compared to the general harvest area. Soil nutrient concentrations are commonly reduced by 30 – 60% on disturbed or compacted soils (Rab, 1994; Rab, 1996; Pennington *et al.*, 2004; Packer *et al.*, 2006). Increased acidity and reduced moisture content on both the firebreak track and the disturbed firebreak may also affect nutrient uptake, contributing to lower foliar N concentrations on these treatments (Taiz and Zeiger, 2010). The decrease in soil nutrients on the firebreak treatments is likely due to both the removal of organic matter including fine and large fuels and humus and to displacement or mixing of the topsoil during firebreak construction (Williamson and Neilsen, 2000; Rab, 2004; Murphy *et al.*, 2009).

Reduced seedling growth on the firebreak track can also be attributed to increased penetration resistance. Soil strengths in the disturbed firebreak were similar to those in the general harvest area and the windrow, while the firebreak track had significantly higher soil strength than other treatments, up to a depth of 40 cm. This confirms that the areas on the firebreaks that appeared to be compacted were, in fact, compacted, and shows that a simple visual assessment is useful for distinguishing between disturbed and compacted soil up to two years after harvest (Whitford *et al.*, 2001b). Soil strength on the firebreak track was 24-52% higher than in the general harvest area. Similar increases in soil strength following trafficking have been reported for wet sites (Williamson and Neilsen, 2000) and clay soils (Ampoorter *et al.*, 2010). Compaction affects the volume of soil that seedlings are able to access, as well as soil moisture and aeration (Greacen and Sands, 1980; Jakobsen, 1983). Root growth is impeded and root concentrations are reduced under compacted soils (Sands *et al.*, 1979; Jakobsen, 1983; Nambiar and Sands, 1992). Misra and Gibbons (1996) found that primary roots of eucalypt seedlings growing at 2500 kPa were only half as long as the roots of seedlings growing at 500 kPA. The maximum soil strengths measured in this study were on the order of 2300 kPa (Table 5-4), and are likely to be contributing to the 60% reduction in eucalypt size observed on the track.

Firebreaks are located around the perimeter of the harvested area. Due to their location near the standing forest edge, edge effects including competition and shading may be contributing to reduced growth on the firebreaks. However, recent studies have found that significant growth reductions occurred only within the first 5 m from the edge in clearfelled low-elevation mixed species forest (Wang *et al.*, 2008), and over a similar distance around small gaps in *E. pilularis* mixed forest (Kinny *et al.*, 2012). The firebreaks in the current study were from 10-15 m wide (Table 5-1), so many of the sampled trees would be outside of the competitive influence of the forested edge and any edge effect is likely to be negligible.

The reductions to seedling growth observed in this study are similar to those reported elsewhere following snig track construction and harvesting disturbance (Williamson, 1990; King *et al.*, 1993a; Rab, 1998; Pennington *et al.*, 2004). However, increased growth was not observed in the windrows adjacent to the firebreaks, despite higher soil nutrient concentrations in this disturbance type. Others have found that reduced growth on snig tracks is offset to some degree by increased productivity in adjacent transitional zones, particularly on more productive sites (Whitford *et al.*, 2001a; Pennington *et al.*, 2004). That was not the case here, although seedlings were only two years old and seedling density was not measured. There were no early differences in treatment response between coupes on productive dolerite soils and those on less productive mudstone soils, although soil strengths were consistently higher in mudstone soils. Re-measurement of these plots at a later age will help to confirm whether the observed early impacts on growth are sustained and whether they differ by soil type, but should include measurements of seedling density across the different disturbance types.

5.5. Conclusions

Firebreak construction in wet eucalypt forest coupes has significant short-term effects on soil physical and chemical properties, foliar nutrient concentrations, and seedling size. Two-year old eucalypt seedlings growing on the firebreak track and the disturbed firebreak were 40% and 60% the size of those growing in the general harvest area, respectively. Despite greater nutrient availability, seedling growth in the burnt windrows was not great enough to offset the reduced growth on the firebreaks at age two. Longer-term studies which include measurements of stand density are needed to accurately determine the magnitude and persistence of these effects.

Chapter 6 - Regeneration

6.1. Introduction

Successful regeneration of wet eucalypt forests depends on adequate seedfall, access to light, availability of receptive seedbed and control of damage due to browsing (Gilbert, 1959; Cunningham, 1960; Gilbert and Cunningham, 1972). For these reasons, clearfelling, followed by a high-intensity burn and aerial sowing has been the silvicultural system of choice in wet eucalypt forests since development of that system in the 1960s (Hickey and Wilkinson, 1999). In recent years the widespread use of clearfell, burn and sow (CBS) silviculture in these forests has raised concerns about aesthetics and impacts on biodiversity, including the possible decline of rainforest species (Lindenmayer and Franklin, 1997; Hickey *et al.*, 2001).

Alternative silvicultural systems (including green-tree retention, structural retention, variable retention, clearfelling-with-reserves) are increasingly being used in native forest management around the world to maintain ecological values and protect biodiversity (Franklin *et al.*, 1997; Vanha-Majamaa and Jalonen, 2001; Gustafsson *et al.*, 2012). These systems retain part of the original stand throughout the following rotation, either as dispersed trees or as small patches (aggregates). Under the Tasmanian Community Forest Agreement, the Tasmanian government committed to using non-clearfell methods for at least 80% of old growth harvesting in State forests by 2010 (Commonwealth of Australia and State of Tasmania, 2005). Based on the results of the Warra Silvicultural Systems Trial (Hickey *et al.*, 2001), variable retention harvesting using aggregated retention systems (ARN) was chosen as the most feasible alternative to clearfelling in old-growth wet eucalypt forests (Forestry Tasmania, 2009a; Neyland *et al.*, 2012). The operational implementation of ARN began in 2005, and over 70 ARN coupes (cutblocks) have now been harvested across Tasmania.

Variable retention in Tasmania aims to "better emulate the natural ecological processes in tall old-growth forest by retaining late-successional species and structures for at least a full rotation" (Baker and Read, 2011). To differentiate variable retention harvesting from clearfelling, the concept of forest influence is used (Mitchell and Beese, 2002; Scott *et al.*, 2011). Forest influence refers to the biophysical effects of the forest stand (or individual trees) on their surrounding environment (Keenan and Kimmins, 1993). A clearfell has been defined as a harvested area large enough that more than half is outside of the above- and below-ground influences of the surrounding trees (Kimmins, 1997). In Tasmania, the goals of variable retention include maintaining forest influence over the majority of the harvested area (Baker and Read, 2011; Scott *et al.*, 2011). This is achieved by retaining patches of trees within or around the coupe boundary such that at least half of the harvested area is within one tree height of retained aggregates. Forest influence for each coupe is calculated using a GIS-based tool, which uses a nominal distance of one co-dominant tree height taken from photo-interpreted stand types to define the area under 'forest influence' (Figure 6-1) (Stone, 1998; Scott *et al.*, 2011).

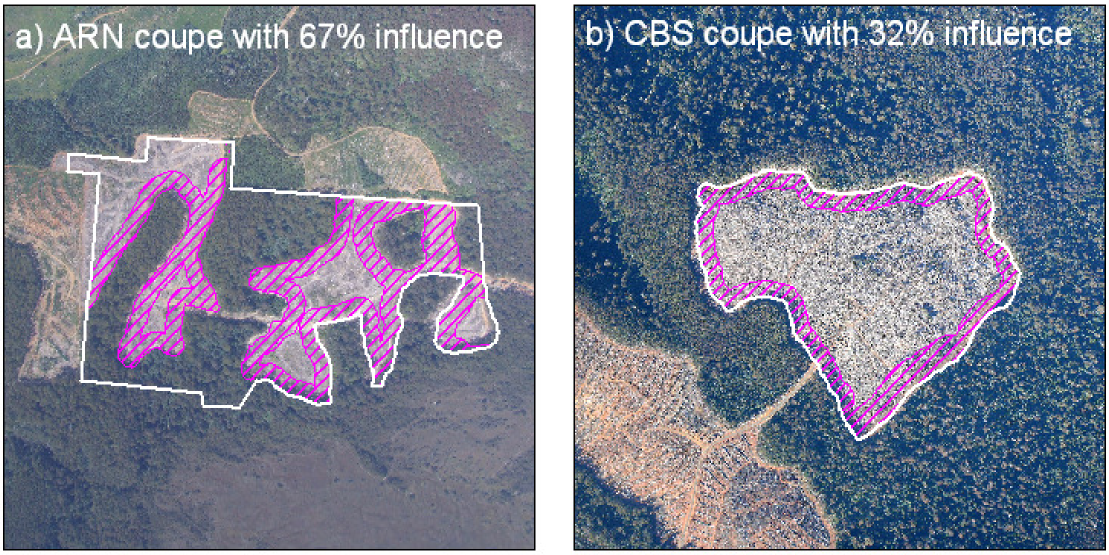


Figure 6-1. An overhead view of an aggregated retention (ARN) coupe and a clearfell, burn and sow (CBS) coupe, showing the area under forest influence. The white line indicates the coupe boundary, while the diagonal lines show the portion of the harvested area within one tree height of standing forest.

The high levels of forest influence associated with alternative silvicultural systems can have both positive and negative effects, depending on the attribute being considered (Mitchell *et al.*, 2004). The use of aggregated retention instead of clearfelling may improve the aesthetics of harvested coupes (Ford *et al.*, 2009b), enhance regeneration of rainforest species (Tabor *et al.*, 2007), and help to meet habitat requirements for some species (Lindenmayer and Franklin, 2002; Lefort and Grove, 2009; Lindenmayer *et al.*, 2010). Eucalypt seedfall may also be enhanced near coupe edges, as eucalypt seed is dispersed by wind and gravity and mainly falls within one tree height of the source (Grose, 1960; Cremer, 1966). However, the complex designs used in aggregated retention harvesting make high-intensity burning difficult and result in less burnt seedbed (Chapter 4), while the higher perimeter-to-area ratio of ARN coupes may lead to increased browsing pressure (Mount, 1976). Retained trees may also suppress the growth of the regenerating eucalypts, particularly where openings are small or influence levels high (Faunt *et al.*, 2006; Wang *et al.*, 2008; Kinny *et al.*, 2012). ARN harvesting has been shown to increase firebreak cover substantially (Chapter 4), and these firebreaks have a negative effect on early seedling growth (Chapter 5). In combination, these factors may lead to reduced eucalypt seedling establishment and growth and lower productivity under this silvicultural system (Neyland *et al.*, 2009b).

This study aimed to determine whether initial stocking, density and height growth of eucalypt seedlings was affected by silvicultural system in Tasmanian wet eucalypt forests. A number of factors which were expected to contribute to regeneration success were also assessed. The following questions were examined:

1. Does ARN silviculture result in reduced eucalypt seedling density, stocking and height at ages one and three years compared to conventional clearfell, burn and sow (CBS) silviculture?
2. Are seed crops in ARN coupes adequate for regeneration purposes, or is sowing necessary?
3. Does browsing pressure increase in ARN coupes compared to CBS coupes?
4. Do regeneration height and density vary with seedbed?
5. Do the higher levels of forest influence in ARN coupes negatively affect regeneration (i.e., is there evidence of suppression or other edge effects)?

6.2. Methods

6.2.1. Study area

The sites and study area have been described in detail in Chapter 4. Sampling was carried out in 62 Tasmanian native forest coupes established from 2007 - 2010, including 31 ARN coupes and 31 paired CBS coupes (Figure 6-2). All coupes were located in mature wet eucalypt forest (Wells and Hickey, 1999), although in some coupes regrowth eucalypts were also present. Although most coupes were harvested using ground-based methods, two ARN coupes and eight CBS coupes were at least partially cable-harvested. Coupes were burnt for regeneration in the autumn (Chapter 4), and aerially sown shortly after burning with locally collected seed at a rate of at least 62,500 viable seeds ha^{-1} (Forestry Tasmania, 2010c). Species composition of the seed mix varied from coupe to coupe but averaged 57% *E. obliqua* L'Herit., 21% *E. regnans* F. Muell, 20% *E. delegatensis* R. Baker, and 2% other *Eucalyptus* spp.

