Appendix A
Consultants' report

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Part 1

Background

1.1 Introduction

Victoria's Department of Environment, Land, Water, and Planning (DELWP) is responsible for the sustainable management of Victoria's entire public forest estate in a manner that complies with the broad principles of sustainability detailed in the State of Victoria's Sustainability Charter. The goal is that Victoria's forests be managed to maintain forest health, biological diversity, and the capacity to produce wood and non-wood values. The provisioning of wood and fibre from the State Forests is a critical component of this management. VicForests, the State-owned Business Enterprise responsible for commercial forest management on State Forests, uses a range of information and modelling to develop estimates of sustainable wood supply levels for the State Forests. These are used to determine the total merchantable volume that is available for harvesting by the Victorian native forest industry in the near-term and identifies trajectories for sustainable harvest levels over the medium- and long-term. Due to recent large-scale fires and recent discoveries of Leadbeater's Possum, there are significant concerns about the long-term prospects for timber supply and its potential implications for the native forest industry and government policy.

The goal of this project is to assess the wood and fibre supply modelling that VicForests conducts to set its sustainable harvest levels. Our assessment considers key model parameters and uncertainties that may impact on projected wood supply levels. Our work focuses on two of the Forest Industry Task Force Terms of Reference:

(b) Identify the current and likely future constraints to [the fibre and wood supply to industry from the specified area]; and

(d) Report on the viability of and capacity for current and potential wood and fibre supply over appropriate time scales.

To address these issues, we:

1. provide a detailed summary of the modelling process that forms the basis of VicForests

sustainable wood supply estimates;

2. conduct a sensitivity analysis of various aspects of the strategic wood supply modelling process;

3. evaluate the potential impacts of bushfires, Leadbeater's Possum, and future climate variability on fibre and wood supply; and

4. assess the potential of Victoria's State Forests to provide a sustainable fibre and wood supply in the coming decades.

1.2 Context

There is growing concern that Victoria's native forest estate cannot provide sufficient wood (*i.e.*, fibre and sawlogs) to sustain a native forest industry. Major fires in 2003, 2006, and 2009 have had a significant impact on the wood resource by killing trees across hundreds of thousands of hectares. Recent discoveries of Leadbeater's possum colonies in the Central Highlands have led to $>$4000 ha of harvestable forest being excluded from future harvests over the past three years. Together these have led to major reductions in the sustainable annual harvest levels. In 2009 the State-wide estimated sustainable harvest levels were 500,000 m^3 yr^{-1} for D+ sawlogs, of which 293,000 m^3 yr^{-1} were D+ ash sawlogs (DSE, 2008). In its 2013 Resource Outlook VicForests estimated 220,000 m^3 yr^{-1} of D+ ash sawlogs (VicForests, 2013). By late 2016 the sustainable harvest level had been reduced to 175,000 m^3 yr^{-1} of D+ ash sawlogs (VicForests, 2017). Based on expected future regulatory impacts associated primarily with new Leadbeater's possum detections, VicForests has further reduced its expectations for sustainable harvest levels to 130,000 m^3 yr^{-1} of D+ ash sawlogs.

Although the estimated harvest levels are described as sustainable, the term "sustainable" is used in two different contexts in discussions about Victoria's forests and the forest industry. "Sustainable" forest management involves harvesting wood at a rate that does not deplete the forest resource. Ideally, a forested landscape would have an even distribution of ages and a fixed proportion of the forest could be harvested each year. The classic example is a forest with a 100-year rotation (*i.e.*, the age at which harvesting takes place) in which 1/100th of the forest is harvested each year, so that by the time the entire forest has been harvested (*i.e.*, after 100 years), the first area harvested would be 100 years old and ready to harvest again. A "sustainable" forest industry is one in which an even flow of wood to ensure predictable revenues, job security, and sensible infrastructure planning. These definitions of sustainable align best when the forested landscape has a relatively even distribution of age classes. However, in native forests that are subject to large-scale disturbances and have historical legacies of exploitation, a balanced age structure across the managed forest estate is rare. In 1939 catastrophic bushfires burnt $\sim$2 million hectares of forest in and around the Central Highlands of Victoria and led to the establishment of several hundred thousands of hectares of forest dominated by the commercially valuable species mountain ash (*Eucalyptus regnans*) and alpine ash (*Eucalyptus delegatensis*). This 1939 regrowth is the primary source of high-value sawlogs in Victoria due to the size and wood quality of the two ash species. The standard rotation age for mountain and alpine ash species is 70-80 years (Flint and Fagg, 2007), which means that the period of peak harvesting of the 1939 regrowth has recently passed. Due to the extremely unbalanced age distribution of the high-value ash forests in the Central Highlands, the Victorian government has actively managed the resource to provide a more even flow to the native forest industry over the past 30 years (Figure 1).

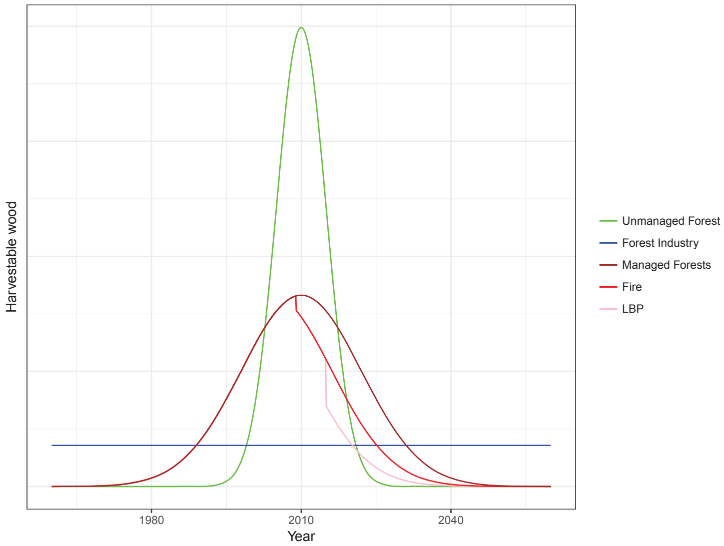

Figure 1: The definition of sustainability differs for forest industry and forest management. In a landscape with a single large age cohort of trees, the area of harvestable wood will peak at the optimal rotation age (green line). Due to variability in site quality some areas will reach harvestable size earlier than others. Sawmills and pulpmills would ideally want a constant, even flow of wood to process (blue line). Forest management (brown line) attempts to reduce the difference between the uneven age distribution and the forest industry's need for an even flow by spreading the harvesting activity out across a longer time period. Unforeseen events such as fires (red line) and new sightings of Leadbeater's possum (pink line) will further reduce the amount of wood available for harvesting.

Forest management by the State government has attempted to spread the relatively narrow age distribution of the 1939 regrowth out over as broad a period as possible. In effect, this means harvesting the more productive sites earlier (as they will reach harvestable size sooner) and the less productive sites later, or harvesting some areas earlier than the optimal age and other areas later than the optimal age, or both. Unless the forest managers intentionally delay a large proportion of the harvesting, there should be a decline in harvesting levels in the years after the rotation age has passed. Current modelling of sustainable harvest rates in Victoria's State Forests suggest that this decline has begun and that in 15-20 years there will be a wood supply bottleneck as the available (*i.e.*, not in Reserves, Protected Areas, or other Forest Practices Code exclusions) 1939 mountain and alpine ash regrowth that dominates the timber supply from the Central Highlands is exhausted and new regrowth from the 2000s is not yet commercially viable. This dynamic has been further exacerbated by the impacts of, in particular, the 2009 Black Saturday fires, and the establishment over the past three years of 400+ exclusion zones to protect newly discovered Leadbeater's possum colonies. A combination of declining wood availability and stochastic events that reduces the area available for harvesting could have long-term consequences if the available volume of wood is reduced below a threshold level required to maintain a sustainable native forest industry. In this report we consider the impacts of potential future threats on Victoria's wood supply. We do not, however, make any assessment as to what the wood supply level threshold necessary to sustain the native forest industry might be.

Part 2

Strategic Wood Supply Modelling

2.1 An overview of VicForests' SWSM

The development of a strategic wood supply model (SWSM) for any organisation, whether public or private, responsible for managing a large forest estate is a complex process. While specific SWSMs may differ in their details, the broad structure of many SWSMs, including VicForests', is quite similar due to the nature of the forest resource, planning constraints, and strategic objectives. Here we describe the process that VicForests uses to determine a sustainable fibre and wood supply level for the State Forests of Victoria. We detail the various data inputs, models, and adjustments that are made to produce an estimate of sustainable yield from the Victorian forest estate, as well as the assumptions that underpin them. Our summary of VicForests' SWSM process is based on discussions with VicForests' staff responsible for the modelling, existing documents describing the modelling process, and our own assessments of a range of model inputs, outputs, and assumptions. Our goal is to identify each component of the modelling process, describe how it is calculated and its underlying assumptions, and to consider the potential uncertainties associated with it.

The process of developing an estimate of sustainable harvest levels to provide the forest industry with sufficient wood is a complex, hierarchical, iterative process that depends on a variety of sources of information. Here we provide a broad overview of the main steps in the model (Figure 2). We then use this framework for a more detailed examination of each step in subsequent sections.

The first step in the SWSM process is an assessment of the existing forest estate (Section 2.2). This involves determining the total area of harvestable forest, the time periods in which individual areas of forest will be sufficiently mature to harvest, and the volume of wood that each forest is expected to provide at the time of harvest. The resource estimates are then adjusted to reflect inconsistencies in the area of forest or volume of wood due to differences in modelled and actual values for forest area, total merchantable volume, and log grades.

The second step takes the identified forest resource and applies a range of specific constraints regarding area and volume harvested, even flows of wood over time, and existing

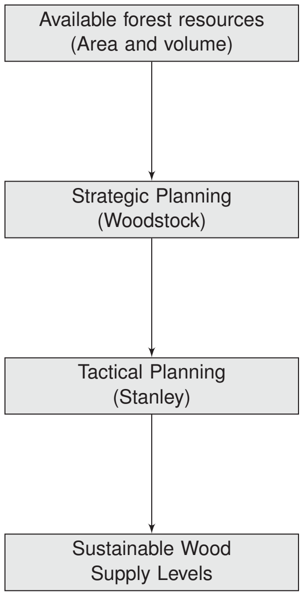

Figure 2: Overview of the strategic wood supply modelling process used to estimate sustainable yields of fibre and wood from Victoria's State Forests. More detailed descriptions of the individual components are provided in subsequent sections.

contract obligations to develop a solution that maximises total merchantable volume (TMV) of wood over the planning period. This is referred to as the strategic-level planning and is conducted using the Woodstock modelling framework (Section 2.3) to identify potential wood supply levels across the entire forest estate (*i.e.*, all seven FMAs).

The third step in the modelling process takes the Woodstock output, which does not incorporate spatial information (specifically, the location of individual management units), and applies a spatial harvest scheduling algorithm, Stanley, to identify the groups of harvest units that can be most efficiently harvested (primarily by grouping adjacent or nearby coupes) within each FMA. This is referred to as tactical-level planning and addresses spatial issues such as coupe size and adjacency. Typically, Stanley reduces the estimated wood volume from the strategic wood supply model by 20-30%.

The fourth step, in which the sustainable wood supply levels are set, involves running dozens of Woodstock scenarios and Stanley reductions to develop a range of plausible wood supply options and discussions with harvest sales managers and district foresters regarding the proposed supply levels. The Woodstock scenarios cover a range of assumptions about potential constraints and expectations about future harvestable areas, regulatory changes, and market fluctuations that attempt to capture potential future conditions. The final sustainable wood supply levels are then set based on an assessment of the modelled scenarios, commercial commitments and realities, and logistical considerations.

2.2 Assessment of the existing forest estate

The first step in developing a SWSM is to quantify the resource. At its most fundamental level this involves an assessment of the area of harvestable forest and the volume of merchantable wood that occurs in that area.

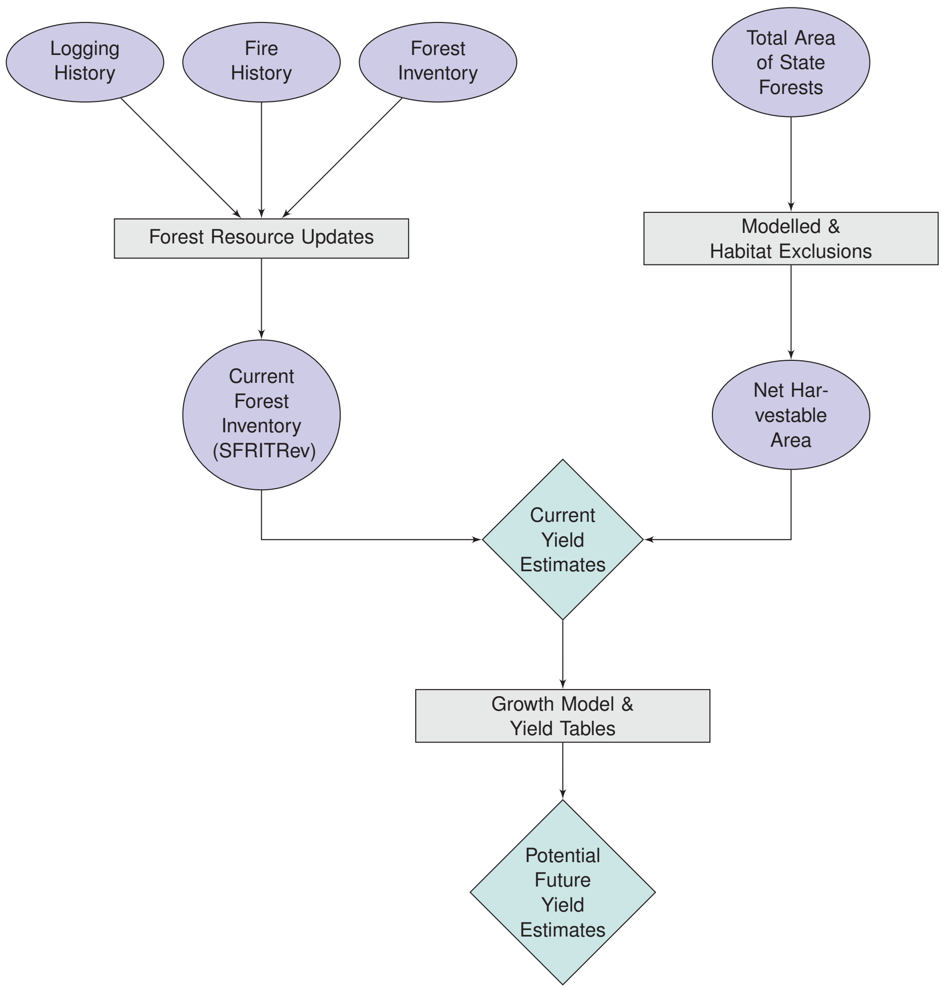

Figure 3: Key components of the strategic wood supply model used to estimate current and future total merchantable volume of fibre and wood from Victoria's State Forests.

2.2.1 Net Harvest Area

Of the total area of Victoria's native forest estate, only a small proportion is available for harvesting. A large proportion of the native forests occurs in protected areas, such as Parks and Conservation Reserves. Forest harvesting operations on public land are restricted to State Forests. However, a large proportion of State Forests is excluded from harvesting due to a range of factors, including Regional Forest Agreement Special Protection Zones, Code of Forest Practice exclusions for steep slopes, riparian buffers, and special exclusions for threatened species (*e.g.*, Long-footed Potoroo, Tall Astelia, Leadbeater's possum) or habitats (*e.g.*, cool temperate rainforest). The Net Harvest Area is a spatial database that describes the area of Victoria's State Forests that is available to harvest once all exclusions have been removed. This forms the basis of the SWSM as it represents the most up-to-date description of the forest area. The Net Harvest Area is spatially stratified into seven forest management areas (FMA) that represent the main areas of native forests in eastern Victoria. The East Gippsland FMA is the largest, accounting for nearly half of the total area of harvestable State Forest in Victoria. The Central Highlands is divided across several FMAs, including the Central, Central Gippsland, and Dandenong FMAs.

It is important to recognise, however, that the Net Harvest Area is an accurate description of the forest area available for harvesting at the time of model runs. While the Net Harvest Area is updated regularly to reflect the occurrence of harvesting operations, fires, and new exclusions, it does not explicitly anticipate future changes to forest area from these types of events. It may be possible to explore the impacts of stochastic events through simulation (see Sections 5, 6, and 4 below for discussion of this issue). However, the Net Harvest Area would have to be modified for each simulated event and then run through the SWSM to evaluate the impacts of these changes.

2.2.2 Forest Inventory, Growth, and Yield

The total merchantable volume (TMV) available for harvest varies widely across the areas of the State Forest that are available to harvest due to site-level differences in species composition, productivity, and stand age. The standing current and future merchantable volume of wood across the net harvest area is based on existing forest inventory data and growth and yield models.

The current forest volumes—that is, the amount of merchantable wood in any given location at the time of modelling—are based on the State Forest Resource Inventory (SFRI) (Wong *et al.*, 2007). The SFRI was initiated in 1993 and completed in 2004 and provides a snapshot of wood volume benchmarked at 2002. The SFRI has not been repeated since, so current (*i.e.*, 2016-17) estimates of wood volume in State Forests are based on updates to the SFRI database to reflect harvesting and fire events and modelled yields. In stands where harvesting or fires have occurred, the stand volume is set back to zero at the time of the event. In stands that have not been impacted by harvesting or fire, current volume is estimated by projecting the 2002 volumes forward using a forest growth model.

The forest growth model that is used to project the current forest inventory forward in time and which underpins VicForests' yield estimates was developed by Yue Wang for VicForests in 2014-15. It is described in detail in a series of reports commmissioned by VicForests (Wang, 2013). The model is cohort-based, which means that the model projects the TMV of wood for a cohort that is defined by a forest growth function and age. Forest growth functions (FGFs) are growth and yield functions that are grouped by individual species or groups of similar species. For example, alpine ash is sufficiently widespread, valuable, and distinct that it is given its own FGF. In contrast, the high-value mixed species (HVM) FGF includes about a dozen non-ash eucalypt species that are commercially valuable. Growth and yield functions are further stratified by FMA for each FGF. The growth model recognises 574 yield classes that are defined by unique combinations of the FMA, FGF, forest condition (*e.g.*, mature, regenerating, uneven-aged), site productivity class, and the relative proportion of non-eucalypts.

Each polygon within the Net Harvest Area shapefile is assigned a yield class based on these attributes. The current TMV is then used to predict future TMV over the planning horizon used in the Woodstock modelling.

It is important to recognise that while VicForests' growth and yield model provides a common framework for predicting total merchantable volume, it is not equally well suited for all forests. Due to differences in stand history and cohort structure, species composition, and the data available for model parameterisation (in terms of both quantity and quality), the quality of the growth and yield predictions varies. For example, the complex age structure and species composition of the mixed species forests of East Gippsland mean that growth and yield projections are made with much less certainty than the predictions for even-aged, single species mountain ash or alpine ash forests in the Central Highlands.

VicForests' growth and yield model was parameterised using permanent growth plot (PGP) data across the range of species groups and stand ages. TMVs predicted by the model can be compared to actual volumes obtained from coupe-level sales records. This allows for out-of-model assessments of the predictive accuracy and precision of the growth and yield model and provides the empirical basis for volume scaling factors. Comparisons of the actual and predicted volumes demonstrate that VicForests' current growth and yield model consistently overpredicts total merchantable volume (Figure 4). The reasons for this are unclear. However, as we discuss in Section 3, this overprediction of yield is addressed through the application of a TMV scaling factor during the Woodstock modelling process.

