Perpetuating trees with hollows under the Coastal Integrated Forestry Operations Approval (IFOA)

Report on a pilot study for the Coffs Harbour Timber Zone

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Summary

In this report I explored the feasibility of using the Forest Resource and Management Evaluation System (FRAMES) developed and maintained by the Forestry Corporation of NSW (FCNSW) to evaluate how many hollow-bearing trees, and hollow-bearing trees suitable for occupancy by vertebrate fauna, are perpetuated in NSW forests under the Coastal Integrated Forestry Operations Approval (IFOA).

Staff from FCNSW used FRAMES to simulate changes in stems per ha (by DBH class and tree species group) across a pilot study area (the Coffs Harbour Timber Zone) over 200 years. I used these data to, in turn, predict how many trees with visible hollows and how many trees with hollows suitable for occupancy by vertebrate fauna will occur in the net harvest area and areas permanently excluded from harvesting under the Coastal IFOA.

Simulations indicated that, in the Coffs Harbour Timber Zone under the current Coastal IFOA (excluding plantations and unclassified areas) over the next 200 years:

- The net harvest area (approximately 49% of the study area) was predicted to support, on average, 8-10 trees per ha with visible or apparent hollows and 2-3 trees per ha with hollows suitable for occupancy by vertebrate fauna.
- In areas permanently excluded from harvesting (approximately 51% of the study), trees with visible hollows were predicted to increase from a mean of 8 per ha to 26 per ha and trees with hollows suitable for occupancy by vertebrate fauna were predicted to increase from a mean of 3 per ha to 10 per ha.
- Tree retention clumps (i.e., Protocol 22 of the Coastal IFOA) and tree retention (Protocol 23 of the Coastal IFOA) are predicted to provide 4% and 37% of all hollow-bearing trees suitable for occupancy by vertebrate fauna in the study area when averaged over 200 years.

With minor changes, outputs from FRAMES can be used to:

- Simulate outcomes of the current IFOA and any proposed changes to the IFOA on the tree hollow resource.
- Simulate impacts of changing fire regimes on tree hollows in state forests of NSW.
- Identify variables that should be collected to improve the information base for managing hollow-bearing trees.
- Spatially map hollow-bearing trees across areas subject to the IFOA.

However, I recommend the following before FRAMES is used more broadly to simulate hollow-bearing trees in NSW forests:

- Source all available data on hollow-bearing trees occupied by vertebrate fauna, develop an improved model to predict which trees are suitable for occupancy by vertebrate fauna and incorporate this model into FRAMES.
- Use the above model to identify a common set of variables that is recorded: (a) when selecting hollow-bearing trees for retention; (b) in inventory plots; and (c) is used in FRAMES to predict which trees contain hollows suitable for occupancy by vertebrate fauna. This will enable predictions from FRAMES to be more easily verified in the field and translated into operational practice.
- Introduce fires—and the associated mortality and collapse of trees and any change in the rate of hollow formation in existing trees—stochastically into FRAMES. This will allow FRAMES to be used to simulate changing fire regimes in NSW forests.
- Compare predictions from FRAMES with data collected through a field-based pilot study.

Introduction

Given hollows suitable for vertebrate fauna do not typically form in eucalypts until they are >120-240 years old (Gibbons and Lindenmayer 2002) traditional approaches to monitoring will not provide information on the effectiveness of the Coastal Integrated Forestry Operations Approval (IFOA) with respect to providing hollow-bearing trees in perpetuity. Simulation modelling can be used in concert with traditional monitoring to inform adaptive management and adaptive monitoring of a slow response variable such as hollow-bearing trees by: (a) predicting likely outcomes of current and proposed management on the tree hollow resource over the long-term so changes to management can be made iteratively; and (b) informing the data that should be collected as part of monitoring programs in order to continually improve these predictions (Figure 1).

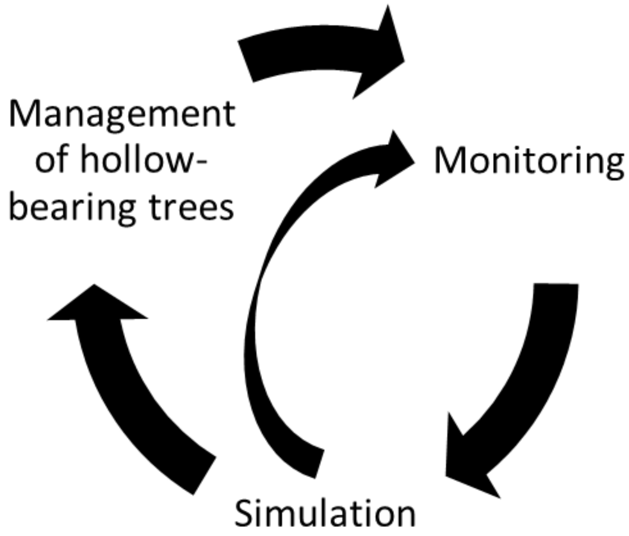

Figure 1. The role of simulation modelling for informing adaptive management and adaptive monitoring for a slow response variable such as hollow-bearing trees.