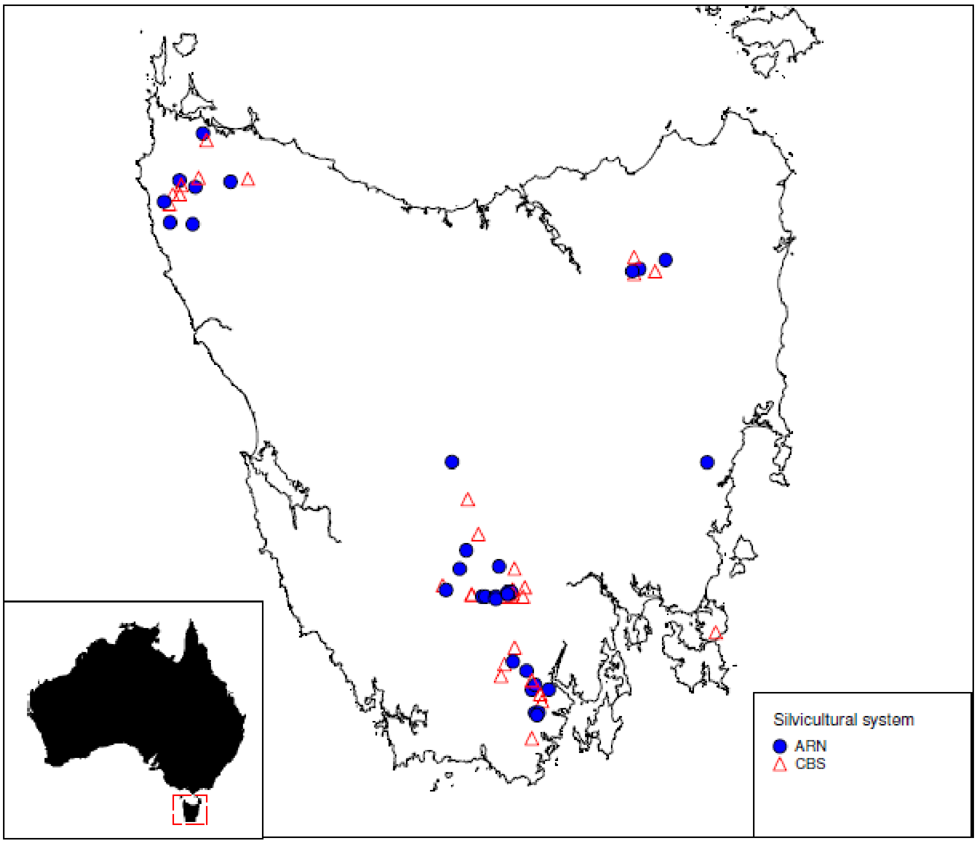


Figure 6-2. Map of the island of Tasmania showing sampled coupe locations by silvicultural system.

6.2.2. Sampling methods

6.2.2.1. Sowing and seed crops

In the first year of the study (2007), detailed seed crop assessments were undertaken in ARN coupes to determine whether aerial sowing would be required. All eucalypt trees which could potentially provide seed to the harvested area were identified and assessed along all or a random sample of aggregates and edge sections. The distance into the edge for sampling varied with tree height and the height of the surrounding vegetation, and ranged from 0 – 30 m (mean 4.7 m). Seed crops were assessed from January to March each year, after harvesting was completed but before the regeneration burn. Coupes which were carried over (i.e., not burnt the same year that harvesting was completed) were re-assessed each year and only the final seed crop survey is reported. Information collected for each tree included: distance from starting point, how far into the edge it was located, and whether the tree was a regrowth or old-growth eucalypt. Crown size and seed capsule density were estimated for each tree, and used to assign it a seed crop score (Table 6-1). Seed crop scores were summed for each 50 m section of edge to obtain a score for that section. A point score of 20 or more is considered high enough for natural seeding to be used (Forestry Tasmania, 2010c), therefore edge sections with scores of at least 20 were considered to be 'stocked' with seed. A mean seed crop score for each coupe was also calculated by choosing a single dominant or co-dominant tree in each 50 m edge section and averaging the scores. In subsequent years, less detailed assessments were conducted to assign an average seed crop score to each ARN and CBS coupe. From 2008 to 2010, a single potential seed tree was selected approximately every 100 m along all coupe and aggregate edges and assessed using the methods described above. The largest-crowned and oldest trees were preferentially selected for assessment, as these trees are most likely to carry large seed crops (Jacobs, 1955). The seed crop score for all 100 m edge segments were averaged to obtain a mean score for each coupe (edge segments with no seed tree counted as 0). The amount of seed (kg ha^{-1}) and species composition of seed sown on each coupe were obtained from Forestry Tasmania's operational database.

Table 6-1. Seed crop values assigned to individual seed trees. In 2007 coupes, scores were summed for all trees within a 50 m edge segment to obtain a point score for that segment. Mean seed crop scores based on a single tree per 50 or 100 m edge segment provide a relative comparison of seed availability within each coupe.

	Crown size rating		
			
Capsule density rating	Large or medium	Small	Very small
 very dense	60	30	10
 dense	40	20	7
 moderate	20	10	3
 sparse	8	4	1
 virtually none	4	2	1
 none seen	0	0	0

6.2.2.2. Browsing

Standard browsing monitoring and control procedures were followed on each coupe by District staff (Forestry Tasmania, 2011c). Fifty eucalypt seedlings were selected and marked on each coupe, and monitored monthly. On coupes where more than 10% of seedlings had been significantly browsed or where mean seedling height had decreased between measurements, browsing control was undertaken. Information on the number of site visits, method of control (shooting or trapping), and numbers of Bennetts wallaby (*Macropus rufogriseus*), brush-tailed possum (*Trichosurus vulpecula*) and pademelon (*Thylogale billardierii*) removed from each coupe were obtained from Forestry Tasmania's mammal browsing database. The following were calculated for each coupe: number and type of browsing control visits (shooting or trapping), total animals removed, number of animals removed per hectare harvested and number of animals removed per visit, and the species composition of the culled animals. The average height of the seedlings on the browsing transects and the mean proportion of those seedlings that had been browsed was also determined for each coupe at 15 months of age.

6.2.2.3. Seedbed

Burn intensity and harvesting disturbance have significant effects on regeneration establishment and growth in wet eucalypt forests (Lockett, 1998; Neyland *et al.*, 2009b). The distribution of seedbed in these coupes immediately following the regeneration burn has been described previously (Chapter 4), and was very similar between silvicultural systems (Table 6-2). In order to more directly relate regeneration success to seedbed, the seedbed at the base of the tallest seedling within each regeneration survey plot was classified into one of six seedbed classes (Table 6-2). This was done during the one-year-old regeneration surveys for the 2009 and 2010 coupes only (see next section).

Table 6-2. Mean difference in proportion of the harvested area falling within each seedbed class, proportion of burnt seedbed and proportion of receptive seedbed for paired ARN and CBS coupes. Means for each silvicultural system are shown (standard deviation in brackets), as well as the mean difference between the paired coupes (ARN-CBS). Tests used, test statistics, n and p-values are shown. Significant differences between the silvicultural systems are indicated in bold. Reproduced from Chapter 4.

Variable	ARN mean (SD)	CBS mean (SD)	Mean difference (SD)	Test used	Test-statistic	n	*p*-value
1 - Unburnt and undisturbed	0.12 (0.12)	0.10 (0.11)	0.02 (0.10)	Wilcoxon	246.5	31	0.5371
2 - Disturbed	0.16 (0.08)	0.15 (0.08)	0.02 (0.11)	Paired t	0.8356	31	0.4100
3 - Compacted	0.09 (0.06)	0.07 (0.07)	0.02 (0.08)	Wilcoxon	340	31	**0.0278**
4+5 - Burnt to litter	0.26 (0.11)	0.27 (0.11)	-0.01 (0.13)	Paired t	-0.4207	31	0.6770
6 - Burnt to mineral soil	0.24 (0.14)	0.27 (0.12)	-0.03 (0.12)	Paired t	-1.4815	31	0.1489
7 - Ashbed	0.13 (0.09)	0.14 (0.08)	-0.02 (0.09)	Paired t	-1.0791	31	0.1635*
Burnt seedbed (4+5+6+7)	0.63 (0.19)	0.68 (0.19)	-0.06 (0.16)	Paired t	-2.0352	31	**0.0254***
Receptive seedbed (2+4+5+6+7)	0.79 (0.13)	0.83 (0.14)	-0.04 (0.11)	Paired t	-2.0794	31	**0.0462**

* One-tailed *p*

6.2.2.4. Regeneration

A systematic survey with random starting point was used to assess regeneration in each coupe approximately one and three years after the regeneration burn. Regeneration was assessed at points located every 20 m along lines 100 m apart. In smaller coupes, additional lines (50 m apart) or additional points (10 m apart) were established to ensure a minimum sample size of 50 points in each coupe. At each sampling point, a 2.26 m radius (16 m^2) circular plot was inspected for acceptable seedlings. An acceptable eucalypt seedling is one with three leaf pairs, which is at least co-dominant with the surrounding vegetation (Forestry Tasmania, 2010b). If an acceptable seedling was present, the plot was marked as stocked; otherwise, it was marked as unstocked. The number of seedlings per plot was counted to allow seedling density to be calculated, and the height of the tallest seedling on each plot was measured to the nearest 10 mm. The percentage of stocked plots was calculated for each coupe. In Tasmania, a coupe is considered successfully regenerated when at least 65% of 16 m^2 plots are stocked at age three years (Forestry Tasmania, 2010b).

Three-year-old regeneration surveys were completed in 2010-2012 for coupes burnt in 2007-2009, respectively. Three-year-old surveys were identical to one-year-old surveys, except that seedbed was not assessed, owing to the difficulty of determining seedbed accurately three years after the burn. In four steep coupes where it was too dangerous to complete a line transect survey at three years of age because of poor footing and reduced visibility, a clustered sampling approach was taken. Ten random sampling locations were chosen across each coupe and a cluster of four standard regeneration plots was completed at each location, for a total of 40 plots per coupe.

6.2.2.5. Forest influence (edge effects)

Forest influence for each coupe was calculated as the proportion of the harvested area within one tree height of standing forest > 15 m tall. Although the forest influence level used to distinguish between ARN and CBS coupes is based on long-term retention only, for this study, the level of 'current' forest influence was determined based on all retained trees that were standing at the time of harvest and for the next three years. The area within one tree height of a standing forest edge was calculated and mapped for each coupe using a GIS-based software program (Scott, 2008). The effects of current forest influence on regeneration were assessed in two ways:

1. A correlation matrix was prepared using coupe-level data to examine the relationship between measures of regeneration success and forest influence level, and

2. All regeneration survey data were mapped in a GIS and a spatial location was assigned to each plot. Within each coupe, the buffer function in MapInfo was used to calculate distance from the standing forest edge for all points within the harvested area. The spatial join function was then used to assign a distance from the edge to each regeneration plot within the following ranges; 0-20 m, 21-40 m, 41-60 m, 61-80 m, > 80 m. Mean stocking, density and height were then calculated for each distance class. Within each coupe, classes containing less than five regeneration plots were excluded from the analysis.

6.2.3. Data analysis

Relationships between variables were examined graphically and using Spearman rank correlations. Hypotheses regarding differences between silvicultural systems were tested using paired t-tests for normally distributed response variables, and the Wilcoxon paired signed-ranks test for variables with non-normal distributions. Differences between years and seedbed classes and differences due to distance from the edge were tested using analysis of variance (ANOVA), followed by Fisher's Least Significant Difference post-hoc test with Holm correction. The following response variables were transformed before analysis to equalise variances and normalise residuals: seed crop score, total browsers removed, and seedling height at age one were square-root transformed; seedling density at age one and three years were log-transformed, and the proportion of burnt seedbed and stocking at age one and three years were arc-sine square-root transformed. Where transformation did not successfully normalise residuals, the non-parametric Kruskal-Wallis test was used to test for differences between years, followed by pairwise Mann-Whitney U tests with Holm correction. All analyses were conducted using R software (R Development Core Team, 2012), and statistical significance was accepted at $\alpha = 0.05$.

6.3. Results

6.3.1. Sowing and seed crops

Sowing rates were similar between the two silvicultural systems (Table 6-3), and coupes were sown with 0.99 kg ha^{-1} (SE = 0.05) of eucalypt seed, on average (containing at least 62,500 viable seeds ha^{-1}). This included remedial and supplementary sowing, which was required for twenty-two percent of coupes across both silvicultural systems (7 of 31 ARN coupes and 7 of 31 CBS coupes).

In 2007, an average of 170 seed trees (min = 91, max = 309) were assessed in and around each ARN coupe (4.8 trees per 100 m of edge). The number of stocked edge segments ranged from 0 - 41% (mean = 16%) in the 2007 ARN coupes. When only one dominant or co-dominant tree per 50 m of edge was counted, the mean seed crop score in the 2007 coupes was 6.1 (SD = 4.8). From 2008 - 2010 a total of 962 seed trees were assessed in both ARN and CBS coupes. Due to their greater perimeter lengths, more seed trees were sampled in each ARN coupe compared to their CBS pairs (Table 6-3). Mean seed crop scores did not vary with silvicultural system (Table 6-3), but did vary from year to year ($F_{(1, 51)} = 17.72$, $p = 0.0003$), and were higher in 2009 and 2010 than in 2007 and 2008 (Figure 6-3a).