The growth and yield model used in the SWSM process does not take into account changes in forest productivity due to climate change. While the expectation is, on average, that forest productivity in water-limited regions will decline under warmer future conditions (Allen *et al.*, 2010, Boisvenue and Running, 2006, Mok *et al.*, 2012), there will be important spatial components to forest productivity responses to climate change. We discuss some of these issues in Section 6.

2.3 Woodstock modelling

Woodstock is the core component of VicForests' SWSM. Woodstock is proprietary software developed by RemSoft and widely used by government and industry around the world to develop strategic timber harvesting plans across large forest estates (*e.g.*, Lee and Barker, 2005). Woodstock has been a central component of the SWSM process for more than 15

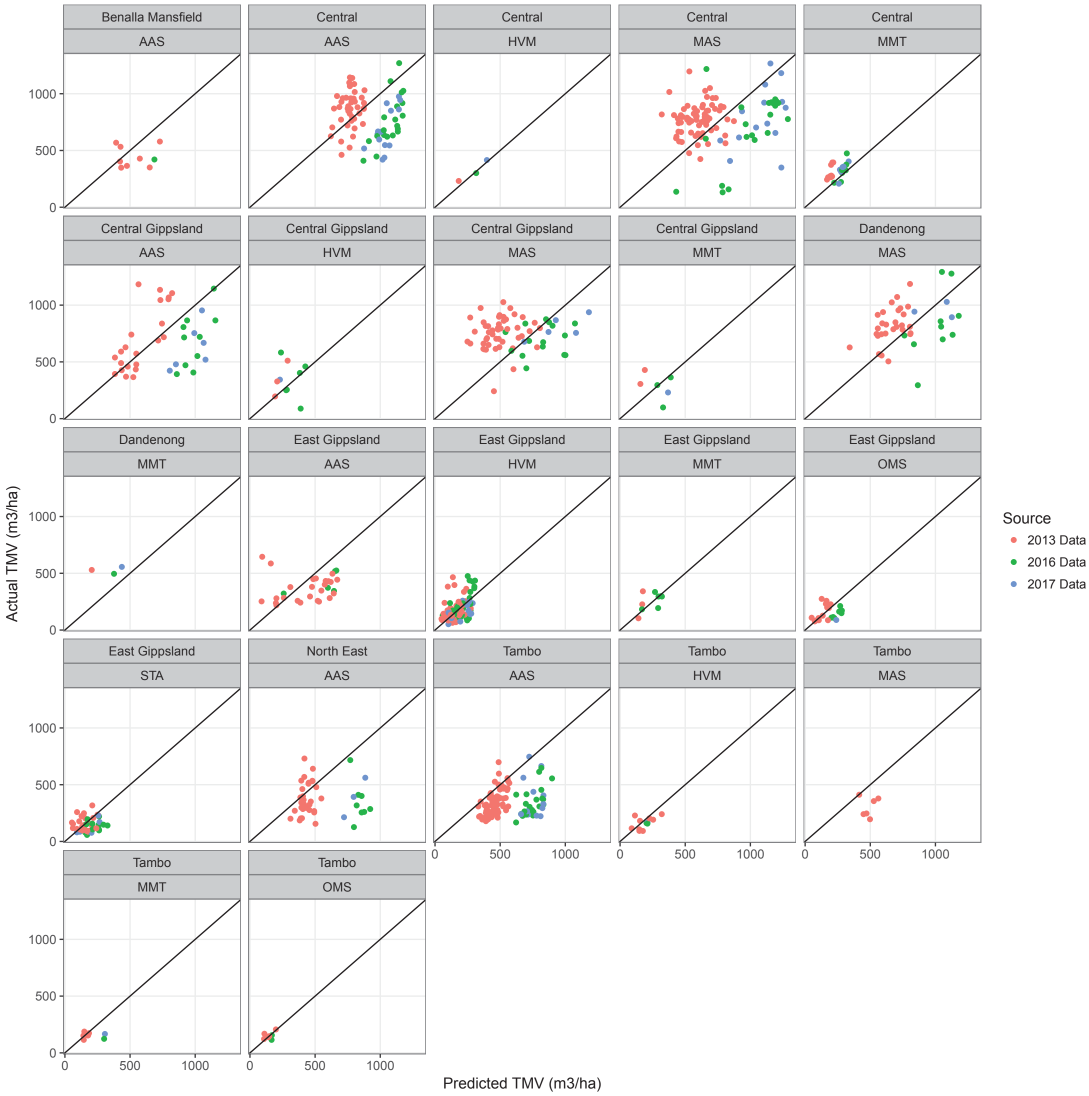

Figure 4: A comparison of estimated and observed coupe-level yields grouped by year of prediction. The data represent individual coupes in which >80% of the total harvested area was dominated by a single species or species group used for modelling (*i.e.*, forest growth function). The solid black line represents a 1:1 relationship in which the predicted yield equals the actual yield. Points below the 1:1 line represent overestimates of yield; points above the 1:1 line represent underestimates of yield. The 2016 and 2017 data represent estimates based on the current growth and yield model used by VicForests.

years, having been used by both VicForests in its current role and the Department of Sustainability and Environment (DSE) before it. Woodstock is a linear optimisation program that attempts to find the best solution to a complex scheduling problem while maximising a specified objective function. VicForests use Woodstock to identify an optimal solution regarding the timing and intensity of harvesting that maximises the future flow of total merchantable volume subject to existing resource availability and constraints over a 100-year period.

In this section, we examine the data, constraints, and scaling factors that are used in Woodstock when modelling the sustainable harvest levels of Victoria's native forest estate (Figure 5).

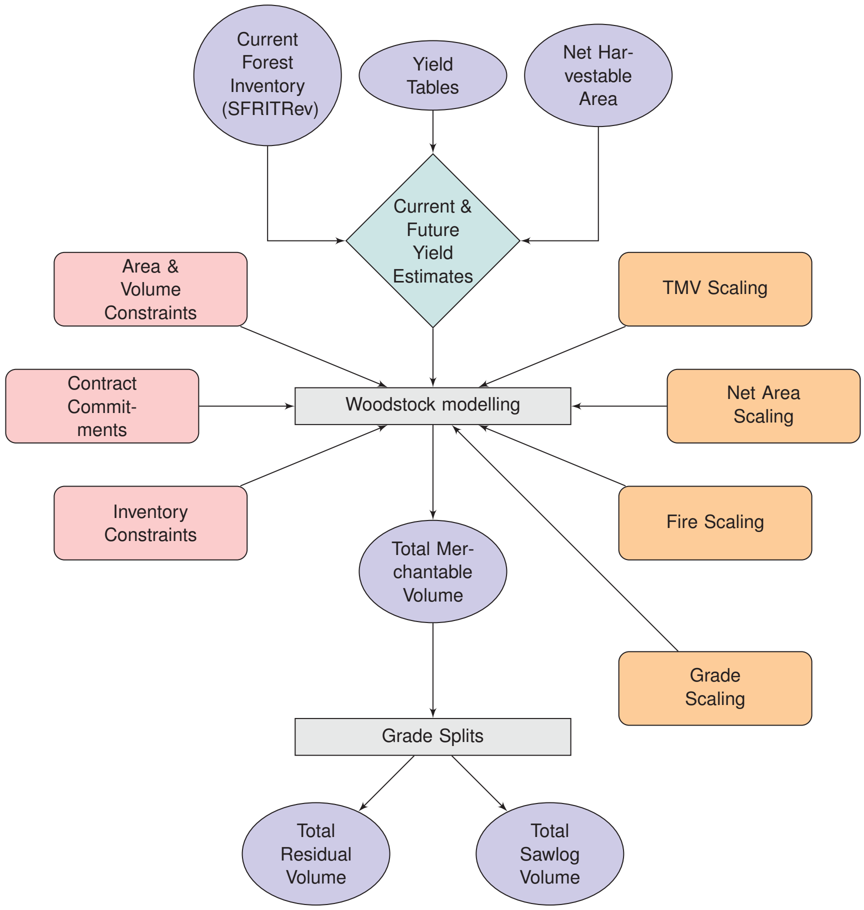

Figure 5: Key components and constraints to the Woodstock component of the strategic wood supply modelling process. Red boxes to the left are constraints on the model; orange boxes to the right are scaling factors used to adjust the total merchantable volumes during the Woodstock modelling.

2.3.1 Data input

Woodstock requires three data components to run: current inventory, net harvest area, and projected growth and yield (as described above). Briefly, the Net Harvest Area describes the total area of State Forests that is available to harvest. This excludes all known Reserves, Protected Areas, Code exclusions, and other exclusion zones. The current forest inventory is represented as yield classes assigned to each polygon in the Net Harvest Area spatial database. Each yield class has an associated time series of TMV values in the yield table that details the total merchantable volume and volume by grade for 150 years of growth. The Woodstock runs are usually done for a 100-year planning horizon and use 5-year time steps.

While the location of all of the polygons in the Net Harvest Area is contained in the GIS datafile, Woodstock itself does not use any spatial data. It effectively works on a table of summed yield class areas subdivided by age. However, each polygon in the Net Harvest Area has a number of data attributes that are used for calculating or modifying TMV. For example, each polygon is associated with a block, a sub-unit of the FMA. This block identifier is used to calculate the net area scaling factor described below. All of the necessary data and metadata for calculating current and future TMV are included in the Net Harvest Area data files.

2.3.2 Constraints

Area and volume constraints—A common objective of SWSMs is to provide an even flow of wood to ensure stability for the local and regional forest industry. VicForests uses two constraints—area and volume—to ensure as uniform a supply of wood as possible. These constraints require that the total harvested area or TMV do not fluctuate by more than a specified percentage from one five-year planning period to the next. These constraints are applied at either the FMA level or to aggregates of FMAs to ensure that harvesting does not jump from one FMA or FMA aggregate to another and back again as this causes significant logistical challenges for the location of workers and infrastructure. In addition, the area and volume constraints ensure that Woodstock does not harvest a single FMA or FMA aggregate to exhaustion before moving on to the next FMA or FMA aggregate. This provides a measure of stability to the local forest industry (*e.g.*, contractors, mill owners, haulage operators) without compromising the regional forest industry. Typically, the area constraint is $\pm$10% and the volume constraint is $\pm$15%. However, these values can be modified to explore the consequences of tighter or looser controls on even flow between FMAs or FMA aggregates over time.

Contract constraints—VicForests and the State of Victoria have existing supply contracts for sawlogs and pulp wood. These contracts are included in the Woodstock modelling process to ensure that the minimum harvest levels necessary to service the contract requirements have been met. Sawlog contracts are typically for three-year periods with the potential for renewal for two subsequent three-year periods. The relatively short length of the sawlog contracts provides a buffer against unforeseen events such as large bushfires that might substantially lower the sustainable harvest levels. The State of Victoria does have a long-term contract with Australia Paper to provide pulp wood to the Maryvale pulp mill. This contract concludes in 2030 and accounts for a large proportion of the harvested volume of wood taken each year from the State's forests.

Inventory constraints—Although an area may be support forest, there are specific constraints on harvesting that depend on the forest inventory (*i.e.*, the size and number of trees). The primary inventory constraints are minimum and maximum harvest ages and minimum harvestable volume. The minimum and maximum harvest ages for mountain and alpine ash in the Central Highlands are 60 and 117 years, respectively. The Code of Forest Practices prevents harvesting of any ash in the Central Highlands that established in 1900 or earlier. In mixed species stands the maximum harvest age is 120 years; however, because stand ages are not known for most mixed species stands and most such stands have multiple age cohorts, it is often difficult to determine the age of individual trees. Minimum harvestable volume sets a lower threshold for TMV per hectare below which it is not worthwhile harvesting. The minimum harvestable volume is typically set at 50 m^3 yr^{-1}. Further constraints are applied in the tactical planning stage, when spatial considerations such as minimum and maximum coupe size and adjacency rules are modelled using Stanley.

2.3.3 Scaling factors

Scaling factors are used to align predicted values of the data inputs (primarily area and volume) with observed values derived from various sources. This provides a mechanism to account for any observed biases in the model predictions to be realigned to empirical observations of harvest areas or harvest volumes. The scaling factors are applied at various levels–some are applied at the block level, others at the FMA and species group level. The final TMV values are obtained by multiplying the predicted TMV by the various scaling factors such that:

$$TMV_{Final} = TMV_{Predicted} \times TMV\ Scaling \times NAS \times Fire \times Grade\ Scaling \tag{2.1}$$

where TMV_{Final} is the final TMV used by Woodstock and $TMV_{Predicted}$ is the predicted TMV derived from the yield tables. Each of the four scaling factors (TMV and Grade Scaling, NAS, Fire) are described in detail below.

Total Merchantable Volume Scaling—Growth and yield modles may over- or under-predict TMV for a variety of reasons. The TMV scaling factor is applied in Woodstock to align the predicted TMV with observed TMV from harvested coupes over the recent past. The growth and yield model currently used by VicForests appears to overestimate TMV in many of the species group x FMA combinations (see Figure 4 above). Because the prediction errors vary by species group x FMA combinations, TMV scaling factors are applied to eaech species group within each FMA to correct them. For each species group x FMA combination the predicted TMV and actual harvested TMV values are compared for the past five years. The comparisons are restricted to coupes that have relatively homogeneous species composition (*i.e.*, $>$80% of one species group). An initialisation run of Woodstock is made using these coupes to obtain predicted TMV (including the scaling for NAS and fire described below). TMV scaling factors are calculated as the ratio of the mean predicted TMV and the mean observed TMV within the species group x FMA combination. Each TMV scaling factor is then applied in a second (and occasionally third or fourth) Woodstock run to align the predicted and observed TMVs.

Net Area Scaling—Net area studies (NAS) factors are used to remove bias from estimates of

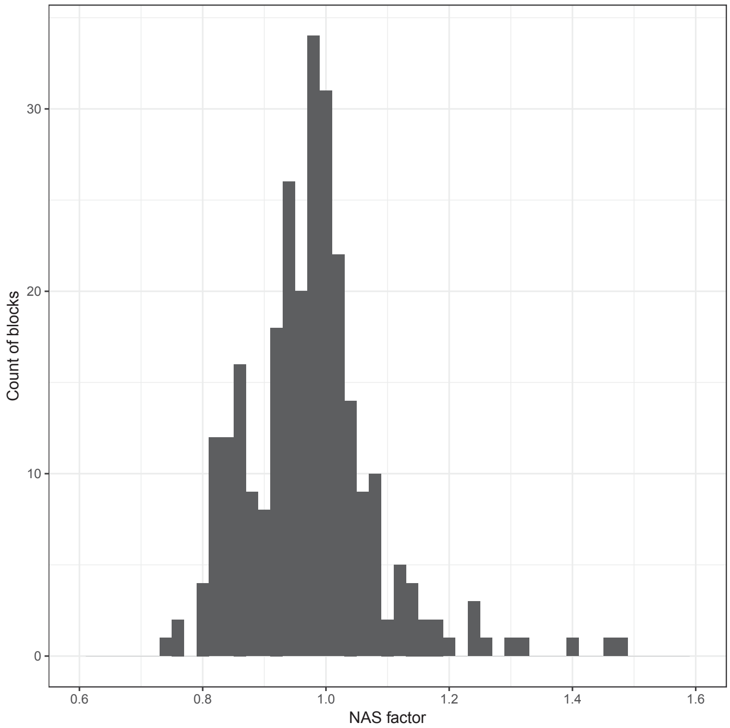

Figure 6: Distribution of net area studies (NAS) factors used to scale predicted harvested area to actual harvested area.

harvested area created by inaccuracies in the Net Harvest Area mapping process. The net area studies themselves are comparisons of predictions of forest availability for harvest and actual harvest areas within coupes. They are based on estimates of:

1. the area predicted to be available that was harvested,
2. the area predicted to be available that was not harvested,
3. the area that were predicted to be unavailable but was harvested, and
4. the area that were predicted to be unavailable and was not harvested.

Together these are used to calculate the ratio of actual harvested area to predicted harvested area—the NAS factor. VicForests calculates NAS factors at the block level, where forest blocks are relatively homogeneous sub-units of 500-1000 ha, and applies them to the predicted TMV. The mean NAS factor across all blocks is 0.98; however, the values range from 0.74 to 1.48 (Figure 6). The underlying assumption of the NAS scaling is that inconsistencies between predicted and actual harvest areas will remain constant over time within a forest block. However, the raw coupe data that was used to calculate the block-level NAS factors is not available, so it is unclear whether this is a reasonable assumption or not. It is also unclear how variable the raw data used to calculate block-level NAS factors are.

Fire Scaling—A fire scaling factor is applied to polygons in the Net Harvest Area that have been subjected to fire. This scaling factor reduces the volume of E+ sawlogs to reflect loss from fire damage and mortality. The scaling factor is based on observed fire severity and dominant species (Table 1). In mixed species forests, in which the species are less susceptible to fire-induced mortality, volume reductions are applied for low- to moderate-severity fires. In ash forests, which are more susceptible to fire-induced mortality, volume reduction only applies to low-severity fires; more severe fires reduce the stand volume to zero.

Table 1: Fire scaling factor for total merchantable volume by species group and fire severity. The scaling factor is multiplied against the predicted total merchantable volume (TMV) to calculate post-fire TMV. Fire severity scores range from 1 (high) to 3 (low); zero is no fire.

Species Group	Fire Severity	Fire Scaling Factor
All	0	1.0
Ash	3	0.8
Mixed species (post-1995)	3	0.9
Mixed species	2	0.7
All	1	0

Grade Scaling—The growth and yield model provides a value for stand-level total merchantable volume. This is then broken down into wood grades that describe the range of quality in the wood. Grade assessments are based primarily on the length, diameter, and straightness of cut logs and the presence of defects. Sawlog grades range from B (highest quality) to E (lowest quality). The residual grade is any wood that is not of sufficient quality to be a sawlog. Each grade (B-E and Residual) is defined as a *proportion* of the total merchantable volume. For example, in mature alpine ash in the Central FMA an 80-year old stand the yield tables predict that TMV will be 1067 m^3 ha^{-1}. Of that, grading algorithms predict that 18% is B grade sawlog, 9% is C grade, 2% is D grade, 15% is E grade, and 55% is residual. These grade definitions are applied in Woodstock for all species group and FMA combinations (*e.g.*, alpine ash in Central). The grade scaling factor is then used to adjust these proportions to reflect differences between the predicted grading and the actual grading observed in previously harvested coupes. Grade scaling factors range from 0.92 to 1.11. For each species and FMA combination, the grade scaling sums to one as an increase in one grade must be accompanied by a proportional decrease in one or more other grades.