The aim of this report is to develop a method to predict how many hollow-bearing trees are provided over the long-term in forests of New South Wales managed under the Coastal IFOA. This report is the outcome of a pilot study undertaken for the Coffs Harbour Timber Zone (58,041 ha) on the north coast of New South Wales.

The aim of the key habitat features strategy within the Coastal IFOA monitoring plan is:

Monitor if key habitat features are being provided in an appropriate number and configuration to ensure persistence of key habitat dependent fauna and determine if habitat resources are being perpetuated within harvested areas at the number required to maintain fauna species. This will include three tasks:
- *a review of hollow use by key dependent fauna*
- *hollow mortality and recruitment modelling*
- *occupancy analysis of key habitat-dependent species.*

This exercise is focused on the second bullet point above. However, this modelling exercise has been informed by the first bullet point (hollow use by key dependent fauna) which was reported in Goldingay (2021). The outputs from this modelling exercise can potentially be used in future as predictors in occupancy models (the third bullet point above) for hollow-dependent fauna across forests managed under the Coastal IFOA.

The brief for this project listed the following expected outputs:

1. A methodology that enables the number of hollow-bearing trees to be predicted or forecast in different parts of NSW State Forests over 200 years using the Forest Resource and Management Evaluation System (FRAMES). This will then form part of an adaptive management framework for hollow-bearing trees in NSW forests.
2. Numbers of hollow-bearing trees and trends in numbers of hollow-bearing trees over time in NSW State Forests predicted separately:
   - for relevant Environmentally Sensitive Areas (ESAs) (i.e., all ESAs that contain trees that are permanently protected)
   - for the net harvest area
   - by DBH class (because some species utilise hollows in certain DBH classes).
3. The proportion of the State Forest estate in which hollow-bearing trees are predicted to increase, remain stable or decline over time.
4. The proportions of the State Forest estate in which hollow-bearing trees occur at different densities.
5. Those variables to which the predictions are most sensitive and therefore should be a priority for collection so future predictions can be improved.

Methods and results

Hollow-bearing trees were modelled using predictions of trees per ha by DBH class and species group for the Coffs Harbour Timber Zone obtained from FRAMES via staff in FCNSW. The steps taken and results are presented below.

Predicted stems by DBH class over time

The predicted numbers of trees with visible hollows that occur over time were predicted using DBH and tree species because these were the only variables that are measured within inventory plots that can be used to predict the presence of hollows in trees and can be simulated over time for each tree in FRAMES.

The number of stems by DBH class and tree species group (Appendix 1) over 200 years was predicted in FRAMES by Tim Parkes (Forestry Corporation of NSW). Predictions were initiated with data from 126 x 0.1ha inventory plots within the pilot study area (Coffs Harbour Timber Zone) measured between 2006 and 2016. All predictions were made under two scenarios: (1) no harvesting to simulate Environmentally Sensitive Areas (ESAs) that are afforded permanent protection from harvesting under the Coastal IFOA (e.g., riparian areas, tree retention clumps, wildlife habitat clumps); and (2) the net harvest area based on simulated timber removals.

The following settings were applied by FCNSW within the net harvest area to simulate relevant Coastal IFOA Conditions:

1. The 8 largest trees per hectare predicted to contain at least one visible hollow were retained at each harvesting event (or all trees with at least one visible hollow where <8 hollow-bearing trees per hectare were available). In the intensive harvesting (or regrowth) zone, which occurs across some of the study area, all hollow-bearing trees present need to be retained at each harvesting event. However, this was not simulated.

2. All “giant” trees (>135cm DBH for *Eucalyptus pilularis* and >110cm DBH for all other tree species—which is equivalent to >160cm and >140cm diameter at stump height over bark respectively) were retained and permanently protected.
3. At least 7 seed trees per ha were retained at each harvesting event. These were only retained if there were <7 trees with at least one visible hollow, seed trees were drawn from the largest trees available >50cm DBH and seed trees that were not also retained as hollow-bearing trees were available for harvesting in subsequent harvesting events.
4. A minimum basal area of 10m^2 was retained at each harvesting event.

In ESA’s the number of stems in the 10-50cm DBH class were predicted to decline over 200 years while stems in the 50-130cm DBH classes were predicted to increase and the number of stems >130cm DBH was predicted to remain at relatively low numbers (Figure 2).