Table 6-3. Mean difference in seed and sowing and browsing control variables for paired ARN and CBS coupes. Means for each silvicultural system are shown (standard deviation in brackets), as well as the mean difference between the paired coupes (ARN – CBS). Tests used, test statistics, n and p-values are shown. Significant differences between the silvicultural systems are shown in bold.

Variable	ARN mean (SD)	CBS mean (SD)	Mean difference (SD)	Test used	Test-statistic	n	*p*-value
Seed sown (kg ha^{-1})	1.01 (0.45)	0.97 (0.41)	0.04 (0.59)	Paired t	0.34	31	0.735
Seed crop score[1]	12.9 (7.8)	12.2 (9.9)	1.1 (8.1)	Paired t	0.65	22	0.522
Number of seed trees assessed per coupe[1]	26 (13.5)	17 (8.8)	9.2 (13.9)	Paired t	3.01	22	**0.005**
Proportion of 100 m edge segments with a seed tree[1]	0.79 (0.18)	0.71 (0.21)	0.09 (0.27)	Paired t	1.72	22	0.100
Total browsing control visits	46.6 (41.1)	45.1 (45.7)	1.6 (41.4)	Wilcoxon	264	31	0.517
Total animals removed	174 (114)	182 (160)	-8 (142)	Paired t	-0.31	31	0.760
Animals removed per visit	5.2 (4.9)	6.1 (4.5)	-1.0 (4.3)	Paired t	0.30	31	0.175
Animals removed per ha	10.8 (9.4)	10.0 (10.4)	0.5 (11.4)	Wilcoxon	270	31	0.678
Mean transect seedling height at 15 months (cm)	46 (27)	47 (27)	-1.1 (26)	Paired t	-0.21	26	0.835
Proportion of transect seedlings browsed at 15 months	0.167 (0.162)	0.155 (0.131)	0.012 (0.160)	Wilcoxon	183	25	0.590
Proportion of total animals – Bennetts wallaby	0.074 (0.092)	0.105 (0.099)	-0.031 (0.119)	Paired t	-1.41	30	0.169
Proportion of total animals - possum	0.390 (0.211)	0.339 (0.175)	0.044 (0.172)	Paired t	1.39	30	0.174
Proportion of total animals – pademelon	0.536 (0.223)	0.556 (0.189)	-0.013 (0.192)	Paired t	-0.38	30	0.710

[1] 2008 – 2010 coupes only

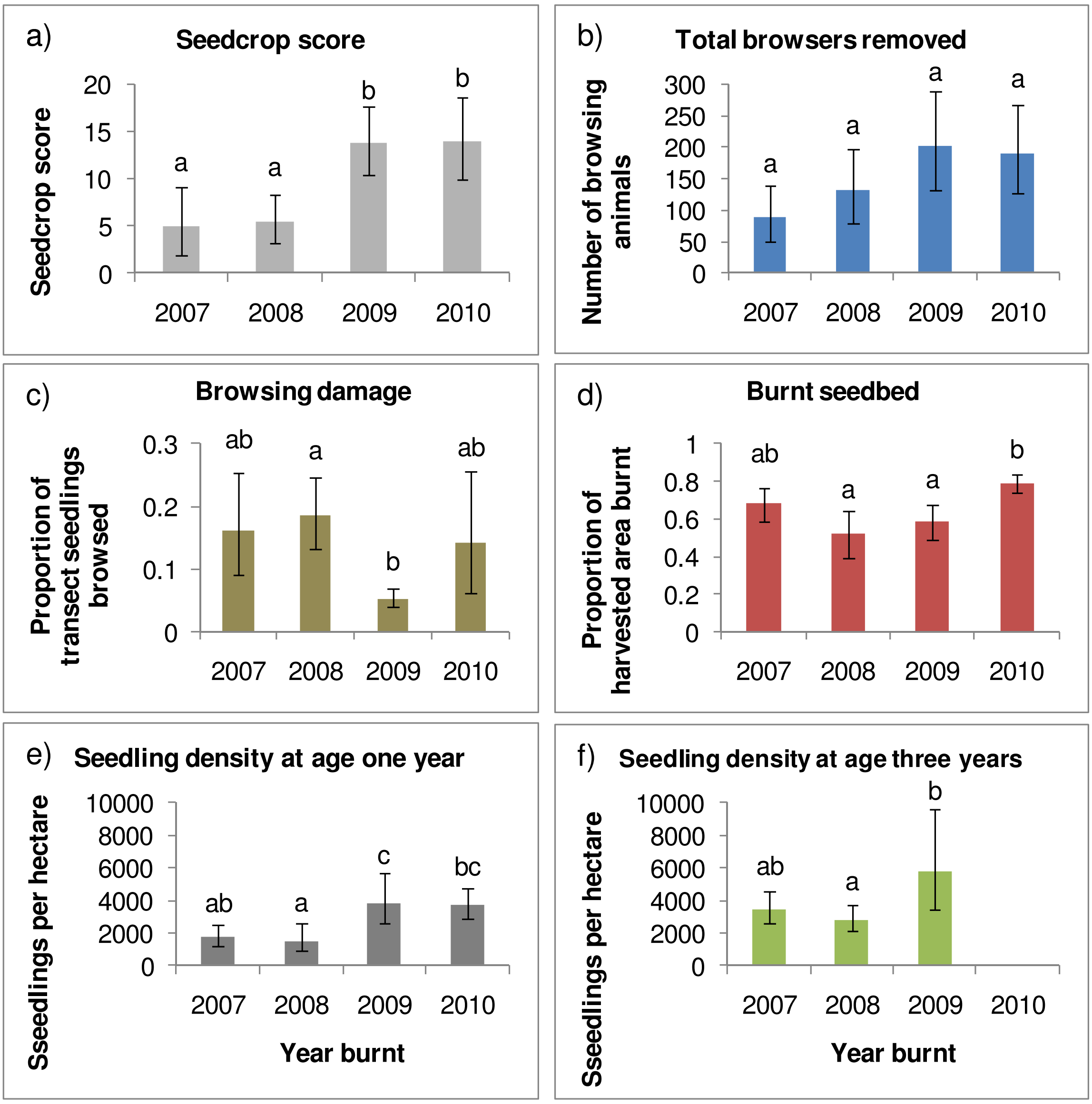


Figure 6-3. Changes in a) seed crop score, b) total number of browsers removed, c) proportion of transect seedlings browsed at age 15 months, d) proportion of burnt seedbed, e) seedling density at age one year and f) seedling density at age three years in ARN and CBS coupes with year burnt. Error bars indicate 95% confidence limits. Bars labelled with different letters are significantly different at $p \leq 0.05$. Back-transformed values are shown for all variables.

6.3.2. Browsing

There were no significant differences in the number of browsing control visits made or the overall number of animals removed from ARN and CBS coupes (Table 6-3). There was also no difference in mean seedling height at age 15 months on the browsing transects, or in the proportion of transect seedlings that had been browsed at the same age (Table 6-3). On average, 178 (SD = 138) animals were removed from each coupe (~10 animals ha^{-1}) and the coupes were visited 45 times (SE = 5.4) for either shooting or trapping. Browsing control continued for an average of 15 months following sowing (min = 4, max = 50). The species composition of culled browsers did not differ between ARN and CBS coupes (Table 6-3). About half of the culled animals were pademelons, ~40% were brush-tail possums and the remaining 10% were Bennett's wallabies. The total number of animals removed per coupe increased over time ($F_{(3, 58)} = 2.95$, $p = 0.040$), although none of the pairwise comparisons were significant after applying the Holm correction (Figure 6-3b). Browsing damage also varied over time ($F_{(3, 49)} = 3.66$, $p = 0.019$), and was lowest in 2009 (Figure 6-3c).

6.3.3. Seedbed

The distribution of seedbed immediately after the burn was very similar between ARN and CBS coupes (Figure 4).There was slightly more compacted seedbed in ARN coupes compared to CBS coupes, and slightly less burnt seedbed, when all burnt seedbed classes were combined (Table 6-2). The proportion of burnt seedbed varied with year burnt ($F_{(3, 58)} = 8.0$, $p = 0.0001$), and was greater in 2010 than in 2008 or 2009 (Figure 6-3d). By contrast, the proportion of disturbed seedbed was the same from year to year, and averaged 30% (data not shown).

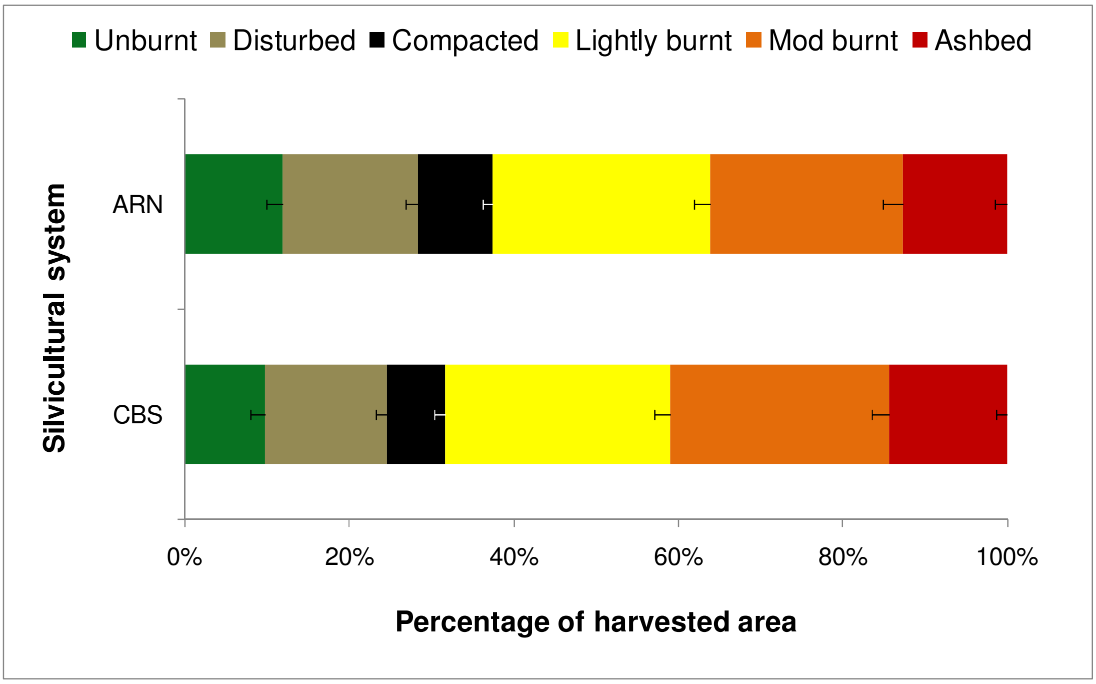


Figure 6-4. Percentage of the harvested area in different seedbed classes by silvicultural system. Bars indicate standard error.

6.3.4. Regeneration

There were no differences in regeneration stocking, density or height between the 31 paired ARN and CBS coupes at one year of age (Table 6-4). The result was the same when only the 2007, 2008 and 2009 coupes were examined. In the 2007-2009 coupes at three years of age, there were again no differences in density or height due to silvicultural system (n = 21). However, three-year-old stocking was 5% lower in ARN coupes when two outliers were removed (Table 6-4). Ninety percent of coupes burnt from 2007 - 2009 experienced further recruitment between one and three years of age. On average, stocking increased by 15% (SD = 15%) and density increased by 1773 stems per hectare (sph) (SD = 2398) between years one and three. Mean stocking at age three years across the 2007-2009 coupes was 82%, and mean seedling density was 4738 sph. At one year of age, 21 coupes out of 42 had less than 65% stocking (11 ARN, 10 CBS), while 28 coupes had seedling densities below 2500 sph (16 ARN, 12 CBS). At three years of age, 5 coupes out of 42 had less than 65% stocking (2 ARN, 3 CBS) and 10 coupes had seedling densities below 2500 sph (5 ARN, 5 CBS).