2.4 Stanley and spatial planning

Stanley is a tactical planning tool that uses spatial data on potentially harvestable coupes identified by Woodstock to identify groups of polygons that are logistically feasible to harvest together as one or more coupes. It is takes the long-term, State-wide assessments of potential wood supply modelled in Woodstock and develops tactical plans over shorter planning horizons (*i.e.*, 20 years) and smaller spatial scales (*i.e.*, individual FMAs). The spatial focus of Stanley allows it to account for adjacency rules, minimum and maximum coupe sizes, proximity to road access, and a variety of other spatial features that are relevant to developing tactical harvesting plans within each FMA. It identifies areas of forest that are too small in area to be harvested and either aggregates them with other adjacent polygons to form a larger aggregate or eliminates them from the list of potentially harvestable polygons. For instance, minimum and maximum coupe sizes are 5 and 120 ha, respectively. Stanley will aggregate adjacent polygons to form individual coupes that fall between these bounds. If a polygon cannot be grouped with others to form a coupe larger than 5 ha, then it is excluded from harvesting. Adjacency rules ensure that there is a minimum of at least five years between harvests for coupes that are next to each other. This prevents maximum coupe size limits from being circumvented by placing separate coupes next to each other and harvesting them at the same time. Stanley also identifies individual polygons that are isolated or too distant from other polygons for aggregation and can remove them from the list of harvestable areas. As a result of these spatial constraints, Stanley typically reduces the TMV estimated in Woodstock by 20-30%. The TMV estimates produced by Stanley are then communicated to the VicForests managers based in each FMA for assessment. The FMA-level managers then compare the Stanley-based TMV estimates with field-based assessments of the timber resource to determine if the predicted TMV estimates are achievable. Where the predicted TMV estimates are too high, the FMA-level managers can then suggest more appropriate targets. Due to time constraints we did not consider Stanley outputs in any of our analyses.

2.5 Sustainable harvest levels

The development of VicForests sustainable wood supply levels involves running a large number of scenarios through Woodstock and Stanley. These scenarios vary in their constraints, land areas, assumptions about changes to tenure, industry activity, and other factors. As many as 30-50 individual runs of Woodstock may be conducted to explore the range of potential sustainable harvest levels. The Stanley outputs are then discussed with FMA-level forest managers for comparisons with field-based assessments of available wood resources. The final sustainable harvest levels are then set based on evaluations of the Woodstock/Stanley scenarios, commercial commitments, potential risks and uncertainties, and other factors. It is unclear how much, if any, buffer is included to account for unexpected future events, such as fires. The process by which these scenarios are aggregated, evaluated, and analysed and then combined with other information to select a single annual sustainable harvest level is not documented and is the least transparent part of the process. However, the sustainable harvest levels are typically within the range of scenarios of Woodstock/Stanley runs.

2.6 Areas for improvement

The SWSM approach that VicForests uses provides estimates of potential future wood supply levels from Victoria's State Forests. While we believe that their approach is rigorous and repeatable, we believe that there are several areas in which it could be improved.

2.6.1 SFRI data

The fundamental data that underpins any resource management model is an accurate assessment of the available resource. The SFRI data are now 15-25 years out of date and are only updated to reflect changes to forest status from harvesting or fire. Over that period a range of factors may have occurred to change the structure, composition, and dynamics of Victoria's State Forests–and these changes may vary widely spatially and temporally. For example, the Millennium Drought may have increased mortality rates and reduced growth rates of trees across much of Victoria, but the effects would have been mitigated or exacerbated by edaphic conditions, species-level variability in drought-susceptibility, and forest structure. Other disturbances such as windstorms, breakage from snow, injury from insect attacks would also impact the forest condition. An up-to-date resource inventory would provide a more accurate assessment of the forests and their ability to provide wood to the native forest industry. Ideally, a forest inventory system for the State Forests would be repeated at regular (5- or 10-yearly) intervals to ensure that the resource modelling is using relatively current data.

The SFRI data would also benefit from being expanded to include non-eucalypt species. Victoria's State Forests are managed for a range of goods and services, including timber, habitat, carbon, water, and soil health. Developing strategic wood supply models that accommodate non-timber values requires having data on non-timber values. While data on non-commercial, non-eucalypt species may not be directly relevant to timber harvest planning, it is relevant for understanding habitat availability. The existing SFRI dataset has almost no data on, for example, *Acacia* species. This inevitably means that our planning for timber and non-timber values is conducted independently. A systematic, repeated inventory of forest resources–as standard practice in most countries with large public forest estates and well-established forest industry–would provide a foundation for integrated forest management that allowed wood supply modelling to inform habitat availability models and vice versa. Recent developments in remote sensing for forest inventory using LiDAR have made this an increasingly affordable option, although it needs to be paired with ground-based inventory assessments as well. Forestry Tasmania has adopted a LiDAR-based approach to forest inventory across its entire forest estate over the past fiver years. Developing a high-quality, continuing forest inventory framework should be a priority for Victoria.

2.6.2 Polygons vs coupes

A significant challenge in understanding and managing the SWSM process for Victoria's State Forests arises from the nature of the spatial data that inform the development of the Net Harvest Area and Stanley reductions. The State Forests are represented in a GIS database as several hundred thousand polygons. Each polygon represents a relatively homogeneous area of forest defined by species, topography, condition, productivity class, and a range of other factors. The Net Harvest Area database contains 238,028 polygons, the median size of which is 0.5 ha. There are nearly 3500 polygons with areas $<1m^2$. The large number of small polygons arises from the fragmentation of the landscape due to complex topography, diverse exclusion zones, and the inherent diversity of the forests. However, once the spatial database becomes so atomised, it becomes increasingly complex to manage the data, quantify variability in the resource, and aggregate the polygons into coupes. It may also lead to unintended biases in the spatial database. For example, Stanley reductions aggregate polygons into minimum coupe sizes. If individual polygons are too small or too isolated, they are not included. Consequently, small and isolated polygons should tend to accumulate in the spatial database. Rationalising the many polygons into coherent management units would make the relationship between the modelled resource data and the eventual coupes more closely aligned and would enable more effective on-the-ground assessments of timber and non-timber resources.

2.6.3 Probabilistic supply level assessments

Current sustainable harvest levels are set as a single figure (*e.g.*, 175,000 m^3 $year^{-1}$). This ignores the considerable uncertainty in the yield estimates that is arises from uncertainty in the forest inventory data, bias in the growth and yield model, and variability in the scaling factors. Developing a probabilistic framework that explicitly accounts for uncertainty in wood supply forecasts would provide a better description of the forest resource and allow for better risk management by VicForests and, more broadly, the native forest industry. This framework would be akin to weather forecasting in which a specified outcome is made with some estimate of certainty (*e.g.*, 75% chance of rain tomorrow). The current projection of D+ ash sawlogs is 175,000 m^3 $year^{-1}$. However, it is unclear what the uncertainty around that estimate is. Is the credible range of potential ash supply 150,000-200,000 m^3 $year^{-1}$? Or is it 75,000-275,000 m^3 $year^{-1}$? A probabilistic framework for assessing uncertainty in the data and models that underpin these forecasts would enable VicForests to say that they estimate a 75% change of being able to provide a sustainable harvest of D+ ash sawlogs of 175,000 m^3 $year^{-1}$. Such estimates would allow for more transparent estimates of risk in contract negotations and government planning of the forest resource.

2.7 Conclusions

Estimating the sustainable wood supply level for a forest estate the size of Victoria's State Forests is an inherently complex process. The diversity of forests, topography, and various constraints that must be taken into account requires a hierarchical, multi-staged planning process. The complexity of this planning process greatly limits the degree to which the public can understand or interpret how VicForests sets sustainable wood supply levels. Based on our assessment of the planning process, however, it appears that VicForests approach is a sound one. They use industry-standard models to develop their strategic and tactical wood supply levels and have staff that are well-trained in their use and interpretation. The assumptions that underpin the various components of their modelling approach are both reasonable and appropriate and the calculations that they perform appear accurate. And while we feel that there are several areas where VicForests could improve their process, overall we feel that the strategic wood supply modelling that VicForests conducts is rigorous and repeatable.

Our assessment of the quality of the SWSM process employed by the State of Victoria is not unique. Previous reviews have delivered similar assessments. For instance, Prof Jerry Vanclay and Dr Cris Brack in evaluating the Joint Sustainable Harvest Level Statement (JoSHL) in 2008 endorsed the SWSM approach used by DSE and VicForests at the time. They concluded that, "JoSHL is a robust process that should inspire confidence that the proposed timber harvest of up to 500,000 m^3 year^{1} of D+ sawlogs is sustainable for the next 15 years, given the specified assumptions." Notably, the assessment was dated 5 May 2008, 9 months before the Black Saturday bushfires would cause dramatic losses of ash forests in the Central Highlands and a significant reduction in the sustainable timber harvest levels–circumstances that could not have been foreseen during the JoSHL process.

As Vanclay and Brack noted, SWSM estimates are contingent on their assumptions–and few, if any, factor in losses in forest resource to stochastic events such as fire, or in Victoria more recently, the discovery of hundreds of Leadbeater's possum colonies on State Forests available for timber harvesting. The next section of the report addresses parameter uncertainty in the forest growth modelling process. After that, we spend the remainder of the report exploring what we believe to be the risks and uncertainties that Victoria's State Forests and the provision of a sustainable supply of wood. We specifically address potential impacts of bushfires, Leadbeater's possum detections, and climate change. While there may be different opinions about the immediacy of any of these threats, it is important to acknowledge them and explore the potential risks that they present to Victoria's wood supply levels over the coming decades.

Part 3

Parameter Uncertainty in Scaling Factors

3.1 Summary

Goal

- To estimate uncertainty in scaling factors and residual error to assess how the uncertainty in actual vs predicted total merchantable volume (TMV) propagates into uncertainty in predicted TMV.

Main findings

- Comparisons of actual and predicted harvest volumes show significant variability. Mean values of the ratio of actual to predicted TMV are used to re-align predicted TMV in Woodstock.
- In the absence of disturbances, total merchantable volume per year is known with $\pm$ 10% certainty. The uncertainty is higher if we break TMV down by species group (around $\pm$ 15% for AAS and MAS, $\pm$ 20% for HVM and MMT, $\pm$ 40% for OMS and STA). The uncertainty is even greater when species groups are split by FMA.
- While some of these differences may "average out" at the strategic level, the application of point estimates of TMV scaling factors masks considerable uncertainty in the predicted TMV.

3.2 Background

The strategic wood supply modelling (SWSM) process described in Section 2 is used to estimate future sustainable harvest levels across Victoria's State Forests. A core element of the SWSM process is the estimation of stand growth and yield at the scale of individual polygons (which are later grouped into coupes based on proximity and homogeneity). However, as discussed, the estimates of TMV are often biased, whether by species group, by FMA, by block within FMA, or by age class. To adjust the predicted TMVs to align with actual TMV (based on observations from recent harvest operations and timber sales), several scaling factors are multiplied against predicted TMV to obtain a final TMV that is used in Woodstock. One of the most important scaling factors is the TMV scaling, which is the ratio of actual to predicted TMV within an FGF x FMA combination (*e.g.*, mountain ash in Central Gippsland). The TMV scaling factor is a point estimate of this ratio and ignores the often substantial noise in the relationship between actual and predicted TMV. We explore this variability and its potential to propogate uncertainty through the SWSM process using actual and predicted TMV data and TMV scaling factors from the past decade.

3.3 Material and methods

3.3.1 Material

Data on predicted and actual TMV for coupes over the period 2013-2016 were provided to us by VicForests. The data included TMV data for six Forest Growth Function (FGF) and all seven Forest Management Areas (FMA). FGFs refer to individual species or groups of species that are treated together in the growty and yield modelling process by VicForests. Examples include single-species FGFs such as alpine ash and messmate, as well as mixed species FGFs, which contain a number of non-ash eucalypts that provide high-value wood.

We followed VicForests data cleaning procedures for calculating TMV scaling factors by applying several filters to the full data set. This allowed us to avoid outliers and to reduce to some degree the noise in the data. These filters select coupes in which:

1. the harvested area is represented by more than 80% of a single FGF (*i.e.*, relatively homogeneous stand);
2. the harvested area is $>$5 ha;
3. the harvested coupe is a final clearance;
4. the harvested coupe had a predicted yield of 50-1300 m^3 ha^{-1}; and
5. the actual TMV at harvest is within two standard deviations of the mean predicted TMV.

We were not able to produce exactly the same results as VicForests. While the differences were relatively small, it appears that they use a slightly different filtering process. In addition, there appear to be two issues in the way VicForests computed their standard deviation of predicted TMV: 1) they use a biased estimator (denominator of n instead of n-1) and 2) they counted missing predicted TMV values as 0 m^3 instead of removing them from the computation, which will inflate the standard deviation.

Another important issue is that the model that VicForests uses to calculate predicted TMV changed after 2013. For the purpose of consistency, we have limited our analyses to data that

Table 2: Summary statistics for actual and predicted total merchantable volume (TMV) aggregated by FGF and FMA. The data were collected between 2012/13 and 2015/16. The Actual/Predicted column provides the unbiased estimate of the TMV scaling factor. The VF factors column provides the value applied in TMV scaling by VicForests. For species with abundant data (*e.g.*, alpine ash (AAS), mountain ash (MAS)), the differences are small. For other species and species groups, the differences can be quite large (*e.g.*, messmate (MMT) in Central Gippsland). The final row (Total) shows the that there is a considerable bias in the growth and yield model when averaged across all FGF x FMA combinations.

FGF	FMA	Coupes n	Area (ha)	Actual TMV (m^3)	Predicted TMV (m^3)	$\frac{Actual\ TMV}{Predicted\ TMV}$ (unitless)	VF's TMV Scaling factor (unitless)
AAS							
	Benalla Mansfield	1	10	4085	6660	0.61	0.61
	Central	26	573	444163	615681	0.72	0.73
	Central Gippsland	16	253	174550	249405	0.7	0.77
	East Gippsland	5	91	35973	49235	0.73	0.76
	North East	10	158	62950	132702	0.47	0.45
	Tambo	25	389	161645	301730	0.54	0.51
HVM							
	Central	2	36	12891	12807	1.01	0.95
	Central Gippsland	4	105	32395	31141	1.04	0.93
	East Gippsland	39	812	147766	163941	0.9	0.8
	Tambo	3	58	9400	11982	0.78	1.1
MAS							
	Central	30	485	380222	527598	0.72	0.78
	Central Gippsland	23	355	275589	314807	0.88	0.9
	Dandenong	10	171	140036	176705	0.79	0.87
MMT							
	Central	10	248	71088	67294	1.06	0.88
	Central Gippsland	4	72	18072	24779	0.73	1.32
	Dandenong	1	26	12901	9805	1.32	0.96
	East Gippsland	6	82	21924	22812	0.96	0.47
	Tambo	2	50	7020	15105	0.46	0.62
OMS							
	East Gippsland	8	171	25391	42927	0.59	2.0
	Tambo	2	49	6925	8280	0.84	0.79
STA							
	East Gippsland	18	391	52677	87449	0.6	0.51
	Tambo	1	23	3318	6484	0.51	0.76
	Total	246	4607	2100981	2879329	0.73	

were recorded after 2013. This includes data records written as 2016 or 2017 in "Source data" in the VicForests database. In Table 2 we provide summary statistics of the TMV data (actual and predicted) aggregated at the FGF and FMA level and the TMV scaling factors.

Once the data have been filtered, VicForests computes scaling factors for each combination of FMA and FGF following: $scaling\ factor = \frac{\sum actual\ TMV}{\sum predicted\ TMV}$.

3.3.2 Modelling the scaling factors

We used a hierarchical linear regression to relate actual TMV to predicted TMV and to compute scaling factors. Equation 3.1 has only a slope (no intercept, so that slope = scaling factor)). We used this approach to try to mimic the way VicForests computes its scaling factors, but also to account for residual errors per coupe.

The hierarchical models allows pooling of information between FMA and FGF group to get better estimates of the scaling factors for groups with few data points. Both the slope (scaling factors) and the residual error terms were allowed to vary per group, and were modelled as the sum of a population term, plus a FMA and FGF-specific discrepancy to this population term (*i.e.*, random coefficient) sampled from a Gaussian distribution with zero mean and standard deviation to be estimated. The model takes the form:

$$\begin{aligned} actual\ TMV_i &= \beta_j \times predicted\ TMV_i + \epsilon_{ij} \\ \beta_j &\sim Normal(\beta, \sigma_\beta) \\ \sigma_j &\sim Normal(\sigma, \sigma_\sigma) \\ \epsilon_{ij} &\sim Normal^+(0, \sigma_j) \end{aligned} \tag{3.1}$$

where i is a coupe with observations of actual and predicted TMV, and j is one of the 22 levels of the grouping factor (*i.e.*, FMA x FGF combinations, equivalent to the number of rows in Table 2, excluding the Total row). β_j is the estimated TMV scaling factor for group j, σ_j is the standard deviation of the residual terms for group j, and ϵ_{ij} is the residual error for observation i in group j sampled from a Gaussian distribution (truncated at 0 to have only positive values) with mean 0 and standard deviation σ_j. β, σ_β, σ and σ_σ are population parameters to be estimated.

3.3.3 Propagating the uncertainty into yield predictions

We used Equation 3.1 to simulate new actual TMV per ha for each coupe from raw predicted TMV per ha given by VicForests. We used uncertainty in both parameter values and residual error terms. These corrected predictions of TMV per ha were then multiplied by the coupe area (provided in the database). We then summed the volume per harvesting season to get one TMV prediction value per year. This procedure was repeated 4000 times, giving us 4000 TMV

Table 3: Parameter estimates for the TMV scaling factor model in Equation 3.1. The model was fit to 2016 and 2017 source data in VicForests database of actual and predicted TMV.

		β_j		σ_j	
FGF	FMA	mean	sd	mean	sd
AAS					
	Benalla Mansfield	0.67	0.11	101	47
	Central	0.73	0.02	129	18
	Central Gippsland	0.69	0.04	172	25
	East Gippsland	0.72	0.07	112	29
	North East	0.49	0.06	153	28
	Tambo	0.54	0.04	141	19
HVM					
	Central	0.87	0.14	94	46
	Central Gippsland	0.90	0.13	100	34
	East Gippsland	0.80	0.05	71	9
	Tambo	0.78	0.08	31	32
MAS					
	Central	0.73	0.03	197	21
	Central Gippsland	0.83	0.03	144	19
	Dandenong	0.81	0.04	135	26
MMT					
	Central	1.01	0.06	50	16
	Central Gippsland	0.74	0.12	116	34
	Dandenong	0.88	0.18	130	42
	East Gippsland	0.89	0.10	76	26
	Tambo	0.63	0.14	91	43
OMS					
	East Gippsland	0.59	0.06	44	17
	Tambo	0.76	0.15	76	41
STA					
	East Gippsland	0.60	0.05	54	11
	Tambo	0.68	0.16	98	47

prediction values that can be summarized by a distribution. We first group these predictions by harvesting year and then by year and FGF.

3.4 Results

3.4.1 Model summary

Estimated model parameters are shown in Table 3. The β_j parameters are the TMV scaling factors and the σ_j are standard deviations of the residual errors. The fitted equation is shown in Figure 7 and captures both the trends and the uncertainty of the data.