In the net harvest area the number of stems in the 10-50cm DBH class were predicted to initially increase, then decrease and remain constant at approximately 200 stems ha^{-1}. The number of stems from 50-90cm DBH was predicted to decrease in the net harvest area and the number of stems 90-130cm DBH were predicted to remain relatively constant over 200 years (Figure 2).

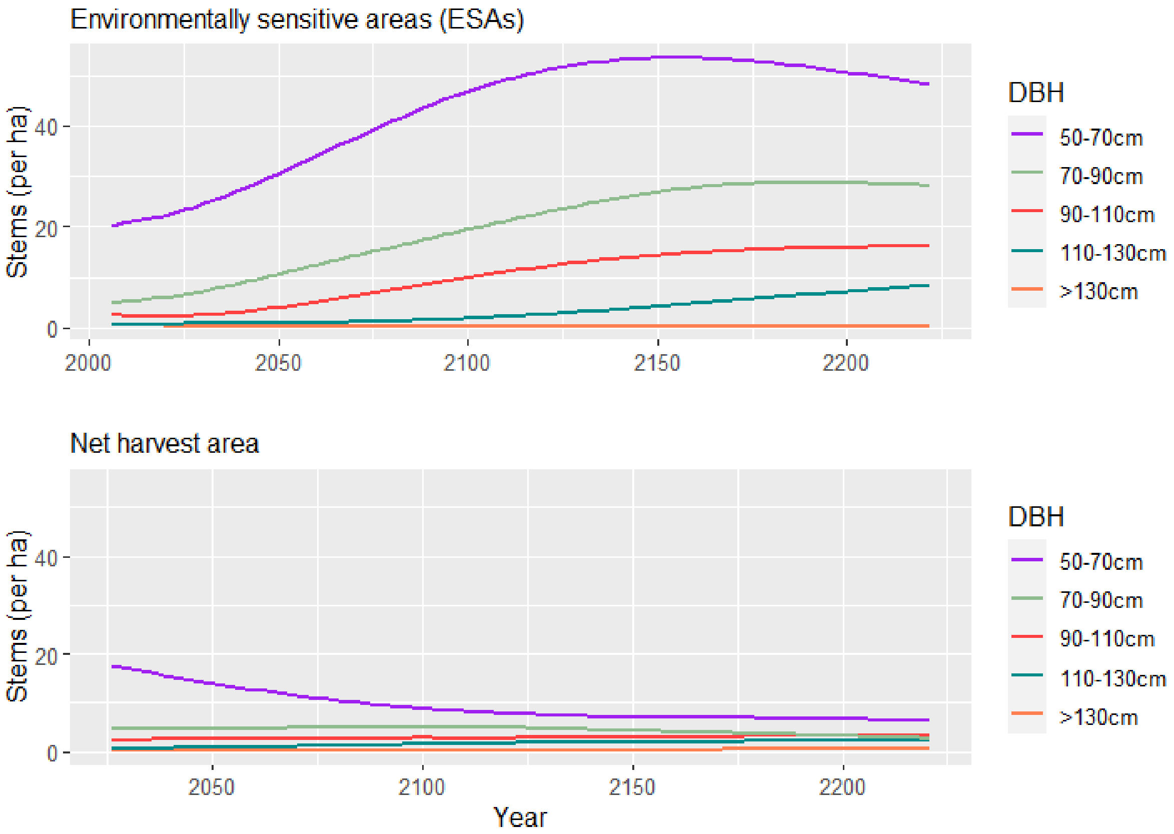

Figure 2. Predicted mean numbers of stems by DBH class (>50cm DBH) under scenarios of no further harvesting (ESAs) and ongoing harvesting (net harvest area) as predicted using FRAMES (v12.01) for the Coffs Harbour Timber Zone. Trend lines are fitted with a loess smoother. Predictions for stems in the 10-50cm DBH class are not illustrated.

Predicting the number of trees with visible hollows over time

The next step in the analysis was to convert the numbers of stems by tree species group and DBH class into predictions of trees with hollows. A model to predict the proportion of trees with visible hollows using DBH and tree species was fitted using data for 103,036 trees in 2431 × 0.1 hectare plots measured as part of the NSW Comprehensive Regional Assessment. Only data from the North Coast Analysis Zone was used given the location of the study area. In this inventory a hollow-bearing tree was defined as a tree in which “hollows suitable for animal or bird nesting are visible” (FCNSW undated). Trees “considered likely to contain hollows (but hollows are not visible)” (i.e., inferred hollows) were recorded as not containing hollows for the purpose of this analysis.

The proportion of trees with at least one visible hollow was predicted using a logistic regression model with the following explanatory variables: DBH and tree species group (Appendix 2). Predictions by species group and DBH class are provided in Appendix 3.