Seedling height varied significantly with seedbed class at one year of age, but not with silvicultural system (Table 6-5, Figure 6-5a). Seedling height increased with increasing burn intensity and decreased with increasing soil disturbance. Seedlings growing on compacted seedbeds were shorter than seedlings growing on most other seedbed types. Seedling density at age one year similarly varied with seedbed, but also varied with silvicultural system and was higher in ARN coupes than CBS coupes (Table 6-5, Figure 6-5b). Seedling densities were low on both compacted and unburnt and undisturbed seedbeds. Seedling densities at one and three years of age also varied with year burnt (Age 1 density, $F_{(3, 58)} = 6.8$, $p = 0.0005$; Age 3 density, $F_{(2, 38)} = 4.1$, $p = 0.024$) and were highest in 2009 (Figure 6-3e and f).

Table 6-4. Mean difference in eucalypt stocking, density and height for paired ARN and CBS coupes. Means for each silvicultural system are shown (standard deviation in brackets), as well as the mean difference between the paired coupes (ARN – CBS). Tests used, test statistics, n and p-values are shown. Significant differences between the silvicultural systems are shown in bold.

Variable	**ARN mean (SD)**	**CBS mean (SD)**	**Mean difference (SD)**	**Test used**	**Test-statistic**	**n**	***p*-value**
All coupes							
Stocking age one year (%)	69 (13)	69 (17)	-0.5 (19)	Paired t	-0.19	31	0.850
Density age one year (sph)	3633 (3245)	3083 (1663)	550 (3326)	Wilcoxon	256	31	0.885
Height age one year (cm)	40 (18)	39 (18)	1 (20)	Paired t	0.16	28	0.876
2007, 2008 and 2009 coupes only							
Stocking age one year (%)	66 (12)	68 (19)	-1.7 (22)	Paired t	0.36	21	0.725
Density age one year (sph)	3258 (3517)	2617 (1448)	641 (3703)	Wilcoxon	116	21	0.999
Height age one year (cm)	39 (21)	40 (18)	1.4 (18)	Paired t	0.35	20	0.725
Stocking age three years (%)	81 (10)	83 (12)	-1.7 (14)	Wilcoxon	78	21	0.203
Stocking age three years minus two outliers (%)	80 (10)	86 (9)	-5.4 (8)	Paired t	-2.9	19	**0.001**
Density age three years (sph)	5264 (4805)	4186 (2740)	568 (3908)	Paired t	0.65	20	0.524
Height age three years (cm)	236 (76)	244 (77)	-12 (109)	Paired t	-0.48	20	0.636

Table 6-5. Results of two-way ANOVA for seedbed and silvicultural system on seedling height and density at age one year (based on 2009 and 2010 coupes only). Results shown are p-values from Wald F-test based on type III sums of squares. Significant effects are shown in bold.

		Variable	
Source	d.f.	Height	Density
Silvicultural system	1,134	0.09	**0.004**
Seedbed	5,134	**<.0001**	**<.0001**
Silv system x Seedbed	5,134	0.99	0.98

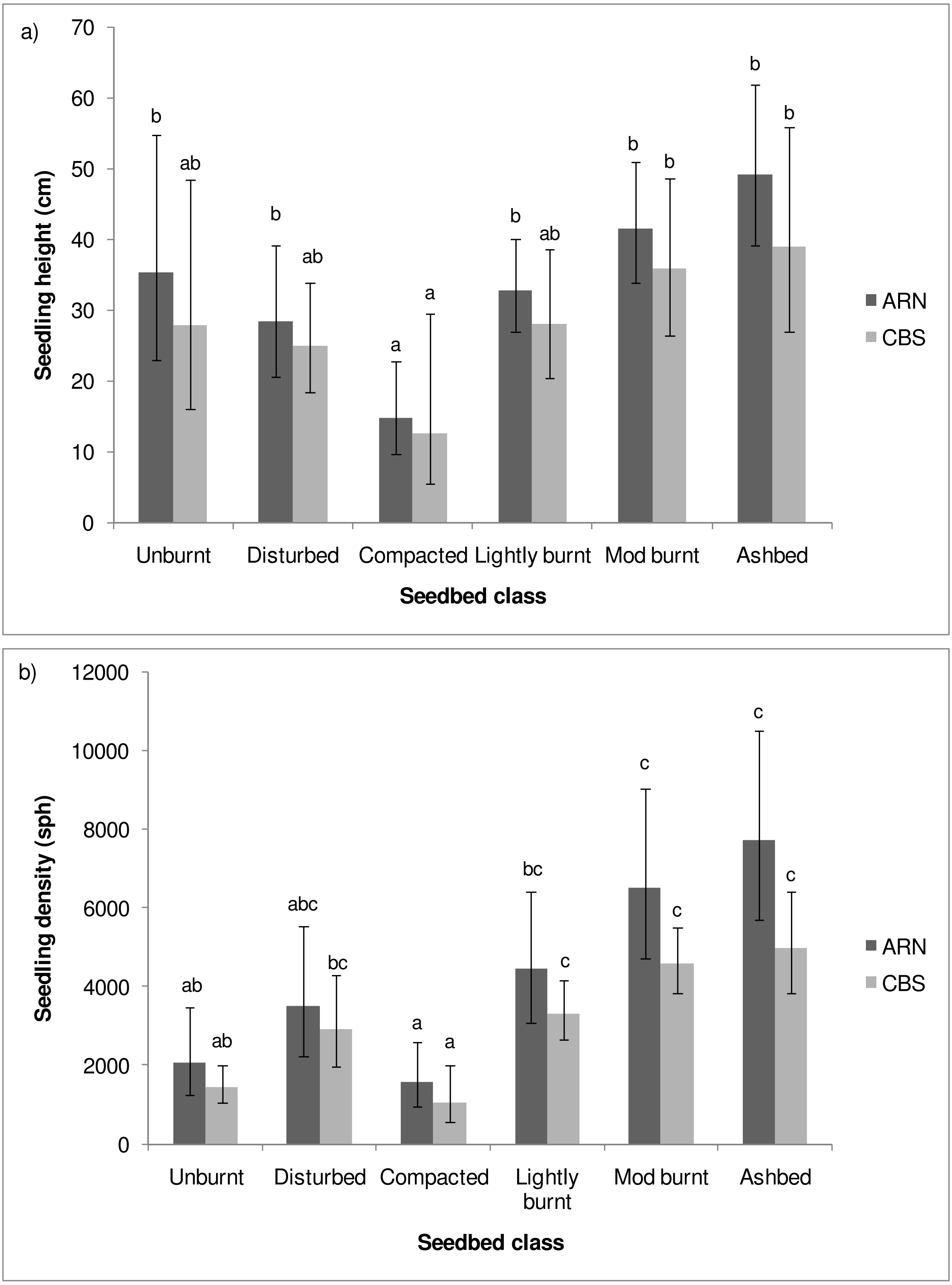


Figure 6-5. Mean seedling a) height and b) density at age one year by seedbed class and silvicultural system (based on 2009 and 2010 coupes only). Error bars show 95% confidence limits. Within each silvicultural system, bars labelled with different letters are significantly different at $p \leq 0.05$. Values have been back-transformed.

6.3.5. Forest influence

The proportion of the harvested area within one tree height of standing trees (currently under forest influence) was 34% higher in ARN coupes compared to CBS coupes (W = 475, $p < 0.0001$, n = 31). Influence level was not significantly correlated with regeneration height or density at one or three years of age (all Spearman r < 0.2, $p > 0.3$). Influence was negatively correlated with stocking at one year of age (Spearman r = -0.28, $p = 0.03$, n = 62), but not at three years of age (Spearman r = -0.17, $p = 0.28$, n = 42). There were no significant changes in three-year-old seedling height or density with distance from edge and this was the same across both ARN and CBS coupes (Seedling height overall $F_{(9, 159)} = 1.15$, $p = 0.332$, interaction $p = 0.322$; Seedling density overall $F_{(9, 159)} = 0.37$, $p = 0.944$, interaction $p = 0.641$; Figure 6-6).

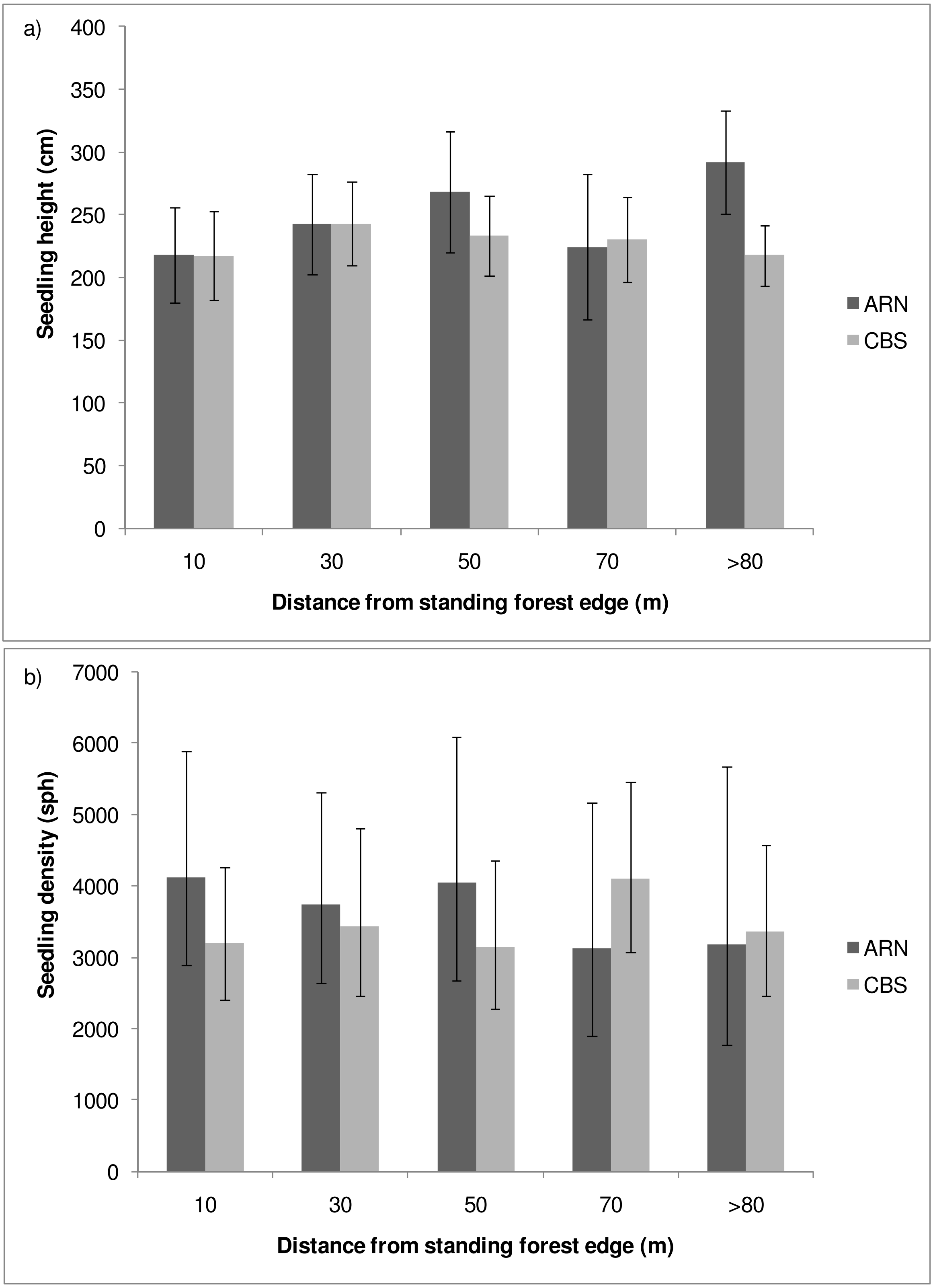


Figure 6-6. Mean seedling a) height and b) density at age three years by distance from edge and silvicultural system. Error bars show 95% confidence limits. There were no significant differences between distance classes. Density values have been back-transformed.

6.4. Discussion

Although variable retention is increasingly being used in Tasmanian wet eucalypt forests as an alternative to clearfelling, the effects of this silvicultural system on eucalypt regeneration establishment and growth were still uncertain when the decision was made to adopt this type of harvesting more generally (Forestry Tasmania, 2004d). This study aimed to assess and compare regeneration success and related silvicultural outcomes after aggregated retention (ARN) and clearfell, burn and sow (CBS) harvesting. No significant negative effects on early regeneration density or growth were observed in ARN coupes, despite more complex coupe designs and much higher levels of forest influence. Seedling density, seed crop scores, browsing pressure and the distribution of burnt seedbed varied more from year to year than with silvicultural system.