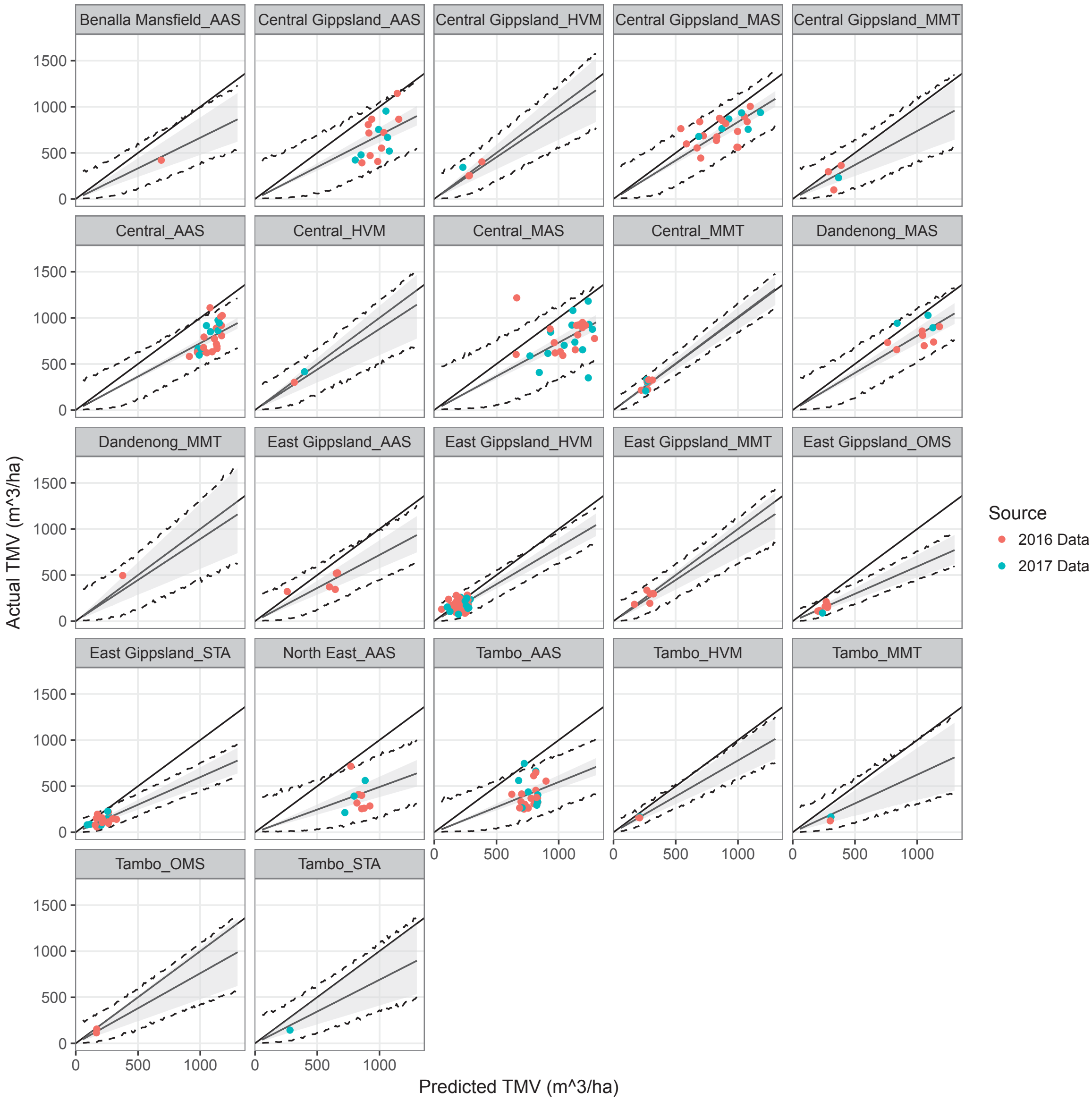

Figure 7: Comparison of actual and predicted total merchantable volume (TMV). Points are observed data from 2016 and 2017 sources. The 1:1 line represents unbiased predicted TMV values. Most actual TMV values lie below the 1:1 line indicating that VicForests growth and yield model overestimates TMV. The thinner solid line shows mean predicted value from Equation 3.1; the shaded area show the 95% credible interval (*i.e.*, parameter uncertainty); and the dashed lines show the 95% prediction interval (*i.e.*, parameter uncertainty + residual error uncertainty).

3.4.2 Uncertainty in predicted TMV per year

Total predicted TMV and actual TMV per harvesting years are show in Figure 8. For the four years of data that we analysed, both actual and predicted TMV values fall within our credible interval after the TMV scaling correction has been applied.

Prediction uncertainties expressed as a percentage (predicted TMV per simulation divided by mean predicted TMV accross all simulations) are shown in Figure 11. These suggest that, in general, when the predicted TMV per year has been corrected (*i.e.*, aligned using the TMV scaling factor), it is known with a $\pm$ 10% certainty.

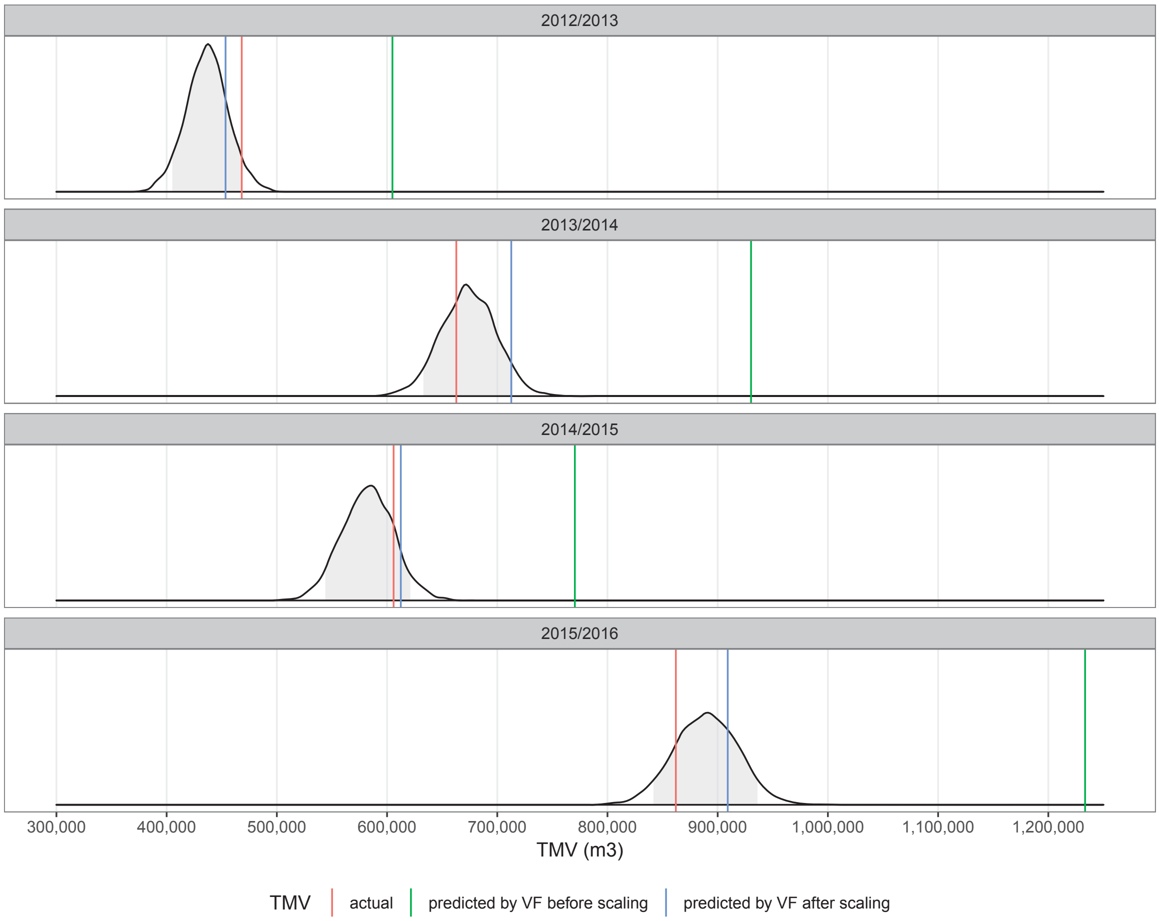

Figure 8: Uncertainty around predicted total merchantable volume (TMV) associated with TMV scaling factors for different harvesting years (with 74, 98, 63 and 86 coupes for each year, respectively). Vertical lines show actual TMV (red), the predicted TMV before scaling (green), and the predicted TMV after scaling (blue) estimated by VicForests. The distribution shows the uncertainty in corrected predictions of TMV using our own scaling factors. Equation 3.1 was used to relate the raw predicted TMV of each coupe to an actual TMV. We then summed corrected TMV for all coupes. The simulation was run 2000 times using uncertainty in both parameter estimates and residual error. We used population parameters when we did not know the scaling factor for a particular FMA x FGF combination. Shaded area show 90% credible intervals and highlight the range of potential corrected (*i.e.*, post-alignment) predicted TMVs associated with uncertainty in the TMV scaling factor.

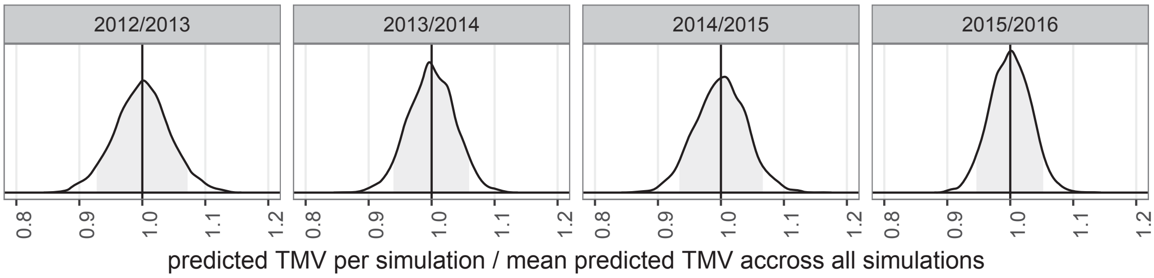

Figure 9: Uncertainty in predicted TMV for each harvesting year. The values are the ratio of the sum of predicted TMV for a given simulation to the mean sum of predicted TMV accross all simulations. Shaded areas show the 90% credible intervals. This figure illustrates the accuracy – not the bias – of our predictions (there is no reference to actual TMV). This tells us how wide our predicted TMV distribution is after correction with the TMV scaling factor compared to the mean of our prediction. Much of this uncertainty comes from sampling uncertainties and is related to the number of harvested coupes per year.

3.4.3 Predicted TMV per year per species group

The uncertainty in the corrected predicted TMV is higher if we use TMV scaling factors broken down by FGF (Figure 10). This greater uncertainty reflects the decrease in available data by group when we look at finer-grained components of the dataset. In contrast, when coupes are aggregated across FMAs or FGFs, the considerable uncertainties across individual coupes largely average out. Prediction uncertainties per FGF expressed as a percentage are shown in Figure 11. Corrected predicted TMV per year per species is known with a ± 15% certainty for AAS and MAS, ± 20% for HVM and MMT, and around ± 40% for OMS and STA.

3.5 Conclusions

A variety of scaling factors are applied to the TMV predicted by the growth and yield model to align it with historical observations of actual TMV obtained from harvested coupes. We focused our analyses on just one of these—the TMV scaling factor. We found that the corrected predictions of TMV (*i.e.*, the TMV predicted by the growth and yield model times the TMV scaling factor) were generally close to the actual TMV. However, our analyses also highlighted that there is important uncertainty in the TMV scaling factors that is not accounted for when applying a single scaling factor value. When averaged across all FGFs within a reporting year, the uncertainty was ±10%; when applied at the FGF level this uncertainty ranged from ± 15-40%. However, because TMV scaling factors area applied at the FGF x FMA level, the uncertainties will be substantially higher as the sample size (of recent coupes with observed actual TMV) per group will be much smaller.

More generally, our results suggest that a more explicit approach to accounting for and describing the uncertainty in TMV estimates would provide a better understanding of the range of potential TMV values that can be used for modelling the sustainable wood supply levels. Four different scaling factors (*i.e.*, TMV scaling, grade scaling, fire scaling, and area scaling) are

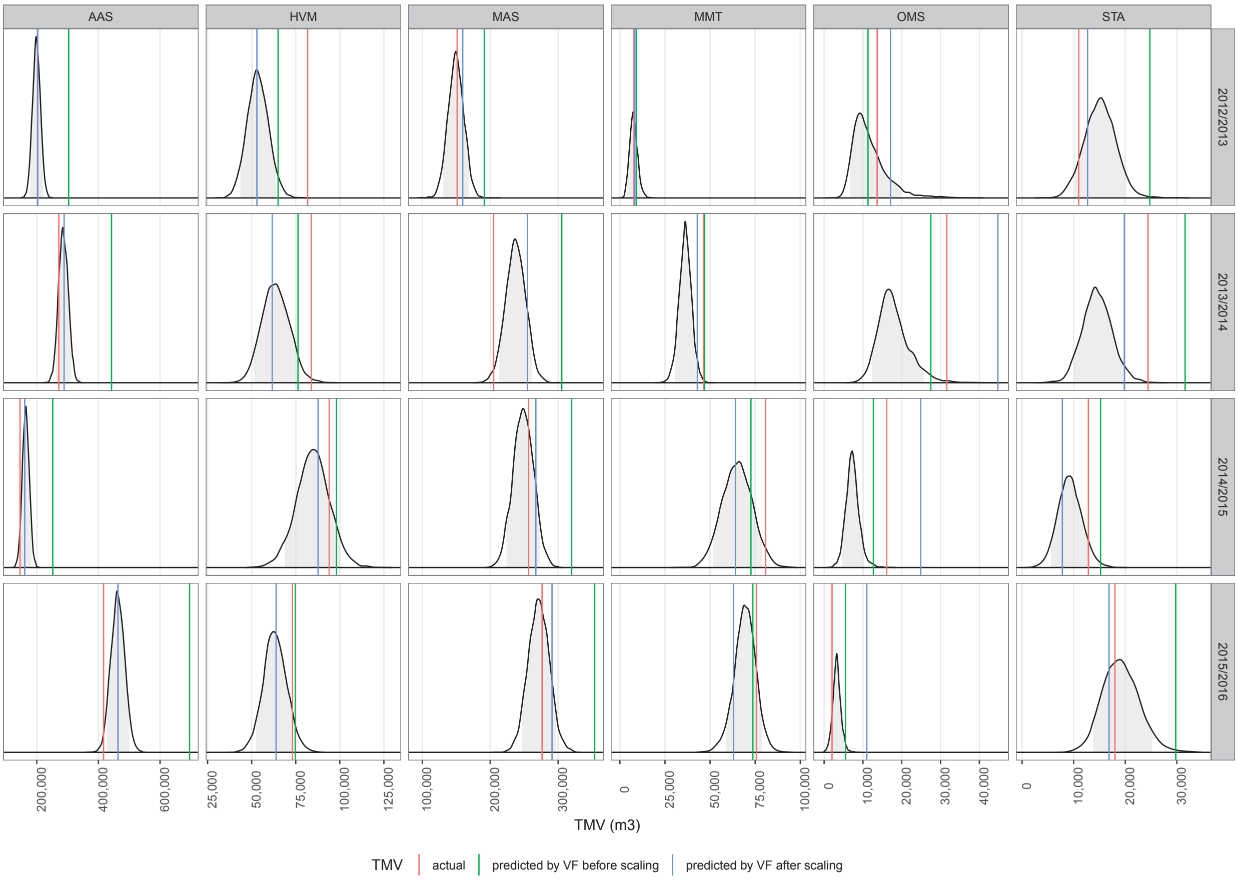

Figure 10: Uncertainty in predicted TMV due to scaling factors for each FGF and harvesting years.

applied multiplicatively to obtain the final predicted TMV. Uncertainties associated with each scaling factor will propagate substantially through multiplication. An approach that explicitly handles the uncertainty should provide a clearer understanding of the range of predicted TMVs for the State Forest. Such a probabilistic approach would be able to generate estimates of the probability of meeting a specific supply target (*i.e.*, an 80% probability of supplying 130,000 m^3 yr^{-1} of D+ sawlogs and a 5% probability of supplying 200,000 m^3 yr^{-1}), which would allow for more effective management of risk for the Victorian government regarding forest policy and the native forest industry.

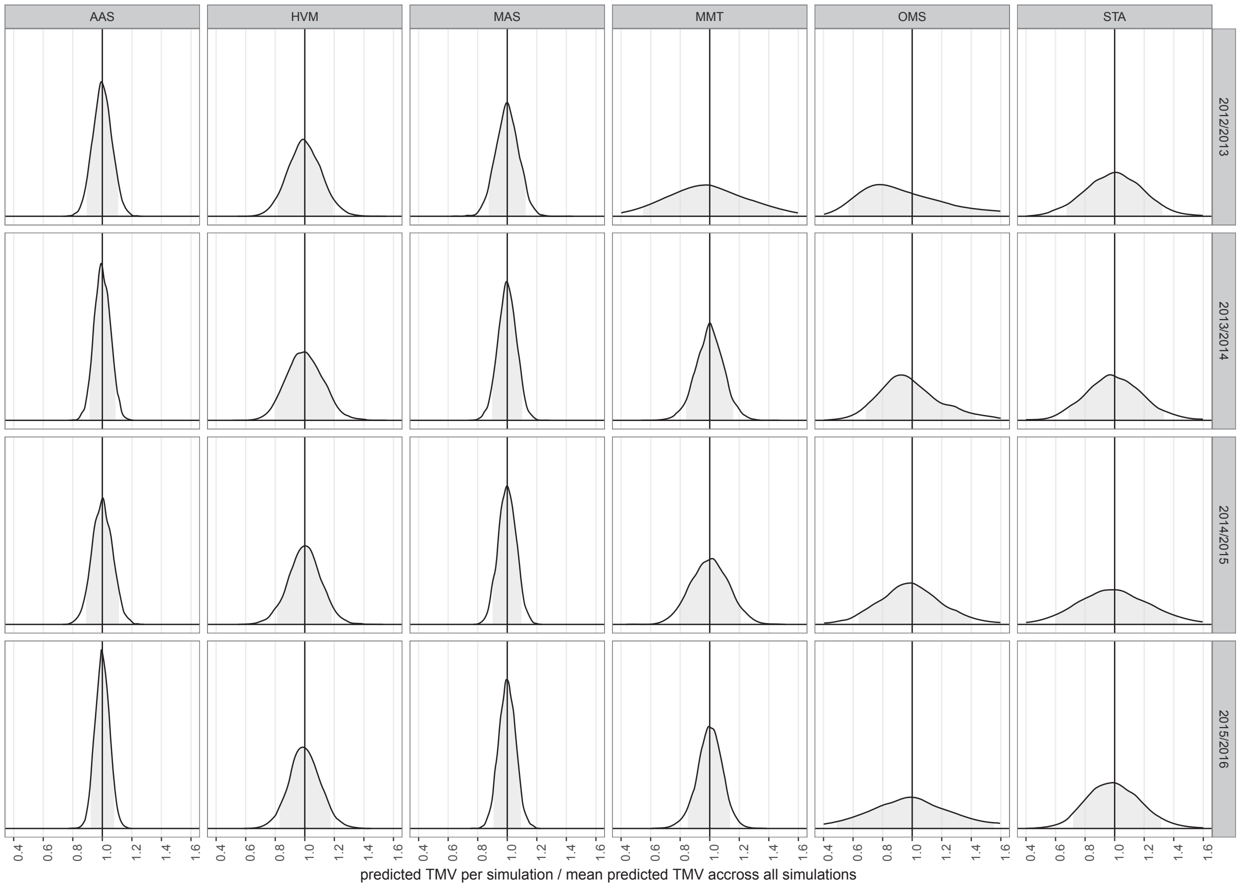

Figure 11: Uncertainty in predicted TMV for each FGF and harvesting year. The analysis is identical to that in Figure 11. The greater uncertainties in corrected predicted TMVs is due to the smaller number of coupes contributing to each estimate upon breaking the yearly data down into FGF sub-groups. The estimates for AAS and MAS are much better than for OMS (Other Mixed Species) and STA (Silver Top Ash) because there are many more harvested coupes of AAS and MAS. It is worth noting that the TMV scaling factors are applied for FGF x FMA combinations for which there are many fewer coupes per combination, meaning that the uncertainties associated with the TMV scaling factors will be higher.