Most eucalypt seed falls within a distance of one tree height from the parent tree (Grose, 1957; Cunningham, 1960; Cremer, 1966), thus the potential contribution of seed trees to regeneration in a given coupe depends to a large extent on the configuration of the edges, and the number and distribution of potential seed trees. In the early operational ARN coupes, intensive seed crop surveys and mapping of individual seed trees was undertaken to determine whether aerial sowing would be required. Although influence levels were high enough that it should have been possible to rely on natural seed, seed crops were poor and only 16% of 50 m edge segments were stocked with seed. Based on these results, all of the 2007 ARN coupes were oversown, and routine aerial sowing was subsequently adopted as a standard procedure (Scott *et al.*, 2011). Thus, all ARN coupes in this study were aerially sown with eucalypt seed at rates similar to those in comparable clearfelled coupes, resulting in good distribution of seed across the harvested area and providing a baseline amount of seed on each coupe. Aerially sown seed was supplemented by natural seedfall from retained edge trees in both ARN and CBS coupes. The number of edge sections with a seed tree and the mean seed crop score did not vary with silvicultural system, but the proportion of the harvested area that could potentially have been influenced by natural seedfall (i.e., that was within one tree height of retained trees) was considerably higher in ARN coupes than in CBS coupes. Eucalypt flowering and seed production are highly variable (Cunningham, 1957; Ashton, 1975; Neyland *et al.*, 2003), and this was demonstrated in this study by seed crop scores that varied from year to year, and were highest in 2009 and 2010. It is likely that natural seedfall contributed to the high seedling densities observed in the 2009 and 2010 coupes, and also to the ongoing recruitment observed in most coupes between one and three years of age (Faunt *et al.*, 2006; Neyland *et al.*, 2009b).

Although browsing pressure was expected to increase in ARN coupes due to greater perimeter-to-area ratios and increased availability of cover habitat (Forestry Tasmania, 2009a), there was no difference in the percentage of transect seedlings browsed at age 15 months, the total number of browsing control visits or the total number of animals removed from paired ARN and CBS coupes. Although some studies have found that browsing damage is greater near forest margins (Wahungu *et al.*, 1999), others have found no relationship between browsing damage and distance from forest edge (Bulinski and MacArthur, 1999; Di Stefano, 2003a). Bulinski and MacArthur (2003) found that both area-to-perimeter ratio and the proportion of the perimeter adjacent to forest were significantly related to browsing damage in plantations, but their best model explained only 47% of between-site variation in browsing damage. The coupes in this study may be small enough (< 30 ha, on average) that common browsers are readily able to disperse across them, and are therefore no more likely to cause damage near a forested edge than in the middle of the harvested area (Bulinski and MacArthur, 1999). Browsing damage (the proportion of transect seedlings browsed at 15 months of age) and the number of browsers removed per coupe varied over time, consistent with a number of other studies (Bulinski and MacArthur, 1999; Di Stefano, 2003b). Few studies to date report on the effects of variable retention on browsing, although in Finland, low levels of dispersed retention were associated with reduced browsing damage to seedlings and attributed to higher levels of suitable forage associated with the retained trees (den Herder *et al.*, 2009). In British Columbia, Sullivan and Sullivan (2001) found that feeding damage to pines by *Microtus* spp. was greater in patch-cuts than in clearfelled sites. The environmental factors which predispose coupes to high browsing damage in Tasmania are still not well understood (Walsh and Wardlaw, 2010). These results imply that the increased perimeter-to-area ratios associated with ARN harvesting do not increase browsing pressure or the need for browsing control in wet eucalypt coupes.

There was less burnt seedbed and more compacted seedbed in ARN coupes compared to CBS coupes, but the differences were small. The proportion of burnt seedbed varied over time, reflecting seasonal variation in fuel and weather conditions at the time of burning. Eucalypt seedling density and height were similar in paired ARN and CBS coupes at one and three years of age. Stocking likewise did not vary with silvicultural system at one or three years of age; however, this result was due to the influence of two CBS coupes with unusually low stocking. One of these was a cable coupe which received a poor burn and thus had poor establishment, while the other coupe was well stocked at one year of age but by age three was suffering from weed competition. When the influence of these two outlying coupes was removed, stocking at age three years was 5.4% lower in ARN coupes compared to paired CBS coupes. This is in line with the 6% difference in burnt seedbed that was observed in the same coupes, but contrasts with the results in the experimental coupes at the Warra SST, where seedling densities and stocking were much lower in two ARN coupes compared to two clearfelled coupes (Neyland *et al.*, 2009b). However, the Warra ARN coupes were not aerially sown, and also had considerably lower levels of burnt seedbed than were achieved in this study. In other Australian studies, alternative silvicultural systems have resulted in either lower eucalypt stocking and density (Van der Meer *et al.*, 1999; Bassett *et al.*, 2000) or reduced survival and growth (Lutze and Faunt, 2006) when compared to clearfell, burn and sow silviculture. In contrast, at a montane coastal site in British Columbia, 10-year old planted conifer growth was found to be similar in an aggregated retention treatment (1.5 ha patchfells) and a 69 ha clearfell (Mitchell *et al.*, 2007). In this study, there were few differences in early regeneration success between ARN and CBS coupes at three years of age; however, continued monitoring will be needed to quantify the longer-term effects of variable retention harvesting on productivity and growth.

A key goal of variable retention harvesting is to maintain higher levels of forest influence across the harvested area, to enhance connectivity across the landscape and facilitate re-colonisation of the regenerating stand by late-successional species (Franklin *et al.*, 1997). Although the level of forest influence was significantly higher in ARN coupes compared to CBS coupes in this study, no significant relationships were found between forest influence and regeneration density or height to three years of age. Similarly, no changes in regeneration density or height were observed with increasing distance from the standing forest edge (Figure 6-5). In other studies, the impact of retained trees on growth of eucalypt regeneration has been significant, particularly in dry forests and where dispersed trees are retained (Bradshaw, 1992; Bassett and White, 2001). Both the size of openings and the spatial pattern of retained trees are important, as is the measure of growth used. Diameter and basal area growth have been affected more than height growth in some studies (Dignan *et al.*, 1998; Wang *et al.*, 2008), although other studies have found all measures of eucalypt seedling size to be highly correlated and largely interchangeable (Neyland *et al.*, 2009b). Aggregated retention (whether retained as patches or as edges) tends to suppress growth of regeneration less than similar levels of dispersed retention (Aubry *et al.*, 1999; Coates, 2000; Palik *et al.*, 2003). Significant growth reductions have also been found in small gaps (< 2 ha) compared to larger clearfells (Bowman and Kirkpatrick, 1986; Van der Meer *et al.*, 1999; Faunt *et al.*, 2006). Reductions in growth are generally attributed to competition for light or moisture (Dignan *et al.*, 1998), although moisture is less likely to be a factor in wet eucalypt forests where rainfall is relatively high (Battaglia and Wilson, 1990).

In two recent studies suppressive growth effects in wet forests were found to extend only 5 m from the forest edge at 15 - 36 years of age (Wang *et al.*, 2008; Kinny *et al.*, 2012). This short extent of edge effects reported for eucalyptus regeneration in wet forests may help to explain the lack of relationship between distance from edge and regeneration growth in this study. The resolution of sampling used here (20 m x 100 m) may not have been sufficient to capture edge effects effectively. This seems likely, given that mineral earth firebreaks were established around most coupe boundaries, and have been shown to reduce seedling height growth in the short-term (Chapter 5). Alternatively, it is possible that competition from edge trees is not an important factor at age three in these coupes, in part because of the relatively low density at which seedlings are establishing. Competitive effects may become more pronounced once crown closure is reached (Florence, 1996), and seedlings may become more shade intolerant as they get older, increasing any effect of light competition (Ashton and Turner, 1979). Further research is required to quantify the effects of competition from edge trees on regeneration growth in wet eucalypt forests. These studies should measure seedling diameter or basal area as well as height, and the sampling design will need to account for the confounding effect of firebreaks and the short distances over which edge effects have manifested in other studies.

One-year old regeneration density and height within each coupe were strongly related to seedbed class. More and taller seedlings were found on well-burnt seedbeds, while fewer and shorter seedlings were found on compacted and unburnt seedbeds. These results support the conclusion of many other studies that well-burnt seedbed is critical for good seedling establishment and vigorous early growth in wet eucalypt forests (King *et al.*, 1993b; Lockett, 1998; Van der Meer *et al.*, 1999; Neyland *et al.*, 2009b). However, regeneration density also varied with year burnt, and was highest in 2009, a poor burning year which produced lower amounts of burnt seedbed, but high seed crop scores and large numbers of browsers removed. Year-to-year variation in regeneration success is also reported in other studies (Faunt *et al.*, 2006), and likely reflects differences in seedbed, seed crops, and the many other biotic and abiotic factors that can influence eucalypt seedling establishment, survival and growth (Stoneman, 1994).

Ongoing recruitment helped to ensure that many coupes which were inadequately stocked at age one were adequately stocked by age three years. This is similar to the findings of Neyland *et al.* (2009b) at the Warra Silvicultural Systems Trial. Lockett and Goodwin (1999) also found that seedling densities increased for some years after sowing, and reached a peak between two and five years of age. Despite this ongoing recruitment, low seedling densities across both ARN and CBS coupes may be of concern. Almost one quarter of coupes had seedling densities of less than 2500 sph at three years of age. Naturally disturbed wildfire-regenerated wet eucalypt stands, by contrast, often have initial seedling densities in excess of 100,000 sph and experience substantial competition leading to rapid reductions in stand density and strong selection for the best and fastest-growing seedlings (Gilbert, 1959; Griffin and Cotterill, 1988). In regrowth wet eucalypt forests, initial densities of at least 2500 sph are considered adequate to allow for commercial thinning and early production of sawlogs in native forests (Forestry Tasmania, 2010b), although considerably higher densities may be needed to avoid problems with large branches and increased defect (Wardlaw *et al.*, 1997), T. Wardlaw, pers. comm.). In good seed years (e.g., 2009), retained seed trees can have a significant influence on seedling density, but these seedlings will necessarily be concentrated around the coupe edges rather than being uniformly distributed. Given that over 20% of both ARN and CBS coupes also required supplementary sowing, it may be worth increasing operational sowing rates for wet eucalypt forests.

6.5. Conclusions

Aggregated retention coupes in wet eucalypt forest can be regenerated to a similar standard as conventional clearfell, burn and sow coupes, with similar seedling density and height measured to three years of age. The early regeneration success observed in ARN coupes in the current study can be attributed to: i) the development of new burning methods, which ensured that seedbed distributions in ARN coupes were very similar to those in CBS coupes, ii) the adoption of aerial sowing as standard procedure in ARN coupes, which ensured good distribution of seed across the harvested area, and iii) the lack of any observed increase in browsing damage or edge-related growth suppression. Large eucalypts retained around the coupes provided an ongoing source of seed and recruitment. Seedling density increased by an average of 1770 sph between the ages of one and three years, but 20% of coupes required supplementary sowing, and nearly 25% of coupes had seedling densities below 2500 sph at three years of age. A review of operational sowing rates in wet eucalypt forests is recommended. Early regeneration height and density were strongly related to seedbed, with more and taller seedlings growing on well-burnt seedbeds and fewer and shorter seedlings on compacted seedbeds. Although these results indicate that initial silvicultural goals for regeneration can be met after variable retention harvesting in wet eucalypt forests, more detailed study of edge effects is needed, and longer-term research will be required to accurately assess the rotation-length effects of variable retention silviculture on productivity and growth.

Chapter 7. Synthesis and discussion

7.1. Thesis aims and major research outcomes

Variable retention silviculture aims to maintain mature-forest values and ecosystem processes at the site level by retaining patches of forest or individual trees (Franklin *et al.*, 1997). Retained areas are intended to maintain old-growth species and structures within the managed forest landscape, in order to provide continuity of structure and function, enhance landscape connectivity, and influence the regenerating forest (Franklin *et al.*, 1997; Baker and Read, 2011; Scott *et al.*, 2011). However, these ecological objectives must be balanced against silvicultural considerations such as obtaining successful regeneration and satisfactory growth rates and minimising damage to retained trees. This study is the first to assess regeneration success and related silvicultural outcomes after operational variable retention harvesting in wet eucalypt forests, and to compare these to outcomes after conventional clearfell, burn and sow harvesting. The major hypothesis was that regeneration success would be reduced in coupes harvested using aggregated retention, due to a combination of factors including the difficulty of burning harvesting residues, less receptive seedbed being created, and the potential for increased browsing pressure and seedling suppression due to greater forest influence and edge effects.