Part 4

Bushfires and Risk to Wood Supply Levels

4.1 Summary

Goal

- To assess the risk of catastrophic bushfires on commercially valuable 1939 regrowth forests over the next 20 years.

Main findings

- Historical data on past fire frequency and size demonstrated that the probability of having a total area of the Central Highlands burnt that is equivalent to the period 1990-2010 (*i.e.*, $\sim$570,000 ha burnt) ranges from 9-18%.
- The mean proportion of the commercially valuable 1939 regrowth ash forests from the Central Highlands that was lost in simulated fires over the next 20 years was 20%, ranging from 3-47%. These results were consistent with the historical data on fire activity.
- Fire simulations suggested substantial differences between FMAs in the proportion of 1939 regrowth ash forests that would be impacted by fires. The Central FMA lost nearly three times as much 1939 regrowth as the Central Gippsland and Dandenong FMAs.

4.2 Background

Catastrophic bushfires have had a profound effect on wood supply levels in Victoria's State Forests. A large proportion of commercially valuable ash forests in the Central Highlands is regrowth from the extensive 1939 bushfires. The resultant age distribution of the forests of the Central Highlands has fundamentally shaped sustainable wood supply levels in Victoria over the past three decades. More recently, the 2009 Black Saturday bushfires burned over

400,000 ha of forest in and near the Central Highlands, including 80,000 ha of ash forests (Cruz *et al.*, 2012). As a consequence, wood supply levels from the State Forests were reduced. If stochastic events such as fires are likely to occur in the future, then incorporating some estimate of their impacts may provide guidance to forest planning about the potential risk to the forest resource. Managing for stochastic events presents a challenge, though, because it is when and where they will occur and how much damage they will do to the forest is unknown. Developing strategic wood supply models (SWSMs) that incorporate unforeseen events to modify sustainable harvest levels is a significant challenge that remains unresolved (McCarthy and Burgman, 1995).

Our approach was to ask a somewhat simpler question: What is the probability that a certain proportion of the 1939 regrowth ash forests will be impacted by bushfires? We took two separate approaches to answer this question. First, we used historical fire data to quantify the frequency and extent of fires over the Central Highlands. Second, we used a landscape fire succession simulator to simulate periods of fire and vegetation change. We focus on the Central Highlands for two reasons. First, the 1939 regrowth is a critical forest resource that is the primary source of commercial harvesting revenues for VicForests and the State of Victoria. If a large proportion of the 1939 regrowth is lost to bushfires in the next two decades, it could potentially spell the end of Victoria's native forest industry. Second, alpine and mountain ash are more susceptible to bushfires as they are obligate seeders and do not resprout following intense fires. A sufficiently large high-intensity bushfire will kill most of the ash. The eucalypts of the mixed species forests, which dominate the East Gippsland FMA and account for more than half of the total State Forest area, are much more resilient to fire and can survive even relatively intense fires.

4.3 Material and methods

4.3.1 Historical fire mapping

Data

To develop a model of historical fire regimes across the Central Highlands, we used the fire map the 'Fire History Records of Fires primarily on Public Land' from DELPW, which is available to download from data.vic.gov.au. We clipped the Central Highlands area from the statewide fire history map and filtered for wildfires. We used the resultant fire map to calibrate the number of fires per year and total burnt area per fire across the Central Highlands. We only kept the 1950-2010 period as reference as many fires were not recorded before this period. Summary data statistics on past fire are presented in Table 4.

Modelling fire count and burnt area

We used a two-step approach to model burnt area per year:

Table 4: Data summary on fire in the 1950-2010 period

Fire count per year (n)		Area burnt per fire (ha)		Area burnt per year (ha)	
Mean	Range	Mean	Range	Mean	Range
7.3	(1-99)	2041	(0-184409)	14950	(3-453037)

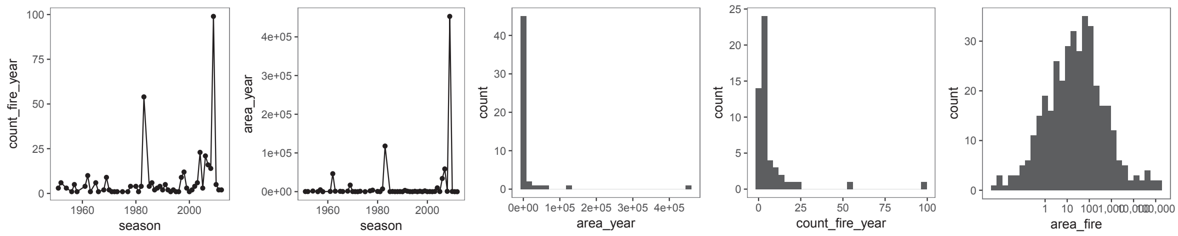

Figure 12: Descriptive figures for fire occurrence in the Central Highlands from 1950-2010. The first two panels (from left to right) are the raw data from the historical fire maps. The increase in fire count in the first panel is likely due to the better recording of small fires over the past 20 years. The centre panel is a histogram of the total area of fires each year. The fourth panel is a histogram of fire counts per year. The last panel is the total area burnt in all fires occurring in the Central Highlands over the observed period.

1. Model fire count per year using a negative binomial distribution (mean and overdispersion parametrization, 60 observations)

2. Model the burnt area per fire using a log-normal distribution (4926 observations)

$$fire\ count \sim NB(\mu_1, \theta) \tag{4.1}$$

$$\mu_1 = exp(\beta_1)$$

$$log(fire\ area) \sim Normal(\mu_2, \sigma) \tag{4.2}$$

where β_1 and θ are estimated model parameters for the negative binomial distribution and μ_2 and σ are estimated parameters of the log-normal distribution fit to the historical data on fire counts and areas, respectively, from the Central Highlands.

Table 5: Parameter estimates for models of fire count per year (4.1) and burnt area per fire (4.2) estimated from DELWP's historical fire database.

	Mean	SD
fire count per year		
β_1	2.00	0.17
θ	0.80	0.15
burnt area per fire		
μ_2	3.18	0.16
σ	3.04	0.11

Simulating burnt area for a 20 year period

We then used these two models to simulate potential burnt area for 1000 20-year periods. We compared the distribution of total burnt area from the simulations against the observed total burnt area for the periods 1950-1970, 1970-1990, and 1990-2010. To ensure that we did not get unreasonably large fires due to the nature of the log-normal distribution, we used a truncated normal distribution to sample burnt area per fire (we resampled burnt area when it was $> 2 \times 10^6$ ha).

To check if our results were robust to the specific model form and to give an idea of the uncertainty associated with a specific model, we used several alternative functional forms to simulate the total burnt area over a 20-year period. These include a negative binomial distribution fitted directly on the aggregated burnt area per year, a bootstrapped (resampled) distribution of aggregated burnt area per year, and a two-step method successively bootstrapping the distribution of fire count per year and the distribution of burnt area per fire.

4.3.2 Landscape fire simulations

We used the landscape fire succession model LANDIS-II (Scheller and Mladenoff, 2004, 2005) to simulate the interaction between topography, vegetation, and fire weather to predict the occurrence of fires in the Central Highlands RFA region over a 20-year time period. LANDIS-II uses a vector-based approach, similar to common fire characterisation models such as PHOENIX, to simulate fire growth processes that are influenced by topography, stochastic fire weather patterns, and transient fuel types (Sturtevant *et al.*, 2009). Fuel types are based on the composition and structure of forest types (parameterised using SFRI and EVC datasets). For ash stands multiple fuel types were parameterised based on the stand age-fire severity relationships described by Taylor *et al.* (2014). A fire weather database, based on nine weather stations in the region, with daily observations spanning the time period 1960 to 2010 was developed and used as the climate input for the fire modelling. Fire size statistics were calculated from the DELWP 100 Year Fire History Database. The number of ignitions was selected from an iterative process until the fire return interval for ash forests was congruent with the range identified by McCarthy *et al.* (2001). Fire weather and fire sizes were randomly selected for each modelled ignition point. Final fire size and intensity were influenced by topography and fuel types across the landscape. Twenty replicates were run for each 20-year scenario with a temporal resolution of 1 year and a spatial resolution of 1 ha. The total area included in the Central Highlands fire simulations was $\sim$2,000,000 ha.

For each simulated 20-year period, we calculated the proportion of the 1939 regrowth forest that was burnt by overlaying the simulated fires on the SFRI database, which contained forest ages. We compared fire impacts across the Central, Central Gippsland, and Dandenong FMAs to account for potential spatial variability in the fire patterns. We also compared the proportion of area burned in the landscape fire simulations with the expected area burned based on the historical fire data models described above to assess the consistency of the different approaches.

4.4 Results

4.4.1 Historical fire mapping

Posterior predictions sampled from the fire count per year model and the burnt area per fire model fit the observed data well (Figure 13). Simulated potential burnt areas for 20-year periods are shown in Figure 14. The 1950-1970, 1970-1990 and 1990-2010 observed burnts area fit well within this distribution. The observed total area burnt during these periods has been increasing with time, in part due to better detections and possibly more human activity associated with accidental fires (*e.g.*, camping, hunting) in these areas. However, the 1990-2010 period was characterised by a number of exceptionally large fires in the Central Highlands area. Depending on the statistical model that was used, the probability of having an area burnt in the Central Highlands that is greater than the 1990-2010 period ranges from 9 to 18%.

It is important to recognise that this approach is not spatially explicit and can only provide a general sense for how much of the Central Highlands is likely to experience bushfire in the next 20 years. It does not actually identify specific areas of forest that burn. The parameterised fire models can provide an empirical basis or test for spatial predictions of burnt area (see below). Spatial predictions could then be integrated to the strategic wood supply model to take into account uncertainties associated with bushfire occurrence and extent in the optimization of the wood supply levels.

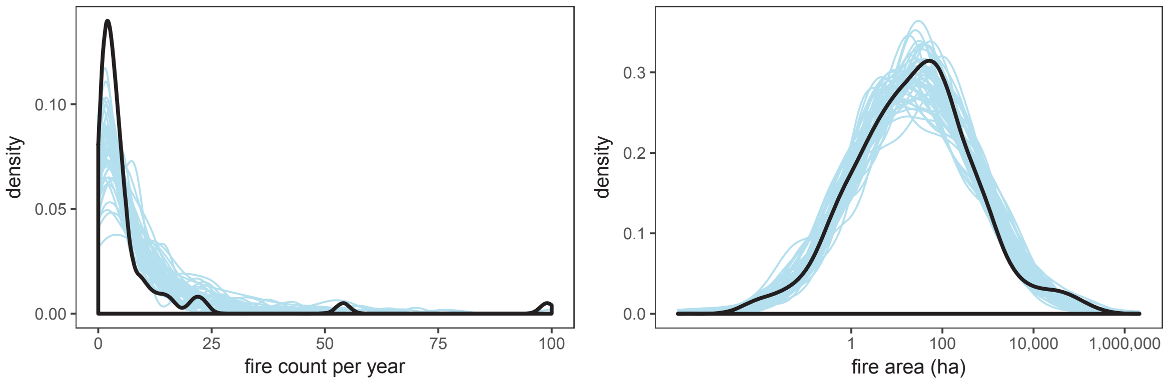

Figure 13: Posterior predictive check of fire count per year (left) and burnt area per fire (right). Solid black line shows the distribution of fire count (fire area) observed in the data over the 1950-2010 period. Each of the 50 blue lines shows one simulation predicted by Eq.4.1 (Eq.4.2) for the same 1950-2010 period.

4.4.2 Landscape fire simulations

Figure 15 illustrates the probability density curve of the proportion of the ∼22,700 ha of 1939 ash regrowth stands burnt over a 20-year period in 20 stochastic simulations. The mean

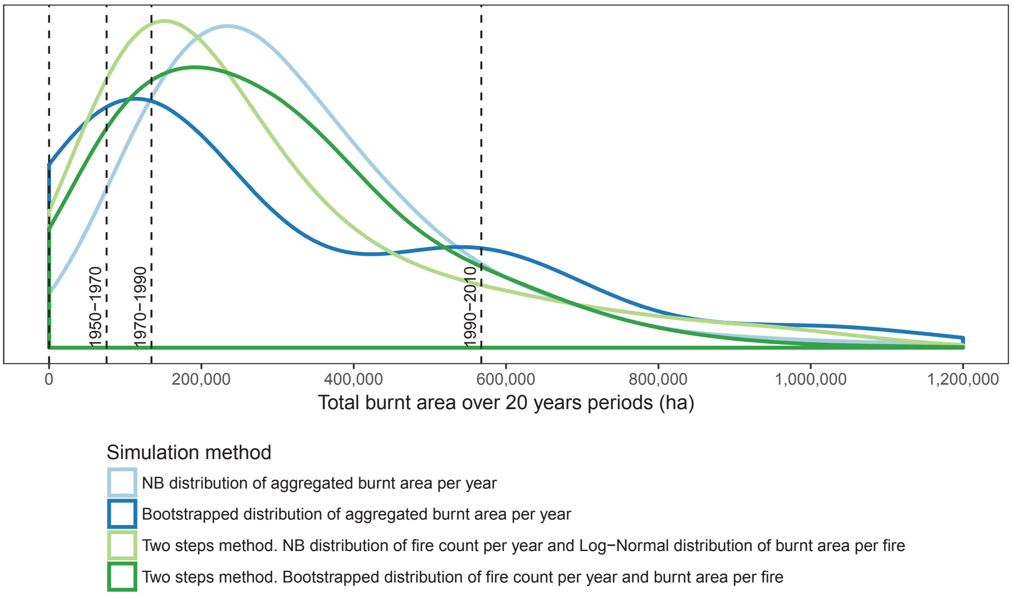

Figure 14: Simulated distribution of burnt area in Victoria in a 20 years period (the blue curve is the two steps method described here, the other curves are alternative methods). Observed area burnt for the 1950-1970, 1970-1990 and 1990-2010 periods are also shown on the graph and fits well within the range predicted by our models. The probability of having an area burnt larger than 570000 ha in 20 years range from 9 to 18 % (depending on the model used).

proportion of the 1939 ash regrowth area that burned in a 20-year period was 20% with a minimum of 3% and a maximum of 47%. Risk to 1939 regrowth was not uniform across the FMAs with the Central FMA having nearly three times the proportion of ash regrowth forest burning in a 20-year period on average than the Central Gippsland and Dandenong FMAs (Figure 16 and 17).

Our results highlight that it is highly unlikely that the entire 1939 resource would be lost over the next 20 years due to the spatial distribution of the resource and varying risk of bushfire across FMAs. The outcomes from the landscape fire simulation modelling suggest that, on average, 20% of the 1939 ash stands may be affected by fire in the next 20 years with a worst case scenario of ∼50% of the resource being impacted. Due to the greater prevalence of fire in the Central FMA, sawmills that receive a majority of their ash resource from the Dandenong and Central Gippsland FMAs should be exposed to less risk from a catastrophic loss of the resource in the next 20 years than mills sourcing their ash sawlogs from the Central FMA.

There are several caveats that accompany our fire simulations. First, our modelling of wildfires did not include simulating fire suppression activities, such as lanned burning and timber harvesting, which tend to reduce fuel loads and subsequent fire spread. However, our simulations also did not account for climate change over the next 20 years, which should have the opposite effect. As climatic conditions change, the probability of extreme climatic conditions will increase. This will tend to increase the risk of fire in the simulations. Second, we did not consider the effect of varying fire intensity on stand mortality and survivorship. Even

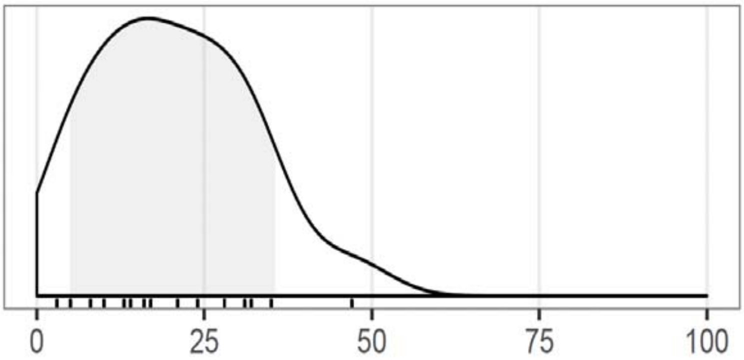

Figure 15: Predicted percentage of 1939 ash area burnt over 20 year period (n= 20). The black line is a smoothed probability density curve; the black ticks are the modelled observations; and the shaded area is the 5 to 95%ile range.

in the catastrophic 2009 bushfires, a significant proportion of the Central Highlands landscape that burned experienced low to moderate severity fires. Not all of the forested areas that experienced fires in our simulations would have complete mortality. Rather, a distribution of mortality from understorey burns that kill few ash to crown fires that kill all trees would likely occur.

4.5 Conclusions

Bushfires present an existential threat to Victoria's native forest industry. A single bushfire of sufficient intensity and extent has the potential to eliminate the 1939 ash regrowth in the Central Highlands that will continue to dominate the State's sustainable wood supply for the coming decade. Our two modelling approaches attempt to quantify the risk that bushfires pose to the 1939 ash regrowth in the Central Highlands. Across a range of simulations based on historical fire data and a landscape fire succession model, we found that the mean proportion of Central Highlands, broadly, and the 1939 ash regrowth, specifically, that can be expected to burn is 20% or less. While losing 20% of the 1939 ash regrowth would impact sustainable wood supply levels, it would be unlikely to eliminate the native forest industry.

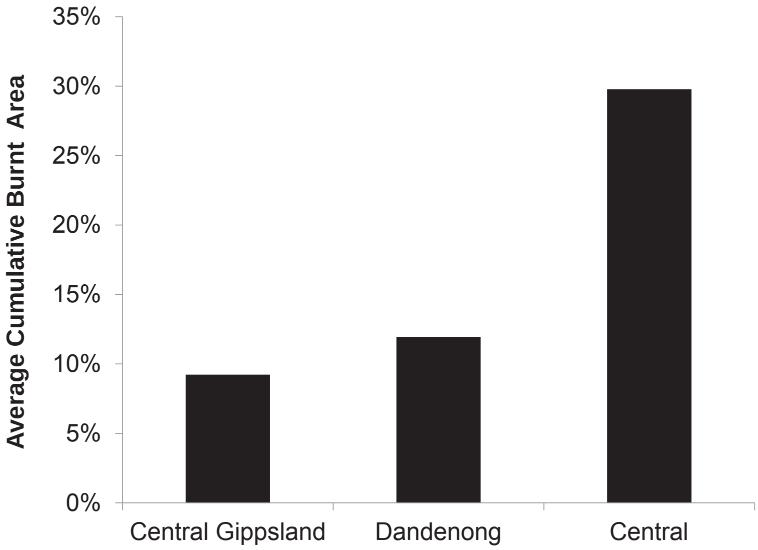

Figure 16: The mean proportion of the 1939 ash regrowth stands grouped by FMA that burned in an ensemble of twenty 20-year simulations.