A total of 38 aggregated retention (ARN) coupes and 31 paired clearfell, burn and sow (CBS) coupes harvested from 2003 – 2009 and regenerated from 2007 – 2010 were monitored to address questions around forest influence and retention levels, the persistence of aggregates, the effects of site preparation including new ‘slow burning’ methods, and early regeneration results. Retention levels in ARN coupes were relatively high, averaging 28% of total coupe area. Levels of forest influence were significantly higher in ARN coupes than in CBS coupes, and 90% of ARN coupes met Forestry Tasmania's target for 50% forest influence (i.e., the majority of the harvested area is within one tree height of trees retained for the next rotation). ARN coupes had higher perimeter lengths and smaller felled areas than comparable CBS coupes, leading to much higher perimeter-to-area ratios. This resulted in relatively high firebreak cover in ARN coupes (20%, on average); however, mean firebreak cover decreased over time. Firebreaks negatively affected soil properties including nutrient levels, pH and penetration resistance and reduced seedling growth at two years of age in both ARN and CBS coupes.

The use of variable retention silvicultural systems did not significantly increase harvesting damage or windthrow, and overall windthrow levels were low. However, the regeneration burn affected more than twice the area of unharvested forest around ARN coupes compared to CBS coupes, due mainly to burning in the retained aggregates. Larger island aggregates were less prone to windthrow and burn impact than smaller ones. New 'slow burning' prescriptions were very effective, with an average of 79% (by area) receptive seedbed created in ARN coupes and only 6% less burnt seedbed created than in CBS coupes. Both ARN and CBS coupes were aerially sown to ensure sufficient seed supply. Eucalypt seedling density and height were similar in ARN and CBS coupes at both one and three years of age, while stocking was marginally lower in ARN coupes at three years of age. Browsing pressure was not increased by aggregated retention silviculture, and no growth suppression due to edge effects was evident. Ongoing recruitment in both ARN and CBS coupes led to increases in seedling density of ~ 1500 sph between the ages of one and three years, but stocking and densities were low compared to densities that occur following wildfire, and were below desired levels in 12% and 24% of three-year-old coupes, respectively.

7.2. Discussion

7.2.1. Retention and influence levels

With an average of 28% of the productive coupe area retained, retention levels in Tasmania are high compared to elsewhere (Tuchmann, 1996; Beese et al., 2003; Gustafsson et al., 2012), while influence levels are similar to those achieved during VR implementation in coastal British Columbia (Bunnell and Dunsworth, 2009). The high retention levels are due, in part, to the decision not to use dispersed retention in these forests, because of the risk of fire damage to the retained trees (Neyland, 2004) and the difficulty of harvesting around dispersed trees in old-growth wet eucalypt stands safely (Neyland *et al.*, 2009a). Retained aggregates are safer for forest operations and less prone to fire damage than single dispersed trees (Neyland et al., 2012), but also require more trees to be retained in order to meet the 50% influence target. When only aggregated retention is used, there is a trade-off between the size and dispersion of retained aggregates and the level of forest influence (Figure 7-1). For a given level of retention, the level of forest influence decreases with increasing aggregate size. The size of retained patches in this study is relatively large (most > 1 ha) and has been increasing (average size of 2.1 ha in 2010), because larger aggregates are less likely to be damaged in the regeneration burn (Chapter 4). The ecological benefits from larger aggregates are also expected to be greater (Baker et al., 2009). However, there may be diminishing ecological returns with increasing retention level (Bunnell and Dunsworth, 2009), and there is a recognised need to keep average within-coupe retention levels below 30% in order to maintain sawlog supply and manage cost increases (Forestry Tasmania, 2009a). The distribution of stand types retained in aggregates is currently intermediate between that of harvested areas and that of other reserves around the coupe (Chapter 2). There may be opportunities to preferentially locate aggregates in less productive but biologically diverse areas (e.g., patches dominated by rainforest species), which will help to minimise losses in overall stand productivity, while still maintaining key ecological values (Beese *et al.*, 2003).

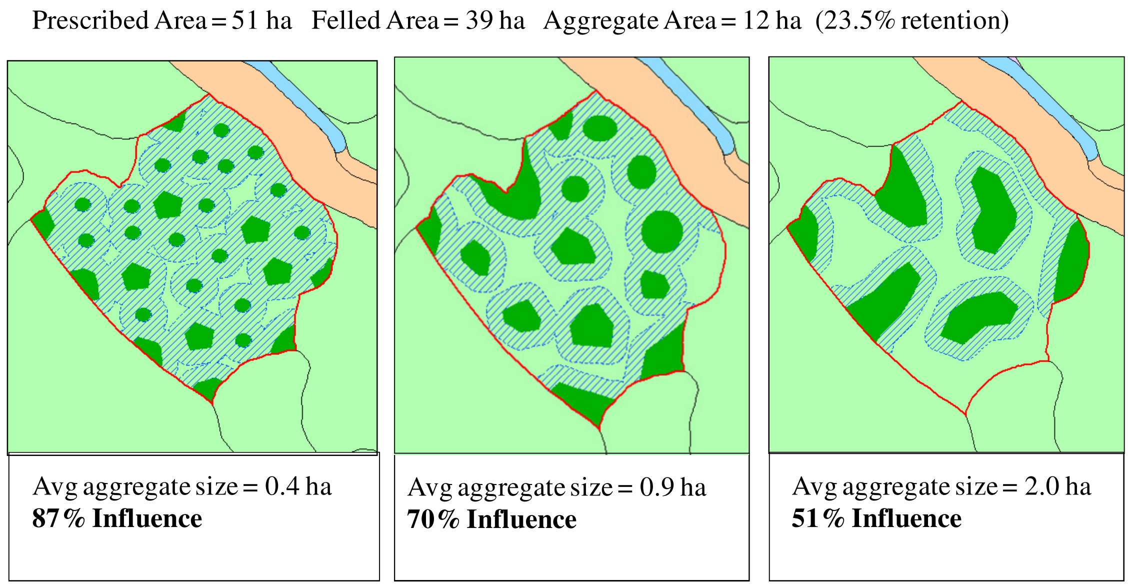


Figure 7-1. Illustration of a theoretical ARN coupe, showing the relationship between aggregate size and dispersion and forest influence. In each case the coupe area, the area harvested and the area retained are identical.

Forest influence was considerably greater in ARN coupes than CBS coupes, although these calculations are approximations based on the average height of the surrounding retained trees. The actual ecological effects of different types of forest influence and the distances to which they extend are still largely unknown for wet eucalypt forests. However, recent research has identified threshold distances from forest edges beyond which no influence of the mature forest on species richness or abundance could be detected for a number of disturbance-sensitive species guilds (Wardlaw *et al.*, 2012), and recruitment of rainforest tree species in harvested areas has been shown to be greater closer to mixed forest edges (Tabor *et al.*, 2007). Shifts in species composition have been observed under alternative silvicultural systems (Lutze and Faunt, 2006), and it is possible that extremely shade-intolerant species (such as *E. regnans*) will be disadvantaged by the ARN system. Based on the high influence levels in ARN coupes, this silvicultural system should help to maintain more biodiversity and result in more rainforest regeneration than conventional clearfelling (Baker and Read, 2011), but further research will be necessary to confirm this.

7.2.2. Persistence of retained trees

Of the various disturbances that are caused by harvesting and regeneration operations, the regeneration burn has had the greatest short-term impact on trees retained after variable retention harvesting in Tasmania, affecting 0.13 ha burnt per ha felled and 28% of island aggregate area. Windthrow, by contrast, affected 0.01 ha of forest per ha felled and 8% of island aggregate area. This contrasts with findings overseas, in which the majority of damage following variable retention harvesting is attributed to windthrow (Maguire et al., 2006; Thorpe and Thomas, 2007; Bladon et al., 2008); however, broadcast burning is not commonly used as a regeneration technique in any of these areas. Windthrow levels following variable retention harvesting in Tasmania appear to be low compared to North America (Beese, 2001; Rollerson et al., 2002), perhaps due to the large size of retained aggregates (Steventon, 2011) and the relatively high retention levels, or to the different wood density and crown characteristics of eucalypts compared to conifers (e.g., Everham and Brokaw, 1996).

Harvesting damage did not vary with silvicultural system, but did affect a large proportion of the eucalypts around coupe and aggregate edges. This may have negative effects on stand health and may affect timber quality and the longer-term persistence of retained trees (Neumann et al., 1997; Vasiliauskas, 2001; Gibbons et al., 2008). The results reported here present only a snapshot of conditions in the aggregates immediately after the regeneration burn. There has since been further damage in some coupes due to windthrow and some fire-damaged trees have collapsed, while conversely a number of damaged trees have also begun to recover through epicormic shoots or lignotuberous sprouts (R. Scott, pers. obs.). This demonstrates the danger, noted by Everham and Brokaw (1996), of equating damage with mortality and highlights the need for longer-term monitoring of the post-harvest dynamics of retained trees in order to evaluate the overall effects of variable retention silviculture (Thorpe and Thomas, 2007). Remote sensing, including LiDAR and low-level aerial photography, may be useful for future monitoring of aggregates.

7.2.3. Effects of site preparation

Despite increasing international interest in the use of prescribed fire as a regeneration and restoration tool (Ontario Ministry of Natural Resources, 2002; Hyvärinen *et al.*, 2006; Schoennagel and Nelson, 2011), Australian wet eucalypt forests are one of the few remaining forest types in which broadcast burning is consistently used as a regeneration treatment (Attiwill, 1994). The development of effective and consistent methods for burning aggregated retention coupes was seen to be critical to allow successful application of variable retention silviculture in wet eucalypt forests (Neyland *et al.*, 2009b). Results presented here confirm the success of the new 'slow burning' methods developed for ARN coupes (Chuter, 2007). The distribution of seedbed in ARN coupes immediately after the burn was very similar to that in CBS coupes, although overall, less burnt and more compacted seedbed was created (Chapter 4).

Associated with broadcast burning is the creation of mineral earth firebreaks around the perimeter of the area to be burnt, to help protect the adjacent forest during the burn and allow access for fire-fighting (Forest Practices Board, 2000; Forestry Tasmania, 2005a). These site preparation practices have significant effects on soil physical and chemical characteristics, and affect regeneration growth (Chapters 5 and 6). Firebreaks affected a larger proportion of the harvested area in ARN coupes, although this was reduced over time through changes in coupe design. The soil disturbance and displacement associated with firebreak construction reduced soil nutrient availability and increased penetration resistance, contributing to reduced seedling growth (Chapter 5). Similar reductions in seedling growth have been found elsewhere on snig tracks and after general harvesting disturbance (Williamson, 1990; Rab, 1998; Pennington *et al.*, 2004). If these effects persist in the longer-term, the overall impact of soil disturbance due to harvesting and firebreak construction on productivity in wet eucalypt coupes could be considerable.

7.2.4. Regeneration

Variable retention silviculture was expected to significantly reduce eucalypt regeneration stocking, density and height, but this was not the case (Chapter 6). Despite more complex boundary shapes and much higher levels of forest influence, the development of successful 'slow burning' methods combined with the adoption of aerial sowing in all ARN coupes has resulted in early regeneration densities and growth rates that are very comparable with those in clearfelled coupes. This contrasts with results from most alternative silviculture trials in Australia, which have found either reduced stocking and density or reduced survival and growth in alternative systems when compared to clearfells (Bassett *et al.*, 2000; Lutze and Faunt, 2006; Neyland *et al.*, 2009b). However, many of these studies examined systems based on dispersed retention or small gap openings, relied on natural seedfall in the alternative systems, or excluded burning as a form of site preparation. In North America, many studies have similarly found reduced growth rates under alternative silvicultural systems involving dispersed retention or small gaps, particularly for shade-intolerant species (Coates, 2000; Huggard and Vyse, 2002; Mitchell *et al.*, 2007). Although all eucalypts can be classified as intolerant to very intolerant of competition, a range of tolerances does still exist with some species being considered very intolerant (e.g., *E. regnans*) while others display a greater ability to persist under competition (e.g., *E. obliqua*) (Florence, 1996). These species differences may help to explain the lack of edge effect observed in this study, since *E. obliqua* was the dominant species on most coupes. In addition, a number of studies have shown that retaining aggregates or patches has less of a suppressive effect than retaining dispersed trees (Aubry *et al.*, 1999; Coates, 2000; Palik *et al.*, 2003), and one study in a coastal montane forest found no differences in 10-year old planted seedling growth in aggregated retention treatments (1.5 ha patchfells) compared to a 69 ha clearfell (Mitchell *et al.*, 2007). Results from North America and elsewhere are not particularly comparable with those obtained here, due to differences in forest type and regeneration methods, but the outcomes of this study do support predictions made by Franklin et al. (1997) and recommendations by Palik et al. (2003) and Coates (2000), that the use of aggregated retention will relieve competitive pressure on regeneration and minimise effects on growth.

Browsing of eucalypt regeneration by native mammals can cause significant damage to individual seedlings, reductions in stocking and growth, and in some cases, total regeneration failure (Cremer, 1969; Wilkinson and Neilsen, 1995; Neyland *et al.*, 1999). In this study, browsing pressure was considerable, with 17% of transect seedlings being significantly browsed at 15 months of age and an average of 178 browsers removed from each coupe over approximately the first two years (Chapter 6). Browsing pressure was expected to increase in ARN coupes due to greater perimeter-to-area ratios and increased availability of cover habitat, although much of the evidence for this effect is anecdotal (Mount, 1979). Results from this study provide no support for the hypothesis that increased perimeter-to-area ratios associated with ARN harvesting will increase browsing pressure or the need for browsing control in wet eucalypt coupes.

Seedling densities and stockings, although similar between ARN and CBS coupes, were lower in many coupes than may be desirable for future stand development (Chapter 6). In regrowth wet eucalypt forests, densities of at least 2500 sph are considered adequate to allow commercial thinning and early production of sawlogs (Forestry Tasmania, 2010b), but considerably higher densities may be needed to avoid problems with large branches and increased defect (Wardlaw, 2003) and to provide selective pressure for the best and fastest-growing seedlings (Gilbert, 1959; Griffin and Cotterill, 1988). A review of sowing rates is recommended, and further research is needed examining density-dependent mortality and quantifying stocking and density at various stages of stand development. Although conventional clearfell, burn and sow coupes were used as a control in this study, in future it would be useful to make comparisons both with unharvested control areas, and with stands regenerating naturally after wildfire.

Although firebreaks affected a greater proportion of the harvested area in ARN coupes than in CBS coupes, based on mean firebreak widths, there was no difference in the overall amount of disturbed seedbed between silvicultural systems, and only a small increase in compacted seedbed (Chapter 4). Similarly, while regeneration height was found to be reduced on firebreaks (Chapter 5), there were no differences in height of regeneration overall, and no evidence of edge-related suppression within coupes (Chapter 6). This suggests that the conventional seedbed and regeneration survey methods used here (systematic point surveys on a 20 x 100 m grid) are unable to capture some changes known to be associated with coupe edges. As the use of high perimeter : area designs such as those associated with ARN increases, the importance of quantifying any edge effects on regeneration will increase (Bradshaw, 1992). Greater sampling intensity, or a different sampling method, such as sector plots (Iles and Smith, 2006), may be needed to better capture these edge effects. To adequately quantify the effects of competition from edge trees on regeneration growth in wet eucalypt forests, future studies should measure seedling diameter or basal area as well as height, and the sampling design will need to account for the confounding effect of firebreaks and the short distances over which edge effects have manifested in other studies.

7.3. The future of VR in Tasmania

Variable retention harvesting is now accepted as 'best-practice' forest management in old-growth forests around the world and a number of recent papers call for the wider use of retention forestry globally (Gustafsson *et al.*, 2012; Lindenmayer *et al.*, 2012). Given this trend, what is the potential for future use of variable retention silviculture in Tasmania? The amount of old-growth wet eucalypt forest harvested in Tasmania has decreased dramatically in the past few years (Forestry Tasmania, 2012), due to a number of factors including the global financial crisis and successful campaigns by environmental non-government organisations against the harvesting of native forest for woodchips (Schirmer, 2010). Future harvesting of old-growth wet eucalypt forests seems unlikely, as there is considerable uncertainty in the Tasmanian forest industry at present, with a high likelihood of increased reservation and decreased native forest harvesting in the future (Tasmanian Government, 2012). Current aggregated retention harvesting and slow burning methods, although developed for old-growth forests, can equally be applied to regrowth forests. A number of scientists have noted that the conservation benefits of using VR in such forests are likely to be greater than applying it in mature forest landscapes where old-growth species and structures are already well-represented (Forestry Tasmania, 2009a).

A limited amount of VR harvesting is feasible in wet eucalypt forests (650 - 1000 ha $year^{-1}$), so long as burning and sowing remain the preferred method of regeneration (Forestry Tasmania, 2009a). The resources required for burning, increasing issues with smoke management and the short window of suitable weather conditions limit the practical application of VR in these forests. The introduction of biomass harvesting could provide an alternative or complementary method of managing harvesting residues and allow a larger burning (and therefore, harvesting) program to be achieved (Forestry Tasmania, 2009a), but the effects of biomass removal on subsequent burning are largely unknown and there may be negative implications for seedling establishment and growth if no burning occurs (Chapter 6). Planting of ash-group eucalypt seedlings is currently not recommended as a regeneration method, due to poor performance of planted trees in trials as well as the much greater cost of planting compared to sowing (Forestry Tasmania, 2009c). Even if planting were feasible, burning or some other form of site preparation would still be required to manage harvesting residues.

There is also potential to apply the retention approach in Tasmania's lowland dry eucalypt forests, which account for nearly half of the area of old-growth harvesting annually (Forestry Tasmania, 2012). These forests typically have a multi-aged structure resulting from gap-phase recruitment to the canopy and are usually partially harvested, with either seed trees, advanced growth or potential sawlogs being retained to provide the next tree crop (Forestry Tasmania, 2009d). Although partial harvesting maintains higher levels of forest cover than clearfelling, successive partial harvesting rotations are likely to remove the largest and oldest trees from the stand and result in a simplified stand structure (Angers *et al.*, 2005). Recent studies have argued that there are structural benefits to be gained from the adoption of some level of permanent or long-term (i.e., multi-rotation) retention in partially harvested forests (Bauhus *et al.*, 2009; Gustafsson *et al.*, 2012). However, in Tasmania, there are already a number of areas within partially harvested coupes which must be reserved from harvesting (Forest Practices Board, 2000). Any assessment of the need for long-term retention within partially harvested stands should take these existing set-asides into account.

This study has shown that overall retention and reservation levels in Tasmanian old-growth wet eucalypt forests are high (Chapter 2). Additional retention in such well-reserved landscapes may have relatively low conservation value compared to additional retention in landscapes lacking in mature forest elements (Bunnell and Dunsworth, 2009). Planning for coupe-level retention within the context of landscape-level reserves provides the best opportunity to meet conservation and native forest timber production goals into the future. This approach will allow optimisation of coupe design and help to avoid excessive retention levels (Chapter 2). A broader analysis of land-use across different tenures would also place Forestry Tasmania's practices into the context of the surrounding landscape and allow a better understanding of how reserves, retained areas and harvested areas all contribute to meeting management objectives in native forests (Forestry Tasmania, 2009a). To facilitate this approach, Forestry Tasmania is developing an estate-wide long-term retention target as well as GIS-based landscape metrics to help identify the areas where variable retention silviculture will provide the greatest benefit (Forestry Tasmania, 2011a; Wardlaw *et al.*, 2012).

One of the goals of variable retention is to better emulate natural ecological processes at the stand level (Baker and Read, 2011). The biological legacies retained in aggregates within ARN stands will contribute to greater structural complexity and will allow the development of stands with multiple age classes in the future, if this is the desired outcome (Neyland, 2010). There may be room for improvement of variable retention coupe design at both the stand and the landscape scale by more explicitly considering the size and distribution of wildfire remnants and regenerating areas that occur in wet eucalypt forests following natural disturbance by wildfire. In fire-dominated landscapes in North America, natural-disturbance based management has been extensively studied (Bergeron and Harvey, 1997; DeLong and

Kessler, 2000; Belleau *et al.*, 2007), and is now being used to guide forest management in some areas (DeLong, 2007). Regardless of how and where variable retention harvesting is applied in Tasmania in the future, the design of variable retention coupes should be ecologically appropriate to the forest type, set within the context of landscape-level reservation, and recognise the importance of variability at multiple spatial-scales (Franklin *et al.*, 1997; Lindenmayer and Franklin, 2002; Bunnell and Dunsworth, 2009).

7.4. Conclusions

This thesis indicates that initial silvicultural goals for regeneration can be met after variable retention harvesting using aggregated retention in wet eucalypt forests. The development of new 'slow burning' methods allowed the creation of sufficient receptive and burnt seedbed, while the adoption of aerial sowing ensured that adequate amounts of well-distributed seed were applied. There were no increases in browsing damage or browsing pressure with ARN harvesting, nor any evidence of edge-related growth suppression. Regeneration density and height in three-year-old aggregated retention coupes were similar to those in comparable clearfell, burn and sow coupes, demonstrating that the ARN system can achieve both silvicultural and ecological goals, at least in the short-term. Further research is needed to assess the longer-term effects of variable retention silviculture on eucalypt productivity and growth, including more detailed study of edge effects. This study confirms that the creation of burnt seedbed is essential for good early regeneration in wet eucalypt forests, and indicates that good regeneration can be achieved after aggregated retention harvesting, so long as stands are managed appropriately.

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Appendix 1. Forestry Tasmania's approach to variable retention

The following goals and guidelines are taken from Forestry Tasmania (2009a).

Goals

Tall oldgrowth forests are naturally regenerated by massive wildfires which nevertheless usually leave late-successional species and structures. These elements are important biological legacies that maintain biodiversity and variability at the stand level. Variable retention (VR) silviculture seeks to emulate these ecological processes, meet timber production objectives, and maintain the social licence to harvest these forests. Specific goals for VR in tall oldgrowth forest include:

1. To more closely emulate natural ecological processes within managed tall oldgrowth forest by retaining late-successional species and structures (biological legacies) for at least a full rotation.
2. To maintain a forest edge influence over the majority of the felled area thereby differentiating the regenerating stand ecologically from stands regenerating following clearfelling.
3. To ensure that each coupe is an example of good forest stewardship.
4. To achieve adequate productive regeneration of both eucalypts and other species.
5. To ensure safety of forest operations.

Guidelines

For safety, biodiversity and fire management reasons, the majority of VR silviculture in Tasmania's old-growth forests will be by aggregated retention. The following guidelines will allow FT's goals for VR to be achieved:

1. The majority of the felled area should be within one tree height of forest that is retained for at least a full rotation (for aggregated retention this requires fairways two to four tree-lengths wide).
2. Retained areas can be free-standing islands (island aggregates) or may be contiguous with standing forest outside of the coupe (edge aggregates). Aggregates should generally be at least one hectare in size.
3. Aggregates should be anchored on specific locations of ecological value (e.g., biological legacies, special vegetation communities) and include the range of habitat types (e.g., vegetation types, stand ages, landforms) present within the coupe.
4. Coupes should look different from clearfelled coupes. Large gap areas and long view lines should be avoided.
5. Coupe layout and fuel preparation should allow safe and effective burning to create a receptive seedbed over >2/3 of the felled area.
6. Firebreak and access track area should be minimised and their preparation should not unduly compact soils, damage soil profiles, or otherwise compromise ecological values.
7. Coupe should meet seedling stocking standard (65% 16 m^2 stocking) at 3 years.
8. Hazardous trees in aggregates and edges should be sufficiently buffered to ensure they do not pose a danger to workers in the harvested area.