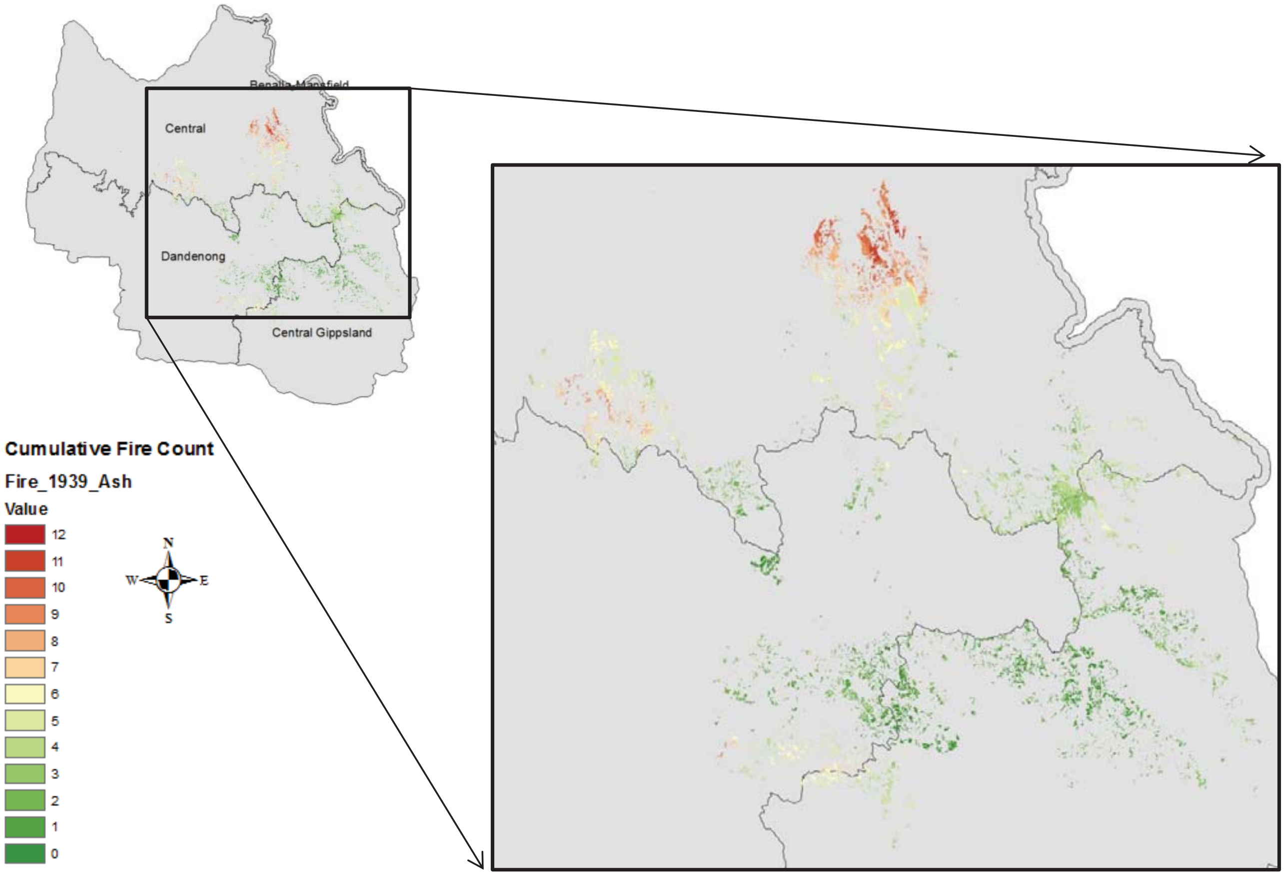

Figure 17: Spatial patterning of fire risk from 20 simulations of 20 years each. The highest bushfire risk to the 1939 regrowth is in the Central FMA, which experiences warmer and drier climatic conditions.

Part 5

Leadbeater's Possum and Risk to Wood Supply Levels

5.1 Summary

Goals

- To quantify the probability of detecting Leadbeater's possum based on available stand-level predictors.
- To estimate potential impacts of Leadbeater's possum detections on wood supply levels from the Central Highlands given different assumptions about exclusion zone sizes.

Main findings

- Based on a model of stand age, elevation, and FMA, the maximum probability of detecting Leadbeater's possum occurs in stands that are ~28 years old, although mean detection rates in 1939 regrowth are only ~20% lower.
- When applied to the current Net Harvest Area database our model of Leadbeater's possum detection probability suggests that a further 518 possums will be found in 1939 ash regrowth in the Central Highlands.
- Given the number of predicted detections, application of the current buffer size (200m radius around point of detection) would result in a loss of 4921 ha of harvestable 1939 ash regrowth, or roughly ~1,100,000 m^3 of D+ sawlogs and ~2,100,000 m^3 of residual wood from the available wood supply levels.
- Losses of harvestable 1939 ash regrowth were approximately six times higher in the Central and Central Gippsland FMAs as in the Dandenong FMA.

5.2 Background

Over the past 25 years, Leadbeater's possum (LBP) has acted as a lightning rod for debates over the management of the iconic ash forests of Victoria's Central Highlands (Attiwill *et al.*, 2013, Burns *et al.*, 2015, Lindenmayer *et al.*, 2011). The tall, straight stems of the dominant eucalypts make these the most commercially viable forests in Victoria. They also serve as critical habitat for the highly endangered LBP. However, not all ash forests are suitable habitat for the possum. Several decades of research by Lindenmayer and colleagues have shown that LBP is closely linked to specific structural features that occur in some, but not all, stands of montane ash. In particular, LBP, which nests in hollows and cavities in the stems of the canopy eucalypts, requires a certain density of large canopy eucalypts as potential nesting trees and a relatively dense and accessible understorey/midstorey (typically of shorter-lived *Acacia* species) for foraging and movement (Lindenmayer *et al.*, 1990, 1991, Smith and Lindenmayer, 1988, 1992). The total area of Central Highlands forests possessing these structures is relatively small and declining rapidly. The 2009 Black Saturday fires burnt nearly 45% of the existing high-quality LBP habitat (Harley 2012) and the ash forests that established after the 1939 bushfires are not expected to provide hollow-bearing trees for decades. Logging has been identified as a potential threat to LBP populations already struggling from existing loss of habitat and is excluded from within 200m of an existing LBP detection. However, over the past three years 400+ new discoveries of LBP have been made in the Central Highland, requiring nearly 4000 ha of harvestable forest to be excluded from future harvest. If discoveries of new LBP continue at the current rate, it may have far-reaching impacts on the native forest industry by substantially reducing the area of available 1939 ash regrowth. In this section we use new data and models to estimate the potential number of new LBP detections that are likely from the Central Highlands and the total volume of wood that may be excluded from future harvest as a result. We consider three different buffer sizes around each new LBP detection point.

5.3 Material and methods

5.3.1 Data

We used LBP survey data collected by Arthur Rylah Institute (ARI) staff. The data were current at the time of our analyses in April 2017. The ARI surveys used infrared remote cameras mounted in trees to detect the presence of LBP and targeted areas adjacent to locations with previous records of LBP sighting or a high modelled probability of LBP presence (based on an earlier predictive model of LBP distribution). The data set included a total of 355 plots (221 absences and 134 presences) and is summarised in Table 6.

It is important to recognise that the ARI surveys are biased toward areas where LBP is known to exist or is believed to have a high probability of occurrence based on other knowledge. Analyses of these data and any insights they generate regarding LBP habitat are conditional on the survey design, which focused on current expectations about LBP habitat. A

Table 6: Summary of the ARI Leadbeater's possum survey data by forest management area (FMA). Note the different numbers of survey points within each FMA.

	Observations	Presences	Absences	Age ($year$)		Elevation (m)	
FMA	n	n	n	median	range	median	range
Central	105	26	79	73	(1-166)	830	(447-1235)
Dandenong	88	38	50	73	(14-84)	657	(209-1061)
Central Gippsland	162	70	92	73	(3-166)	904	(199-1308)
Total	355	134	221	73	(1-166)	783	(199-1308)

more systematic approach to sampling LBP presence/absence that employed either a random or grid-based survey design across the entire forest estate, independent of tenure (*i.e.*, Parks, Reserves, State Forests) would provide a more rigorous understanding of their distribution and habitat preferences.

We used a range of predictor variables in our model. The final three that were included were stand age, elevation, and FMA. Stand age at the time of the LBP survey was calculated from the State Forest Resource Inventory (SFRI) database. Each survey point was identified as being in one of three forest management areas (FMAs) in the SFRI database. In the SFRI, FMA8 is Central, FMA 9 is Dandenong, and FMA 11 is Central Gippsland. The elevation at each survey point was obtained from a State-wide digital elevation model. Several other variables (% eucalypt cover, forest type, wetness index, slope, aspect) were obtained from the SFRI or DEM datasets and considered in the analyses, but were not significant and were excluded from further analyses.

5.3.2 Modelling LBP presence

We used a two-step approach to build a generalized linear logistic presence-absence model of LBP occurrence based on stand age, FMA, and elevation. Because we had no prior knowledge of the functional form relating stand age to LBP presence, the first step was to apply a generalized additive model (GAM) spline smoother to relate stand age to LBP presence. In the second step, we used transformations of the age predictor to approximate the functional shape of the GAM smoother and fitted the model using a regular GLM procedure. Linear combinations of $log(age)$ and $\frac{1}{age}$ gave the best results and the final GLM model actually slightly outperformed the GAM model.

FMA parameters were modelled as the sum of a population term, plus a FMA-specific discrepancy to the population term (*i.e.*, random coefficient) sampled from a Gaussian distribution with 0 mean and standard deviation to be estimated. The model is described as:

$$
\begin{aligned}
presence_{ij} &\sim Bernoulli(p_{ij}) \\
p_{ij} &= \frac{1}{1 + exp(-logit_{ij})} \\
logit_{ij} &= \beta_{1j} + \beta_2 \times log(age_i) + \beta_3 \times \frac{1}{age_i} + \beta_4 \times Elevation_i \\
\beta_{1j} &\sim \beta_1 + N(0, \sigma_{\beta_1})
\end{aligned} \tag{5.1}
$$

where $presence_{ij}$ is the observed presence or absence of LBP in survey i in FMA j. The β_1's and σ_{β_1} are population and β_{1j}'s are FMA-specific parameters to be estimated.

We derived the age at which the probability of presence of LBP is maximum ($age\ at\ p_{max}$) by taking the derivative of Equation 5.1 with respect to stand age and solving for $\frac{\delta p}{\delta age} = 0$. Algebra gives the simple relationship $age\ at\ p_{max} = \frac{\beta_3}{\beta_2}$.

5.3.3 Predicting LBP presence on SFRI polygons

The average coupe area in ash forests in the Central Highlands is much larger (16.2 ha) than the average polygon size in the SFRI data (1.7 ha) (Figure 18). During the strategic wood supply modelling process, Stanley typically groups multiple polygons to form individual coupes, which are then surveyed once for LBP presence. Applying raw predicted probabilities of LBP presence from Equation 5.1, which were sampled at the coupe scale, to each polygon implicitly assumes that each coupe would be surveyed several times. This would then overestimate the probability of finding LBP in an individual coupe.

To address this issue, we weighted the probability of detecting a LBP in a SFRI polygon by its size relative to mean coupe size. The sum of n binomial trials with corrected probability p_{cor} coming from n SFRI polygons that will form a coupe needs to be equal to the probability of finding a LBP in one coupe (one survey = one prediction from the model). The expected value of a binomial distribution with n trials and probability p equals $n \times p$. Setting $n \times p_{cor} = 1 \times p$ and $n = \frac{mean\ coupe\ area}{polygon\ area_i}$ (number of polygons needed to form one coupe), and solving for p_{cor} gives Equation 5.2:

$$
p_{cor_i} = p_i \times \frac{polygon\ area_i}{16.2} \tag{5.2}
$$

where p_{cor_i} is the corrected probability of LBP presence in polygon i. p_i is the raw predicted probability from the model (equivalent to one LBP survey) for the polygon. Coupe area was fixed to its mean value (16.2 ha). The area correction was only performed on polygons that were smaller than the mean coupe size.

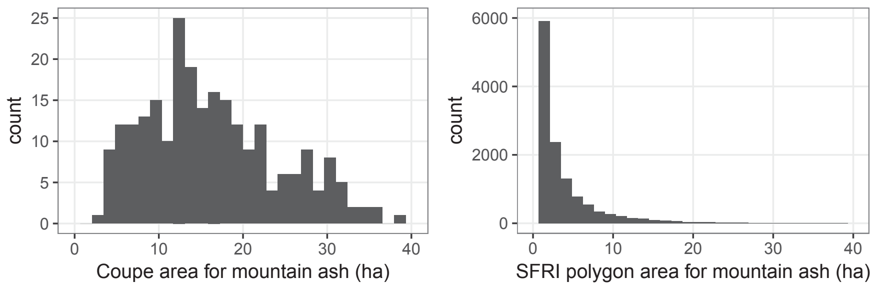

Figure 18: Distribution of coupe area and SFRI polygon area

5.3.4 Harvestable area loss per LBP colony

The mean harvestable area lost per LBP detection was computed using the LBP observations in the ARI dataset. We tested three potential exclusion zone distances: 100m, 200m, and 300m. The theoretical harvestable area loss per LBP presence equals $\pi \times buffer\ size^2$. Because not all areas around LBP colonies are harvestable and some LBP exclusion zones overlap, the actual harvestable area lost will be lower than the theoretical prediction.

Because the total loss of harvestable forest depends on the size of the buffer established around detection points, we estimated the impacts of three different buffer sizes. We used the currently applied buffer of 200m radius around the detection location, as well as a smaller buffer (100m radius) and a larger buffer (300m radius). To calculate the average actual loss of harvestable area due to LBP exclusion zones, we summed the total area lost and divided that number by the number of LBP exclusion zones. Table 7 shows the comparison between actual and theoretical harvestable area lost to LBP exclusion zones of varying radius. As the buffer size increases, the proportion of harvestable area actually excluded decreases because the larger buffer is more likely to have some area that falls into a previously excluded area.

Table 7: Harvestable area loss per LBP colony for different exclusion areas. Theoretical area lost is the area of a circle of the specified radius (=buffer size). Actual area lost is based on spatial analyses of the area around each LBP observation that is already in exclusions. See text for a detailed explanation.

Buffer size (m)	Theoretical area lost (ha)	Actual area lost (ha)	Ratio of actual to theoretical area lost
100	3.14	3.1	0.99
200	12.6	9.5	0.75
300	28.3	15.6	0.55

5.3.5 Potential impacts of LBP detection and exclusion size on wood supply

The probability of LBP presence was estimated for every polygon in the Net Harvest Area spatial database masked to exclude the East Gippsland and Northeast FMAs. These occupancy probabilities were then combined to estimate the total number of new LBP detections across the ash regrowth in the Central, Central Gippsland, and Dandenong FMAs. We then multipled the number of new LBP detections against the expected loss of harvestable forest area shown in Table 7 to estimate total harvestable area of the 1939 ash regrowth that would be lost under each exclusion zone scenario. Because the estimated probabilities were done for individual polygons, we could stratify the new detections by yield class and calculate the total merchantable volume in 2017 (corrected with the TMV scaling factor) to estimate the predicted TMV by grade that would be predicted to lost to new LBP detections.

5.4 Results

Stand age, elevation, and FMA were all significant predictors of LBP presence. Figure 19 shows the marginal effects of each of these predictors on LBP presence. LBP presence was low in extremely young stands, but rose rapidly to peak at ∼28 years (Figure 20, $age\ at\ p_{max}$ in Table 8). However, due to the uncertainty in the model, the mean probability of occurrence of LBP in 1939 regrowth was only about 20% lower than the maximum mean detection rate. In general, the probability of LBP occurrence increased with increasing elevation, although there is substantial uncertainty in the relationship. Detection probabilities differed strongly among FMAs with the Dandenong FMA having the lowest probability of observing LBP. Central and Central Gippsland FMAs had nearly identical probabilities of observing LBP. The parameter estimates for the model (Equation 5.1) are given in Table 8.

Table 8: Parameter estimates for the LBP presence model described in Equation 5.1. FMA8 is Central, FMA9 is Dandenong, FMA11 is Central Gippsland.

		95% CI	
	Median	Min	Max
β_1	4.4227	0.6112	9.7389
β_{1,FMA_8}	4.0319	0.0492	9.2420
β_{1,FMA_9}	4.7833	1.1327	9.6920
$\beta_{1,FMA_{11}}$	4.6506	0.8792	9.7948
β_2	− 1.3247	− 2.4214	− 0.5343
β_3	−36.3763	−74.2266	−13.4453
β_4	0.0015	0.0005	0.0026
σ_{β_1}	0.5472	0.0938	1.6562
$age\ at\ p_{max}$	27.8584	17.9279	39.0702

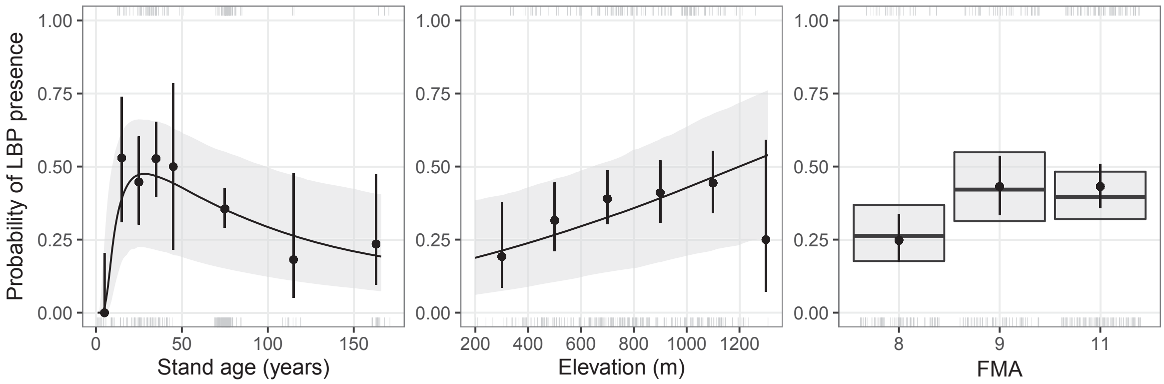

Figure 19: Predicted and observed probability of LBP presence as a function of stand age, elevation and FMA. In each panel, we varied one predictor and held the others constant and equal to their median values (75 years for age, 785 m for elevation). Population parameter β_1 was used to visualize the effect of stand age and elevation, while FMA-specific parameters (β_{1,FMA_8}, β_{1,FMA_9} and $\beta_{1,FMA_{11}}$) were used to show effect of FMA on the probability of LBP presence. Lines and shaded areas are the mean and 95% credible interva from the model predictions, respectively. Points are observed presence probabilities by relevant classes. 95% Wilson binomial CI (Brown *et al.*, 2001) are shown for observations.

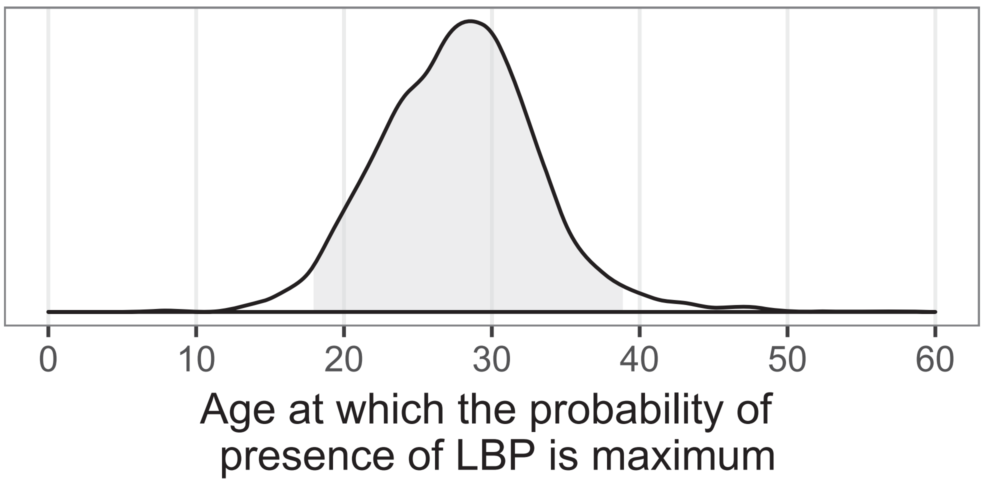

Figure 20: Age at the maximum probability of LBP presence ($age\ at\ p_{max}$). The shaded area represents the 95% credible intervals of the posterior distribution of $age\ at\ p_{max}$.

Simulated counts of LBP detection by FGF and FMA are given in Table 9. The model predicts approximately 1240 new LBP detection in ash forests in the Central, Central Gippsland, and Dandenong FMAs. Of these, 518 new detections were predicted for 1939 ash regrowth forests. Of the LBP detections in 1939 regrowth forests, 47% occur in the Central Gippsland FMA, 35.5% in the Central FMA, and the remaining 17.5% in the Dandenong FMA. We used the predicted counts of new LBP detections to estimate the total area of harvestable 1939 ash regrowth forest that would be placed in exclusions zones of various sizes by multiplying the count data by the area lost values in Table 7. The total harvestable areas lost to exclusion zones are shown in Table 9).

Because the predicted probabilities of LBP detection were calculated for every polygon in the Net Harvest Area file, we were able to estimate area lost per yield class and calculate losses of harvestable volume based on the estimated 2017 yields (corrected using the TMV scaling factor). If the current practice of a 200m buffer around the detection site was applied to all of the new detections predicted by our model, 4921 ha of 1939 ash regrowth forest would be removed from harvesting. The estimated loss of wood volume for a 200m radius exclusion zone was $\sim$1,075,177 m^3 for D+ sawlogs and $\sim$2,157,140 m^3 of residual wood (Tables 10 and 11). For a 100m radius exclusion zone the area loss was estimated to be 1605ha, and the volume losses were $\sim$351,426 for D+ sawlogs and $\sim$705,082 m^3 for residual wood. For a 300m radius exclusion zone the area loss was estimated to be 8081ha and the volume losses were $\sim$1,753,678 for D+ sawlogs, and $\sim$3,517,795 m^3 for residual wood. The losses in area and volume varied spatially; the fewest new detections and, therefore, lost harvestable forest area and volume was in the Dandenong FMA. The Central and Central Gippsland FMAs both had about three times the number of detections and six times the loss of harvestable forest area and volume as the Dandenong FMA.

VicForests has forecast annual reductions of 1939 ash regrowth D+ sawlogs of 43,000 m^3 yr^{-1} (VicForests, 2017). For the purposes of comparison, we divided our estimate of lost volume (assuming a 200m buffer exclusion) by 22 years (as 1939 regrowth can not be harvested after 2039 when it reaches 100 years old) to get an average annual loss of 48,872 m^3 yr^{-1}. This is quite similar to VicForests estimate. However, of their 43,000 m^3 yr^{-1} loss of D+ sawlogs, they estimated that only 18,000 m^3 yr^{-1} was directly attributable to new LBP detections. Their total estimated volume reduction included a range of other factors, such as loss of access to harvestable forests caused by new LBP detections, that our analyses did not consider, making direct comparisons between our approaches difficult.

Table 9: Number of new detections of Leadbeater's possum and total harvestable 1939 ash regrowth forest area lost based on detection probabilities calculated from Equation 5.1. All new detections includes ash regrowth in all age classes. New detections in 1939 regrowth is limited to the single age class. Total area lost in exclusions is calculated from the 1939 ash regrowth detections and the expected area lost for different exclusion zone sizes (see Table 7). FGF codes are: alpine ash (AAS), and mountain ash (MAS). FMA codes are: Central Gippsland (CG), Central (CT), and Dandenong (DD).

FGF	FMA	All LBP detections (N)	LBP in 1939 regrowth (N)	Total area in 100m exclusions (ha)	Total area in 200m exclusions (ha)	Total area in 300m exclusions (ha)
AAS						
	CG	283	109	337.9	1035.5	1700.4
	CT	163	105	325.5	997.5	1638
	DD	5	1	3.1	9.5	15.6
MAS						
	CG	333	124	384.4	1178	1934.4
	CT	212	108	334.8	1026	1684.8
	DD	244	71	220.1	674.5	1107.6
Total		1240	518	1605.8	4921	8080.8

5.5 Conclusions

Using the largest available dataset on Leadbeater's possum sightings, we developed a new model to estimate the probability of LBP occurrence as a function of stand age, elevation, and FMA. Our model predicted 518 new observations in harvestable 1939 ash regrowth forests in the Central, Central Gippsland, and Dandenong FMAs. Depending on the size of the buffer applied (100, 200, or 300m radius), losses of harvestable 1939 ash regrowth area ranged from 1605-8081 ha, losses of D+ sawlogs ranged from ~350,000-1,750,000 m^3, and losses of residual wood ranged from ~705,000-3,520,000 m^3. These losses varied among the three FMAs, with the Dandenong FMA having substantially less loss of harvestable 1939 ash regrowth area and volume than the Central and Central Gippsland FMAs.

Table 10: Estimated volume of D+ sawlog from 1939 ash regrowth lost for different exclusion zone sizes based on simulated LBP detections. Volume losses are grouped by FGF and FMA (codes as in Table 9). TMV D+ available is the total merchantable volume of D+ sawlogs available under different exclusion zone scenarios. The No Buffer options represents the baseline volume estimates for the FGF x FMA classes. The other three buffer scenarios is total TMV available under different buffer sizes. TMV D+ is the difference between the TMV available under a given buffer condition and the baseline (*i.e.*, no buffer). All values (except LBP count) are in m^3.

		TMV D+ available (m^3)				TMV D+ loss (m^3)		
FGF	FMA	No buffer	100m buffer	200m buffer	300m buffer	100m buffer	200m buffer	300m buffer
AAS								
	CG	894166	822032	673218	534534	72134	220948	359632
	CT	1227548	1153431	1000964	856102	74117	226584	371446
	DD	7420	6356	4159	3993	1064	3261	3427
MAS								
	CG	1199644	1124165	968467	821272	75479	231177	378372
	CT	1506370	1428424	1267569	1116895	77946	238801	389475
	DD	806064	755377	651659	554738	50687	154405	251326
	Total	5641212	5289786	4566035	3887534	351426	1075177	1753678

Table 11: As in Table 10 except for estimated losses in volume of residual wood.

		TMV RL available (m^3)				TMV RL loss (m^3)		
FGF	FMA	No buffer	100m buffer	200m buffer	300m buffer	100m buffer	200m buffer	300m buffer
AAS								
	CG	1818162	1671489	1368896	1086900	146673	449266	731262
	CT	2250496	2114614	1835091	1569512	135882	415405	680984
	DD	15866	13590	8892	8537	2276	6974	7329
MAS								
	CG	2438218	2284800	1968331	1669145	153418	469887	769073
	CT	3062903	2904417	2577354	2270993	158486	485549	791910
	DD	1723094	1614747	1393036	1185857	108347	330058	537237
	Total	11308739	10603657	9151599	7790944	705082	2157140	3517795

Part 6

Climate Change and Risk to Wood Supply Levels

6.1 Summary

Goals

- To evaluate the potential impact of climate change on future wood supply from mountain ash forests.
- To predict the effect of changes in mean annual temperature (MAT) on total volume per ha at harvest.

Main findings

- A 3°C increase in mean annual temperature (MAT; from 9.5°C to 12.5°C, which is consistent with expectations for MAT in the southeastern Victoria by the end of this century) leads to a reduction in the total number of trees (*i.e.*, stand density) at a given mean tree diameter.
- A 3°C increase above current MAT leads to a decrease of 15% in tree volume per ha, although there is substantial variability among different stands.
- Future harvest volumes are expected to decline due to increasing MAT in southeastern Australia. Current growth and yield models do not account for the potential reduction in future harvest volume.

6.2 Background

Regional and global warming has already begun to have direct and indirect impacts on plants and plant communities around the world. Climate change has the potential to affect all aspects of forest population dynamics—recruitment, growth, and mortality—as well as the disturbances that often influence them. A growing number of studies has shown that warmer, drier conditions can lead to widespread mortality in forests (Allen *et al.*, 2010). Stand density—the number of trees per unit area—is an important determinant in stand-level responses to extreme climatic conditions. Stands growing at lower densities tend to have lower mortality rates than stands growing at higher densities when subjected to the same climatic conditions (*e.g.*, Horner *et al.*, 2009). As mean temperatures increase, the rate of density-dependent mortality is likely to increase as well, resulting in fewer trees in a stand for a given average tree size.

The self-thinning line defines the upper limit of stand density for a given average tree size and has been the empirical basis of forest density management techniques for more than a half century. Using a recently developed modelling approach to estimate the self-thinning line, we examine how stand density will change with increasing mean annual temperature (MAT) and how that will impact on potential future wood volume in forests. We limited our analysis to a single species, the commercially valuable mountain ash (*Eucalytpus regnans*), to illustrate our approach and the scale of the potential impacts on future wood supply from Victoria's State Forests.

We also summarise recent work that has explored the impacts of predicted climate change on recruitment and productivity in the forests of the Central Highlands. As temperatures increase and water becomes more limiting, germination and seedling establishment, two processes that are highly sensitive to environmental conditions will be directly affected. In addition, overall forest productivity in these water-limited environments will be reduced in many sites (and increased in others, particularly at higher elevations). We compare current and projected recruitment and productivity patterns across the Central Highlands and consider the impacts of these dynamics on future wood supply.

6.3 Material and methods

6.3.1 Material

We used long-term, unthinned permanent sample plots from the HWPLOTS database to calibrate the relationship between stand density (N, the number of trees) and average tree size (Dq, quadratic mean diameter at breast height (DBH)). The N-Dq relationship is commonly known as the self-thinning line in plant population biology and forest science. The HWPLOTS database is composed of silvicultural experiments and permanent sample plots. It was historically curated by the Victorian Department of Environment, Land, Water, and Protection (DELWP) and its various precursor organisations, and is currently maintained by VicForests. We filtered the database to keep only undisturbed and unthinned control plots of pure mountain ash. Table 12 provides a summary of the permanent plot sample data, including the range of observed MAT, N, Dq, and stand basal area.

Table 12: Data summary for the permanent sample plots

Plot	Inventory	MAT(C)		Age ($year$)		Dq (cm)		N ($tree.ha^{-1}$)		BA ($m^2.ha^{-1}$)	
n	n	mean	range	mean	range	mean	range	mean	range	mean	range
71	608	11.4	(9.3-12.3)	50	(18-87)	50	(21-79)	371	(98-1457)	60	(34-99)

We used climate data from the Bureau of Meteorology's Australian Water Availability Project (AWAP) to compute the MAT for each permanent sample plot over the period 1961-1990. We then used MAT as the predictor variable in our analyses.

6.3.2 Modelling the self-thinning line

The self-thinning line describes the maximum number of trees of a given mean size that can be stocked per unit area. It is analagous to the concept of maximum carrying capacity for animal populations. Self-thinning arises as a dynamic equilibrium between stand growth and density-dependent mortality in even-aged stands. As trees get larger, they require more space and resources to grow and survive; smaller trees become increasingly suppressed and eventually die, reducing stand density and increasing mean Dq. Since the maximum stocking level described by the self-thinning line depends on the amount of resources available, we expect it to decrease as climatic conditions become warmer and drier.

We modelled the $log(N) - log(Dq)$ relationship using a hierarchical linear model with a plot random effect on the intercept and then tested for an effect of MAT on this relationship. The plot-specific intercept was modelled as the sum of a population intercept, plus a plot-specific discrepancy away from the population intercept (*i.e.*, random coefficient) sampled from a Gaussian distribution with zero mean and standard deviation to be estimated. The model is described as:

$$
\begin{aligned}
log(N_{ij}) &= \beta_{1j} + \beta_2 \times log(Dq_i) + \beta_3 \times MAT_i + \epsilon_i \\
\beta_{1j} &\sim \beta_1 + N(0, \sigma_{\beta_1}) \\
\epsilon_i &\sim N(0, \sigma)
\end{aligned} \quad (6.1)
$$

where i denotes observation i in plot j. N is the stand density (number of trees per ha), Dq is the quadratic mean diameter, and MAT is the 30-year (1961-1990) average of MAT. β_{1j} is the intercept of the regression for plot j, and ϵ_i is the residual standard error, sampled from a Gaussian distribution with mean zero and standard deviation σ. β_1, σ_{β_1} and σ are population parameters to be estimated. Parameters estimates for Eq. 6.1 are shown below in Table 13.

Table 13: Self-thinning model summary

	Median	95% CI Min	95% CI Max
β_1	12.317	11.653	12.951
β_2	− 1.538	− 1.563	− 1.512
β_3	− 0.053	− 0.106	0.004
σ	0.047	0.044	0.050
σ_{β_1}	0.032	0.023	0.044

6.3.3 Effect of temperature on stand density at harvest

We demonstrate the estimated effect of MAT on stand density at harvest by varying MAT in Eq. 6.1 while keeping Dq constant. Dq at harvest was fixed to 70 cm. Note that because N is log-transformed in Eq. 6.1, the model is multiplicative. This means that the absolute decrease in N with MAT, not the relative decrease, depends on the specific value of Dq.

6.3.4 Effect of temperature on harvest volume

We estimated maximum volume per ha at harvest from maximum stocking N at harvest (Dq in the 65-75 cm range), DBH distributions, a DBH-height allometry, and a volume allometry. These provided us with, respectively, the number of trees, their DBH, their height, and their total wood volume.

We used a bootstrap resampling procedure to propagate the uncertainty arising at different levels in the modelling process and to avoid making simplistic assumptions about the DBH distributions of stands at harvest. Predictions from all models shown here include uncertainty in parameters, plot random effects, and residual errors. Each bootstrap replicate predicts volume per ha for a single stand picked at random from the population; several runs gives us a distribution of potential volumes for any one stand selected at random from the population.

For each simulation:

1. We randomly select a plot with Dq in the 65-75 cm range as a potential plot.
2. We apply Eq. 6.1 to predict maximum stand density from the stand's Dq.
3. We generate DBH distributions by resampling from the DBH distribution of the selected stand (upper panels of Figure 21).
4. We predict individual tree height by using a saturating function (Mitscherlich equation, not shown), calibrated on plots with Dq in the 65-75 cm range (*e.g.*, lower panels of Figure 21).
5. We used Vicforests's underbark volume allometry equation (Eq. 6.2) to predict individual tree volumes (m^3) from tree DBH (cm) and height (m). The allometry was calibrated on trees ranging from 15-140 cm DBH (although there are few trees $>$100 cm DBH).

6. We sum these individual tree volumes per ha to get one estimate of stand volume per ha.

We repeated this procedure 2000 times for each MAT value in the 9.5-12.5°C range. This generates a distribution of potential stand volumes per ha across a range of MAT. It is important to note that the calculated volumes are total tree volume, not total merchantable volume (TMV), as TMV allometries were not available. This means that the estimated volumes described here will be higher than the TMV's estimated in Woodstock as our allometry does not account for losses associated with the merchantability of the wood in a tree. However, if allometric equations were available for TMV, it would be easy to recalculate the results using TMV.

$$\begin{aligned} v_i =& 0.2736404135 - 0.0146406305 \times dbh_i - 0.0171243928 \times h_i \\ &+ 0.0000137170 \times dbh_i^2 \times h_i + 0.0012474354 \times dbh_i \times h_i + \epsilon_i \\ \epsilon_i &\sim N(0, 1.008193 \times 10^{-6} \times dbh_i^2 \times h_i) \end{aligned} \tag{6.2}$$

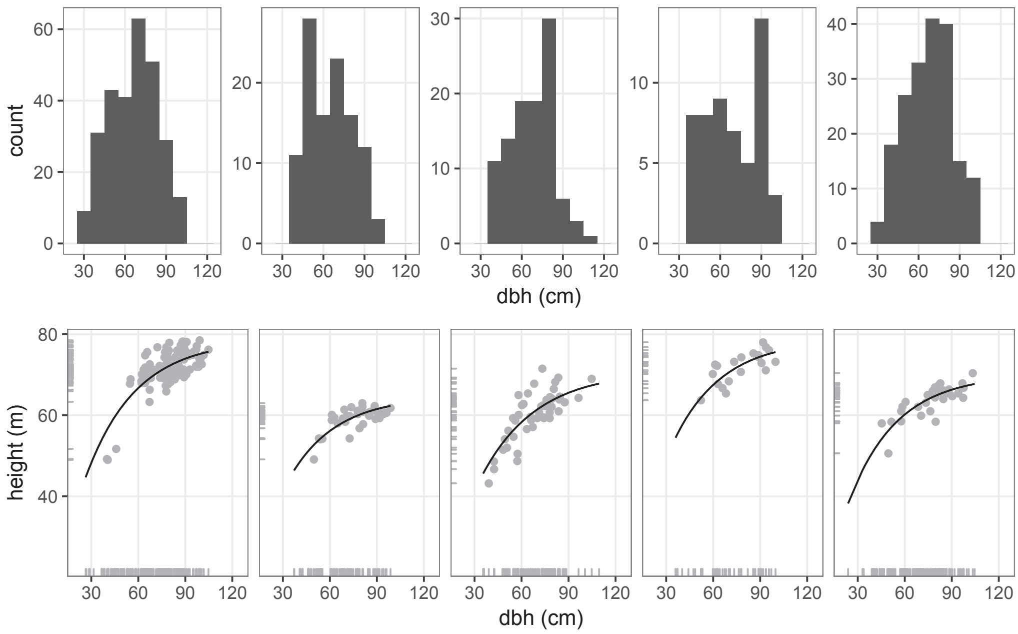

Figure 21: Examples of diameter distribution of stands with Dq in the 65-75 cm range (upper panels). Fitted dbh-height allometry for these same stands (lower panels).

6.3.5 Modelling the impacts of climate change on recruitment and productivity

Mok *et al.* (2012) developed the regeneration model, TACA-GEM, a species distribution model that simulates the ability of a species to germinate and establish under different soil and climatic conditions. They used it to evaluate the impacts of future climate variability on the regeneration dynamics of the dominant eucalypt species in the Central Highlands. TACA-GEM incorporates a process-based approach that combines the phenological activity of physiological processes involved in germination with observed or predicted climate data. We used TACA-GEM to estimate regeneration success for the commercially and ecologically valuable mountain ash under current (2015) and future climate conditions (2080) based on an assumed 3°C warming. We also used parameterised vegetation and climate modules in LANDIS-II to simulate the impacts of 3°C warming on forest productivity across the Central Highlands landscape.