Appendix 2. Detailed site characteristics

Year burnt	SilvSys	Coupe	Pairs	District	Aspect	Slope%	Mean Elev	Annual rainfall (mm)	Easting	Northing	Harvest method	Date harvest ended	Burn date	Ignition time	Temp (C)	Relative Humidity	FFMC - logged coupe	FFMC - unlogged forest	Wind direction	Windspeed	Harvested area (ha)	Perimeter length (m)
2007	ARN	AR023E	a	HU	NW-SW	13	300	1420	485360	5222723	ground	31-Oct-06	09-Apr-07	12:40:00	19	66	13	19	W	<30	28.15	6139
2007	CBS	WR013C	a	HU	E	20	140	1187	479958	5233541	ground	01-May-05	02-Apr-07	13:40:00	20	50	13	25	E	0-5	74.53	3947
2007	ARN	EP081B	b	HU	SE-SW	20	555	1549	487580	5213303	both	10-Feb-06	27-Mar-07	14:30:00	15	67	13	22	SE	0-7	40.48	8789
2007	CBS	PC034D	b	HU	NE-SE	27	320	1798	473215	5220280	cable	28-Jun-06	22-Mar-07	14:15:00	25	42	10	21	N	0-5	45.05	4035
2007	ARN	PC007C	c	HU	NW	14	255	1572	478920	5226821	ground	30-Dec-05	27-Mar-07	12:00:00	21	68	13	23	NNW	<5	15.64	3242
2007	CBS	PC023C	c	HU	SE	11	255	1703	474486	5225448	ground	30-Jun-05	22-Mar-07	15:12:00	24	43	10	21	N-NW	0-5	44.66	3487
2007	ARN	SR037C	d	MU	flat	5	70	1348	319126	5457145	ground	22-Mar-04	09-Apr-07	13:00:00	24	61	11	20	NNE	10 to 15	31.53	8107
2007	CBS	SR052B	d	MU	N-NE	9	85	1367	318975	5450150	ground	08-Mar-07	26-Apr-07	16:00:00	16	60	14	30	ENE	10 to 15	18.10	3142
2007	ARN	SX004B	e	DE	N-NW	12	480	1458	464001	5257966	ground	12-Dec-06	14-Apr-07	16:45:00	18	63	9	22	SW	0	18.02	5310
2007	CBS	TN048A	e	DE	variable	10	500	1546	459306	5259108	ground	01-Feb-06	21-Mar-07	15:50:00	20	52	17	19	NW	<5	22.63	1965
2007	ARN	SX007A	f	DE	NW	7	450	1413	465701	5257596	ground	09-Feb-06	27-Mar-07	14:30:00	18	50	12	25	N	<10	19.51	5663
2007	CBS	SX022A	f	DE	NW	20	760	1194	477943	5258531	ground	22-Sep-06	21-Mar-07	14:00:00	17	63	20	28	WNW	5 to 10	12.38	1790
2007	ARN	SX018E	g	DE	NE	8	510	1145	476410	5260092	ground	13-Oct-06	27-Mar-07	17:15:00	18	49	12	16	NE	<5	21.57	4786
2007	CBS	SX018F	g	DE	SW-W	11	505	1169	475963	5258796	both	13-Dec-05	09-Apr-07	14:00:00	22	41	15	25	NW	<5	20.10	2432
2007	ARN	TE020C	h	MU	NW	4	150	1456	315080	5437247	ground	22-Dec-04	26-Mar-07	16:00:00	20	46	11	23	NE	10-15	20.15	6512
2007	CBS	TE011G	h	MU	flat	0	110	1349	314576	5445089	ground	04-Nov-05	24-Apr-07	13:30:00	18	64	12	25	NE	0 to 5	12.85	2594
2008	ARN	BS118L	i	BA	E	10	775	1457	538935	5414271	ground	31-Dec-07	16-Apr-08	15:00:00	14	69	14	22	S	<5	14.57	2867
2008	CBS	BS117C	i	BA	SE	8	770	1309	536821	5412594	cable	25-Sep-07	16-Apr-08	14:00:00	17	64	12	19	W	10 to 15	50.79	3792
2008	ARN	FR039B	j	MU	flat	0	200	1619	325590	5436273	ground	12-May-08	17-Apr-08	15:20:00	13	88	12	28	SW	<5	18.16	7689
2008	CBS	CH013E	j	MU	flat	0	45	1396	328182	5457979	ground	15-Jun-07	16-Apr-08	15:25:00	21	66	14	19	SW	5 to 10	29.36	3572
2008	ARN	KD023E	k	HU	NW	20	630	1529	489273	5215344	ground	16-Nov-07	23-Apr-08	14:55:00	14	60	14	25	NW	<5	17.68	3166
2008	CBS	KD009E	k	HU	N-NW	15	640	1493	487993	5217932	ground	16-Oct-07	23-Apr-08	14:15:00	16	55	13	25	N	<5	33.30	2583
2008	ARN	NA023A	l	MU	W	10	155	1352	343520	5456789	ground	07-Mar-07	09-Apr-08	15:28:00	16	70	15	26	NE	10	16.29	5336
2008	CBS	NA015A	l	MU	SW	10	170	1383	352158	5457134	ground	30-Apr-06	08-Apr-08	14:50:00	16	79	16	30	NNE	5 to 10	15.84	2827
2008	ARN	SR112C	m	MU	flat	0	45	1410	326883	5454087	ground	12-May-08	17-Apr-08	15:05:00	16	56	14	26	SW	10	51.58	9112
2008	CBS	SR049C	m	MU	SE-SW	20	90	1332	316137	5449708	ground	29-Jan-08	09-Apr-08	14:30:00	19	82	15	29	NNE	0 to 5	35.57	4820
2008	ARN	SX020A Sec 1	n	DE	NE	11	590	1135	477398	5259365	ground	06-Dec-07	21-Apr-08	15:38:00	14	68	12	25	W	<5	37.15	8205
2008	CBS	SX021A	n	DE	N	36	350	1063	479080	5261025	cable	17-May-07	09-Apr-08	13:45:00	20	61	13	20	NNE	12	22.96	2446
2008	ARN	TO006F	o	DE	E- SE	25	640	867	572016	5321970	ground	26-Sep-07	05-Apr-08	13:32:00	16	58	13	17	NE	5-10	10.33	1738
2008	CBS	FT013H	o	DE	SW	15	225	962	576164	5240560	ground	06-Aug-07	08-Apr-08	13:45:00	17	81	14	24	NW	5-10	11.04	1609
2008	ARN	HU323Y		ME	E	11	550	1150	463494	5382428	ground	30-Nov-07	17-Apr-08	17:15:00	11	55	11	19		<5	32.73	5550
2008	ARN	TE014A		MU	variable	5	150	1506	321249	5438884	ground	30-Jan-05	19-Apr-08								15.63	8506
2009	ARN	BW121E	p	BA	S	18	660	1396	535682	5413397	ground	31-Jul-08	07-Apr-09	12:45:00	14	68	14	20	SW	10-15	15.28	3358
2009	CBS	BS124B	p	BA	N	10	560	1186	546921	5413009	ground	09-Apr-08	07-Apr-09	11:30:00	16	52	16	20	W	0-5	17.42	3247
2009	ARN	EP031E	q	HU	N	16	295	1486	489720	5202312	ground	24-Apr-08	02-Apr-09	16:30:00	21	68	12	20	NW	0	28.51	6226
2009	CBS	LU008C	q	HU	E	22	230	1545	487931	5190294	both	22-Dec-08	23-Apr-09	12:19:00	19	64	13	25	NW	5-8	36.32	2829
2009	ARN	FO042F	r	DE	SE-SW	16	445	1576	453568	5271433	ground	11-May-07	11-Mar-09	15:27:00	25	42	12	20	NE	0-5	15.21	3875
2009	CBS	RP037F	r	DE	E	20	883	1359	462177	5287596	cable	31-Mar-07	12-Mar-09	13:45:00	20	50	15	20	N	5	37.47	3038

Year burnt	SilvSys	Coupe	Pairs	District	Aspect	Slope%	Mean Elev	Annual rainfall (mm)	Easting	Northing	Harvest method	Date harvest ended	Burn date	Ignition time	Temp (C)	Relative Humidity	FFMC - logged coupe	FFMC - unlogged forest	Wind direction	Windspeed	Harvested area (ha)	Perimeter length (m)
2009	ARN	SX010F	s	DE	N-NW	10	500	1302	470283	5258242	ground	13-May-08	02-Apr-09	15:02:00	20	67	17	25	NNE	15-20	19.27	3947
2009	CBS	TN048A Sec 2	s	DE	flat	5	510	1546	459228	5259523	ground	17-Jan-09	11-Mar-09	14:03:00	18	60	14	25	SE	10	15.04	2344
2009	ARN	SX011B Sec 2	t	DE	N	20	613	1317	470860	5257356	ground	20-May-08	02-Apr-09	15:02:00	20	67	17	25	NNE	15-20	9.05	1964
2009	CBS	SX015A Sec 3	t	DE	N-NW	18	495	1206	475146	5257711	ground	27-Jun-08	02-Apr-09	15:00:00	21	63	15	19		5	7.56	1760
2009	ARN	TG001E	u	MU	flat	5	40	1178	330066	5479512	ground	30-Nov-08	10-May-09	14:00:00	15	89	21	25	NE	5	18.88	3466
2009	CBS	TG016A	u	MU	flat	5	50	1226	331898	5475498	ground	13-Feb-09	10-May-09	13:00:00	15	86	17	25	E	10	12.08	1627
2009	ARN	KA005A		MU	NE	10	445	1500	405895	5431987	ground	13-Feb-09	01-Apr-09								5.08	1274
2010	ARN	SX018C	aa	DE	flat	0	545	1164	476222	5259104	ground	15-Apr-09	28-Mar-10	13:20:00	21	60	15	22	NE	5-15	13.73	1689
2010	CBS	SX021E Sec 3	aa	DE	N	23	690	1128	479049	5259535	ground	31-May-08	28-Mar-10	16:00:00	20	68	14	22	NNE	0-5	3.88	1335
2010	ARN	SX020A Sec 2	bb	DE	NE	8	480	1097	478121	5260598	ground	29-Oct-08	28-Mar-10	14:30:00	21	58	14	20	N	0-5	14.18	3366
2010	CBS	SX032B	bb	DE	S	15	705	1046	483527	5257638	ground	25-Jun-10	06-Apr-10	14:30:00	23	52	16	30	NE	0-5	44.60	3636
2010	ARN	TE005H	cc	MU	flat	0	95	1279	311608	5447117	ground	26-Mar-10	12-Mar-10	14:00:00	15	70	14	22		0-5	35.94	6557
2010	CBS	SR039B	cc	MU	SW	8	65	1362	320151	5454359	ground	15-Feb-10	03-Apr-10	13:55:00	20	75	14	24	SW	0-5	60.16	4089
2010	ARN	TN021B	dd	DE	E	15	520	1087	472513	5272541	ground	28-Feb-09	06-Apr-10	15:45:00	18	60	16	30	NE	5-10	16.22	2608
2010	CBS	TN068E	dd	DE	NE	23	700	1009	479733	5271476	ground	24-Feb-09	01-Apr-10	15:45:00	17	54	13	28	SSW	0-5	49.97	3614
2010	ARN	WE003C	ee	DE	W	30	470	1814	446561	5261630	cable	05-Sep-09	06-Apr-10	14:30:00	16	80	16	20	N	0-5	6.65	1064
2010	CBS	WE003D	ee	DE	S-SW	25	415	1802	445498	5262968	cable	28-Feb-09	06-Apr-10	14:30:00	17	64	14	23	NW	0-5	11.60	1479
2010	ARN	WW032B	ff	DE	SE	14	730	1272	449665	5322086	ground	30-Apr-09	25-Mar-10	15:45:00	21	56	16	30	NW	5-10	21.51	4471
2010	CBS	CO002B	ff	DE	E	22	425	1184	457098	5304599	ground	01-Sep-09	25-Mar-10	17:10:00	24	50	9	30	N-S	0 (gusts to 30)	14.96	1793
2010	ARN	BS109D Sec 1	v	BA	S-SW	20	615	1407	551715	5418977	ground	24-Mar-10	24-Mar-10	13:15:00	22	44	14	17	SW	0-10	16.76	3528
2010	CBS	BS101F Sec 2	v	BA	E	17	800	1551	536782	5419961	ground	22-Jun-09	24-Apr-10	12:30:00	21	50	13	18	NW	8-12	23.76	3085
2010	ARN	EP004D	w	HU	W	25	270	1448	490847	5202695	ground	26-Nov-09	17-Apr-10	16:00:00	19	70	14	24		0	12.65	2484
2010	CBS	EP061D	w	HU	SE	20	240	1333	492847	5208053	both	30-Jan-09	31-Mar-10	13:58:00	18	65	14	22	E	5-10	10.28	1554
2010	ARN	FO025C	y	DE	flat	0	400	1357	456380	5280552	ground	01-Jul-09	05-Apr-10	12:30:00	17	56	15	21	VAR	0-5	10.68	2417
2010	CBS	SX038B	y	DE	W	12	615	957	484837	5262119	ground	04-Mar-10	05-Apr-10	14:30:00	14	68	14	30	SE	0-5	50.30	3693
2010	ARN	KD054A	z	DE	SW	18	290	1265	495578	5213953	ground	17-Jun-09	18-Apr-10	16:20:00	19	74	12	24		0	27.70	6232
2010	CBS	EP078B	z	HU	SW	12	355	1444	491729	5210939	ground	04-Mar-09	17-Apr-10	13:55:00	21	69	15	25	NNE	0	38.08	3755
2010	ARN	EP004F		HU	E	16	300	1428	490428	5201827	ground	31-Dec-08	18-Apr-10								4.93	1082
2010	ARN	FO042E		DE	N-NW	10	440	1601	453356	5270822	ground	24-Mar-09	28-Mar-10	14:15:00	19	70	18	30		0	18.16	3024
2010	ARN	RP034A		DE	SE	15	850	1273	465550	5286348	ground	16-Jul-08	28-Mar-10								59.54	9861
2010	ARN	RP034H		DE	S	12	800	1253	464455	5285850	ground	16-May-09	28-Mar-10								67.78	10851