6.4 Results

Our model predicts that maximum stand density will be lowest for stands growing in the warmest conditions (left-hand panel, Figure 22). On average, an unthinned, fully stocked stand growing at 9.5°C with a Dq of 70cm has a stand density of 200 trees ha^{-1} and a stand volume of 1650 m^3 ha^{-1} at harvest, whereas an equivalent stand growing at 12.5°C has 170 trees ha^{-1} and 1400 m^3 ha^{-1} (centre and right hand panels, Figure 22). This is equivalent to a 15% reduction in both stand density and total stand volume. Figure 23 shows the 90% prediction intervals for maximum volume at harvest for fully stocked stands with Dq of 70cm for MAT 9.5°C and 12.5°C.

These results come with several caveats. First, the MAT that underpins the model is based on spatial variability in MAT, not temporal variability. As such, it already accounts for adaptation and plasticity of populations to local climate. Temporal variability in MAT may lead to greater than expected reductions in stand density and volume. Second, our model does not explicitly address the impact of warming conditions on growth. Under warmer or drier conditions it may take individual stands longer to reach a Dq of 70 cm, which would reduce the available wood volume over a given time period. Third, there is uncertainty about future MAT at regional and global scales. This means that, at the local scale, MAT may increase by $<$3°C, in which case the modelled reduction in density and volume would be less. However, if future MAT was higher (or lower) than 3°C, then we would expect these reductions to be greater (or smaller) than projected here. Fourth, our analyses only examined the impacts of future warming on mountain ash. Other species or species groups that are widespread in Victoria's State Forests, particularly the mixed species eucalypt forests, may not show such pronounced responses. A broader analysis of stand-level productivity responses to climate change would be necessary to ascertain the net impact on wood supply levels across the State Forests.

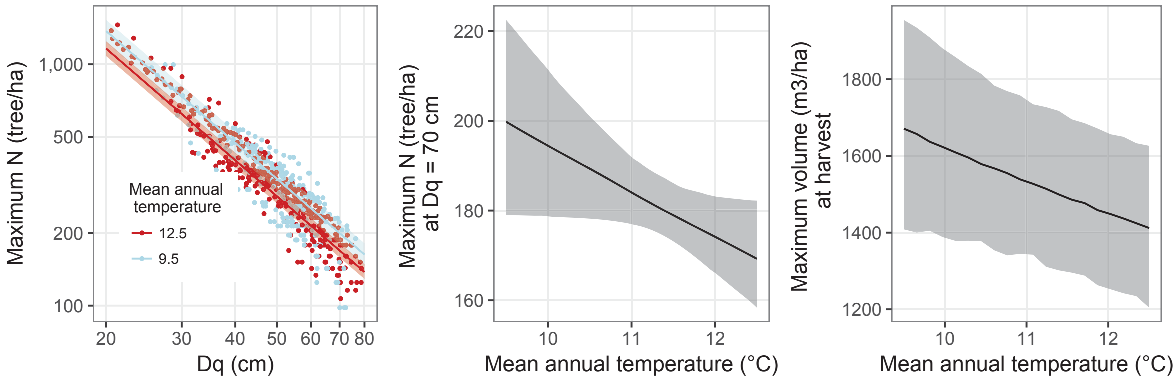

Figure 22: The influence of mean annual temperature (MAT) on stand density and volume. Left panel: Effect of MAT on maximum stand stocking per ha. Centre panel: Effect of MAT on maximum stand stocking at harvest ($Dq = 70cm$). Right panel: Effect of MAT on maximum volume per ha at harvest (Dq in the 65-75 cm range). The estimated volume is total tree volume, not total merchantable volume. The shaded areas in the left and centre panels are 95% credible intervals (*i.e.*, uncertainty in parameters values only = uncertainty in the mean value). The shaded area in the right panel is the 95% prediction intervals (*i.e.*, uncertainty in parameter values plus uncertainty in the error distribution = range of volume per ha for any one stand picked at random from the population).

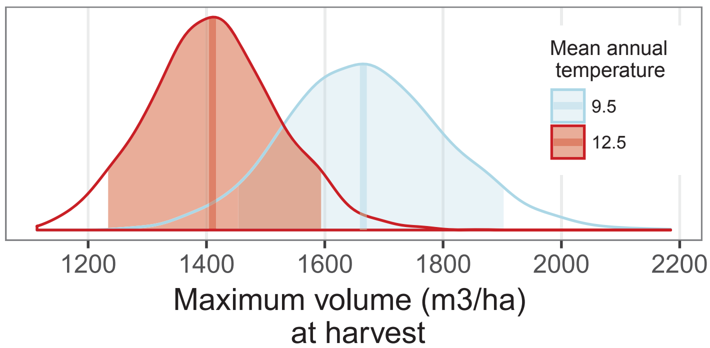

Figure 23: Maximum volume per ha at harvest at 9.5°C and 12.5°C MAT. The shaded area shows the 90% prediction intervals (*i.e.*, the range of volume per ha for any one stand picked at random from the population). This is analagous to vertical slices through the right panel in Figure 22 at 9.5°C and 12.5°C. The estimated volume is total tree volume, not total merchantable volume.

Changing future climatic conditions had dramatic impacts on the regeneration capacity of mountain ash, reducing the total area suitable for natural regeneration by more than 80% by 2080 (Figure 24). This has significant potential consequences for the native forest industry because it suggests that most of the area in which mountain ash currently grows may not be suitable for regeneration from seed before the end of the century. Separate analyses have demonstrated that planted seedlings will be able to grow across much of the area that is defined as productive (Figure 25). The mismatch between future sites that are productive and those at are suitable for regeneration from seed suggests that in the future forest regeneration practices, whether after harvesting or large-scale bushfires, may need to be modified to incorporate seedling nurserys and outplanting programs across large parts of the Central Highlands

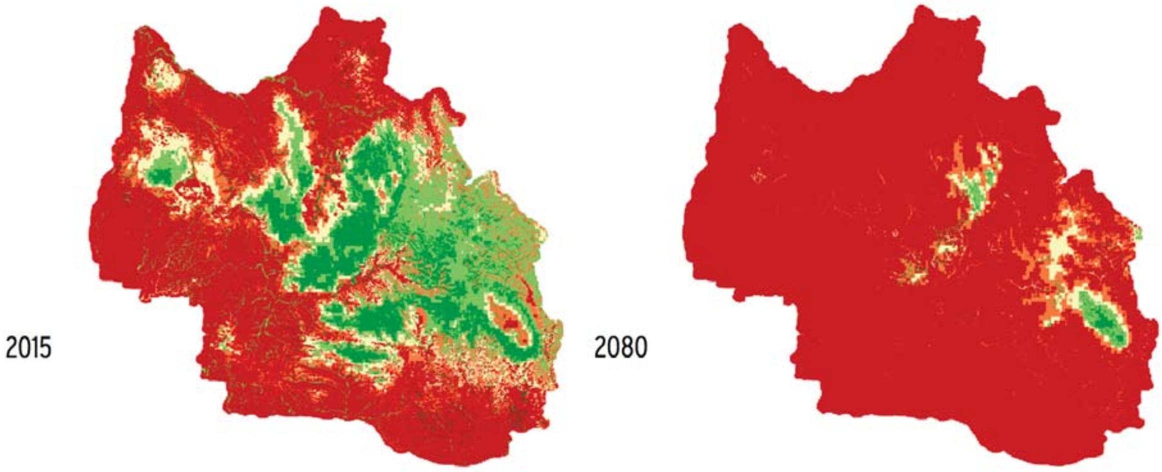

Figure 24: Regeneration suitability of mountain ash (*Eucalytpus regnans*) across the Central Highlands under current climate conditions (left panel) and a future climate that is 3°C warmer (right panel). The colour scale runs from unsuitable for natural regeneration (red) to well suited for natural regeneration (green). The total area suitable for regeneration of mountain ash decreases by ∼80% between the two scenarios.

landscape.

6.5 Conclusions

Changes to the global climate system are having and will continue to have profound impacts on the productive capacity of natural ecosystems around the world. Our analyses provide a framework for assessing the impacts of changes in MAT on maximum stocking levels and total stand volume in eucalypt forests in Victoria, as well as regeneration and growth dynamics at landscape scales. We found that a 3°C increase would be expected to reduce total stand density and stand volume in mountain ash stands by ∼15%. In addition, an increase in MAT of that scale would lead to a dramatic reduction in the area of forest suitable for natural regeneration from seed of one of the dominant tree species in these ecosystems. The mountain ash forests of the Central Highlands are amongst the most commercially valuable in the State of Victoria. While the timing of the impacts of future climate change on stand productivity is contingent upon on-going rates of regional and global warming, and is therefore uncertain, a reduction in total stand volume of that magnitude across an entire landscape would be significant. In addition, an 80% reduction in the area suitable for regeneration from seed would require sweeping changes to regeneration practices used in forest management and bushfire amelioration. While climate change may not appear as an immediate threat to wood supply levels, our analyses suggest that developing proactive forest management practices to adapt to future climatic conditions should be considered sooner, rather than later.

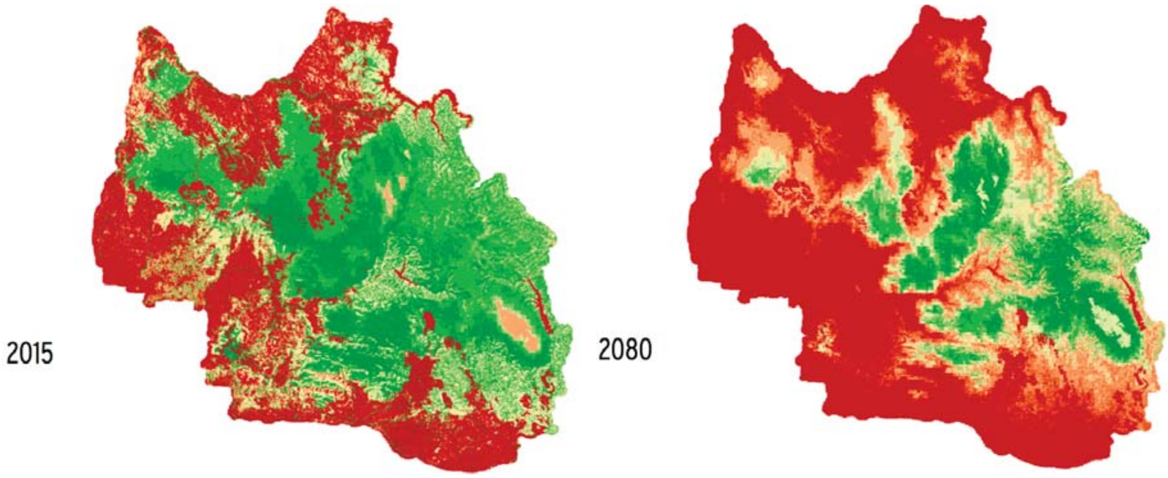

Figure 25: Forest productivity of mountain ash (*Eucalytpus regnans*) across the Central Highlands under current climate conditions (left panel) and a future climate that is 3°C warmer (right panel). The colour scale runs from non-productive (red) to highly productive (green).

Part 7

Conclusions

We have reviewed the strategic wood supply modelling process employed by VicForests to set wood supply levels from Victoria's State Forests and have analysed a range of potential risks and uncertainties that Victoria's native forest industry may face in the coming decades. The current environment of declining sawlog yields can be attributed to a range of factors including the nature of the forest resource dominated by the 1939 ash regrowth in the Central Highlands, the impacts of several large, catastrophic bushfires since 2000, and the recent detection of hundreds of new Leadbeater's possum colonies in the Central Highlands. Over the past 10 years projected sustainable harvest levels of D+ ash sawlogs, the primary high-value timber asset from the State Forests, have been reduced by more than half, from 293,000 m^3 to 130,000 m^3. The primary challenge facing VicForests and the native forest industry is the exhaustion of the 1939 ash regrowth after 2030, but before sufficient new forest resources from subsequent regeneration events are available to harvest. While we have confidence in VicForests projections based on current assumptions, further fires, detection of new LBP colonies, or reductions in volume due to climate or other disturbances, will exacerbate put create pressures for further downward revisions of wood supply level. This will add to growing stress on existing sawmills, logging and haulage contractors, and other forest-related workers. Our analyses provide estimates of potential levels of LBP discovery rates and fire activity over the next 20 years based on a range of data sources, as well as FMA-level variation in these potential impacts (Table 14).

Table 14: Summary of variability amongst FMAs in potential impacts of bushfire and new LBP discoveries on wood supply levels of 1939 ash regrowth based on analyses in this report. ++ indicates relatively greater fire activity or LBP discovery rates; – – denotes the opposite.

Impact	Central Gippsland (CG)	Central (CT)	Dandenong (DD)
Bushfire	– –	++	– –
LBP	++	++	– –

Both bushfires and new LBP colony discoveries have the potential to reduce the harvestable area of 1939 ash regrowth by about 20%. However, because the 1939 ash regrowth accounts for ∼40% of the new LBP discoveries, the combined impacts of catastrophic bushfires and new LBP discoveries would likely be a 25-35% reduction in wood supply over the next 20 years. We expect that these impacts will be greatest in the Central FMA (high probability of bushfires and new LBP discoveries) and least in the Dandenong FMA (low probabilities of bushfires and new LBP discoveries) (Table 14). In the following section, we summarise our results and discuss their implications for sustainable wood supply levels from Victoria's State Forests.

Key points

1. VicForests uses a widely used modelling approach to estimate sustainable fibre and wood supply levels for the State Forests of Victoria. Their approach applies industry-standard modelling tools (Woodstock and Stanley), makes sensible assumptions, and produces reasonable estimates of sustainable wood supply levels. VicForests' current strategic wood supply modelling process is rigorous and repeatable. Our findings are consistent with previous reviews of Victoria's strategic wood supply modelling process that found that the modelling approach is sound, that the assumptions that underpin the approach are appropriate, and that the sustainable harvest levels are reasonable. However, the modelling framework, which requires diverse data inputs, sub-models, constraints, and adjustment factors, is complex. This complexity is difficult to communicate and makes the process seem opaque to the public.

2. Despite several assessments endorsing the strategic wood supply modelling process and past estimates of wood supply levels, sustainable harvest levels have been reduced by more than 50% over the past decade. These reductions have occurred due to the impacts of unexpected stochastic events, such as catastrophic bushfires and Leadbeater's possum discoveries, which are not addressed in the strategic wood supply modelling process. VicForests primarily manages this type of risk through short-term supply contracts. However, accounting for potential future losses due to unexpected events presents a significant challenge for VicForests and creates a potential vulnerability for the native forest industry, which requires some security in the forest resource in the medium- to long-term.

3. The strategic wood supply modelling framework used by VicForests depends on several scaling factors to align predicted total merchantable volume with actual merchantable volume data collected during harvest sale operations. There is considerable variability in the data that underlies each of the scaling factors that is not propagated through the re-alignment of predicted TMV values and into the Woodstock optimisation. Consequently, the estimates of sustainable harvest levels (*e.g.*, 175,000 m^3 ha^{-1}) do not reflect the uncertainty inherent in the modelling process given the data inputs and scaling factors that are used. Developing the capacity to conduct more probabilistic wood supply forecasting would benefit VicForests by explicitly accounting for uncertainties in their modelling framework and facilitating the communication of these uncertainties to government and

the public. This would provide a more transparent estimate of the available resource and its uncertainty (*e.g.*, a 65% probability of producing 175,000 m^3 ha^{-1}) and would allow for better risk management by both VicForests and the native forest industry.

4. A major source of uncertainty in the strategic wood supply modelling process is the actual forest inventory that underpins the growth and yield predictions. The original State Forest Resource Inventory (SFRI) was conducted from 1993-2004 and is now 20 years out of date in places. While the SFRI dataset is routinely updated to reflect forests that have been harvested or burnt, the actual forest inventory measurements of tree size, species, and number (*i.e.*, plot-based estimates of forest structure and composition) have not. The forest inventory used in VicForests growth and yield modelling is based on modelled predictions from original inventory. Potential impacts of changing growing conditions, such as the Millennium drought, are not accounted for and ecologically important species, such as various Acacias, are not included. In addition, the more complex management objectives of contemporary forests require more detailed inventory data for parameterising non-yield based forest models (*e.g.*, habitat suitability models, individual tree growth models). Forest resource planning and management—for wood production, conservation, and other amenity values—would greatly benefit from the State of Victoria adopting a mechanism for regular forest inventories using remotely sensed data (*e.g.*, LiDAR) and better coupe-based management protocols.

5. Catastrophic bushfires present an existential threat to the native forest industry. If a large, catastrophic bushfire killed a large proportion of the remaining 1939 ash regrowth, it could hae a significant impact on the native forest industry. Using a combination of simulations based on historical data and a fire succession model, we estimated that over the next 20 years $<$20% of the 1939 ash regrowth in the Central Highlands is likely to experience bushfire. No scenario led to bushfires burning $>$50% of this commercially valuable resource over the next 20-year period. While a loss of 20% of the 1939 ash regrowth to bushfires would lead to a reduction in wood supplies, on its own it would be unlikely to reduce the harvestable forest resource to a point that would challenge the viability of the native forest industry.

6. Recent discoveries of 400+ new Leadbeater's possum colonies has reduced the forest resource available for harvesting. More discoveries would lead to further reductions in sustainable harvest levels. We used a large presence/absence dataset set from ARI to develop a model to estimate the probabilty of LBP detection based on stand age, elevation, and FMA. We then applied the model to every harvestable polygon in the VicForests database to estimate the number of potential new LBP detections. Our model estimated $\sim$520 new LBP detections in 1939 ash regrowth. Depending on the exclusion zone size and assumptions about mean total merchantable volume, these detections would lead to reductions in total harvestable area of 1939 ash regrowth of 1605-8081 ha, and reductions in harvestable volumes of $\sim$350,000–1,750,000 m^3 of D+ sawlogs and 705,000–

3,520,000 m^3 of residual wood. These losses varied substantially across the three FMAs (Central, Central Gippsland, and Dandenong) that had predicted new LBP detections.

7. Climate change presents a longer-term threat to the viability of the native forest resource. However, it is a threat that is real and should be incorporated into modelling and planning frameworks. Our modelling of climate change impacts predicts that by the end of the century there will be reductions in standing volume and stand density of 15%. In addition, natural regeneration of mountain ash from seed will only be viable across less than 20% of its current distribution and will be primarily limited to high elevation sites. This suggests that forest regeneration practices after harvesting and large bushfires will need to shift to planting seedlings. The timing of this shift is uncertain.

8. A recurring theme in preparing and colleting the data for our analyses is that the State of Victoria would benefit from a more integrated approach to managing its native forest estate for multiple objectives. Forest management for commercial wood supply and broader objectives, such as climate mitigation, species conservation, and fire management, are often in direct conflict. VicForests is a State-Owned Business Enterprise with a legislated interest in commercial sustainability; DELWP is governmental Department with a legislated interest in environmental sustainability. Both are focused on the same resource, the State Forests, which must supply wood, support biodiversity, protect water catchments, sequester carbon, and provide other social amenities and aesthetic values. This has led to conflict as the primary interests of the different agencies differ. The separate reports on wood supply and biodiversity that were commissioned by the Forest Industry Task Force highlight this divide. The analyses for these reports have been based on different data sets, different models, and different assumptions—and will come to different conclusions about a common resouce. This approach perpetuates the polarisation around forest management of Victoria's State Forests. The State of Victoria urgently needs to develop a framework for integrated forest planning that can account for the many benefits and values that the State Forests provide. This would provide a common, transparent platform for assessing and evaluating the impacts of forest management decisions on a wide range of values, would allow for more rigorous assessments of future threats such as fire and climate change, and would provide a more transparent mechanism to actively engage the public in developing a shared vision for Victoria's State Forests.

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