I first compared predictions provided in FRAMES with my own predictions based on the logistic model described above. The version of FRAMES used initially for this project predicted considerably more hollow-bearing trees than I predicted independently and at numbers above those typically observed in unharvested forest (Figure 3). FRAMES was subsequently reconfigured with the logistic regression models described above. The revised predictions from FRAMES were similar to those I obtained independently. Minor differences occur because FRAMES makes a prediction for individual trees throughout the simulation, whereas my independent predictions are based on the number of stems in each DBH class produced by FRAMES, and thus are based on the median DBH of trees in each diameter class.

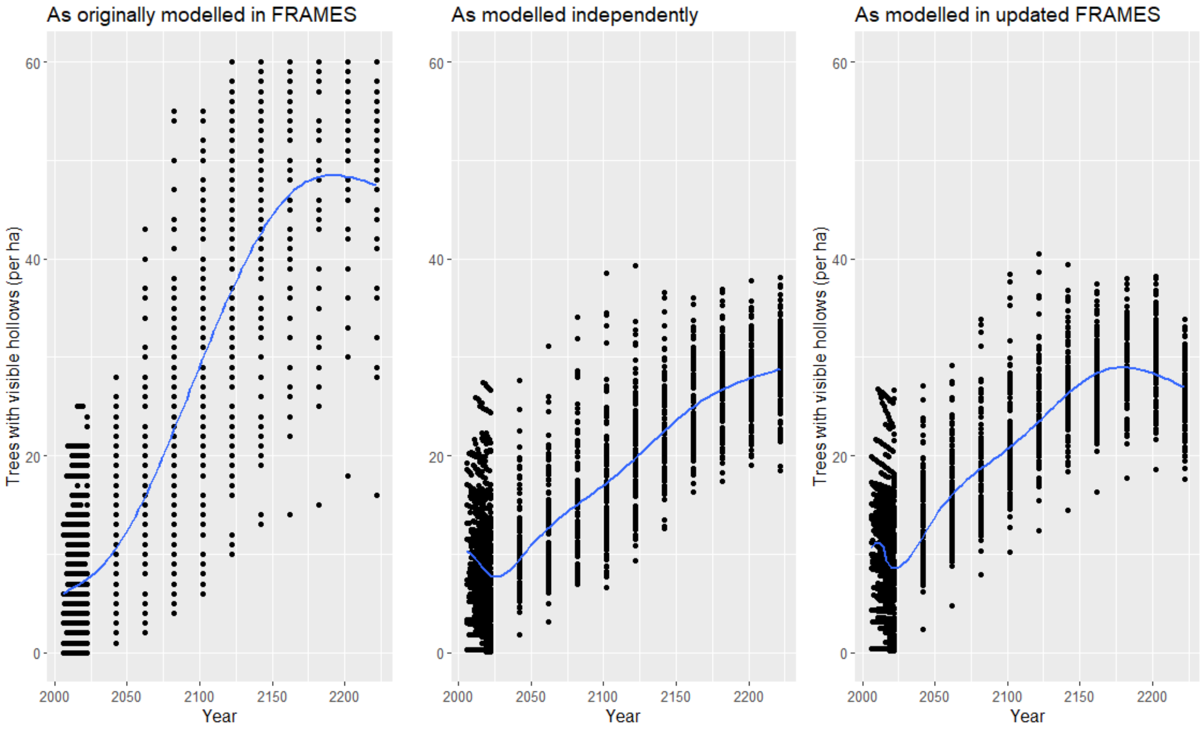

Figure 3. Predicted numbers of trees with visible hollows (per ha) for ESAs (i.e., no harvest scenario) from 2006 to 2222 for the Coffs Harbour Timber Zone as predicted: (a) using an earlier version of FRAMES; (b) independently for this project; and (c) using an updated version of FRAMES that used the logistic model in Appendix 2. Trend lines are fitted with a loess smoother.

The predicted numbers of trees with hollows in ESAs and the net harvest area over 200 years are illustrated in Figure 4. After an initial decline over the period from 2006 to 2016 (i.e., the period over which inventory plot data are available), the mean number of trees with hollows in ESAs is predicted to increase from an approximate mean of 8 per ha to 26 per ha after 200 years. In the net harvest area the mean number of trees with visible hollows remains at approximately 8-10 per ha over the duration of the simulation (200 years) (Figure 4). The number of trees with visible hollows are predicted to occur at a relatively constant number of 8-10 per ha over 200 years due to a constant number of trees with hollows in the smallest DBH class (10-50cm DBH), a relatively constant number of trees in the 90-110cm DBH class and increasing numbers of trees in the DBH classes used to simulate the protection of giant trees (>110cm DBH) (Figure 5).

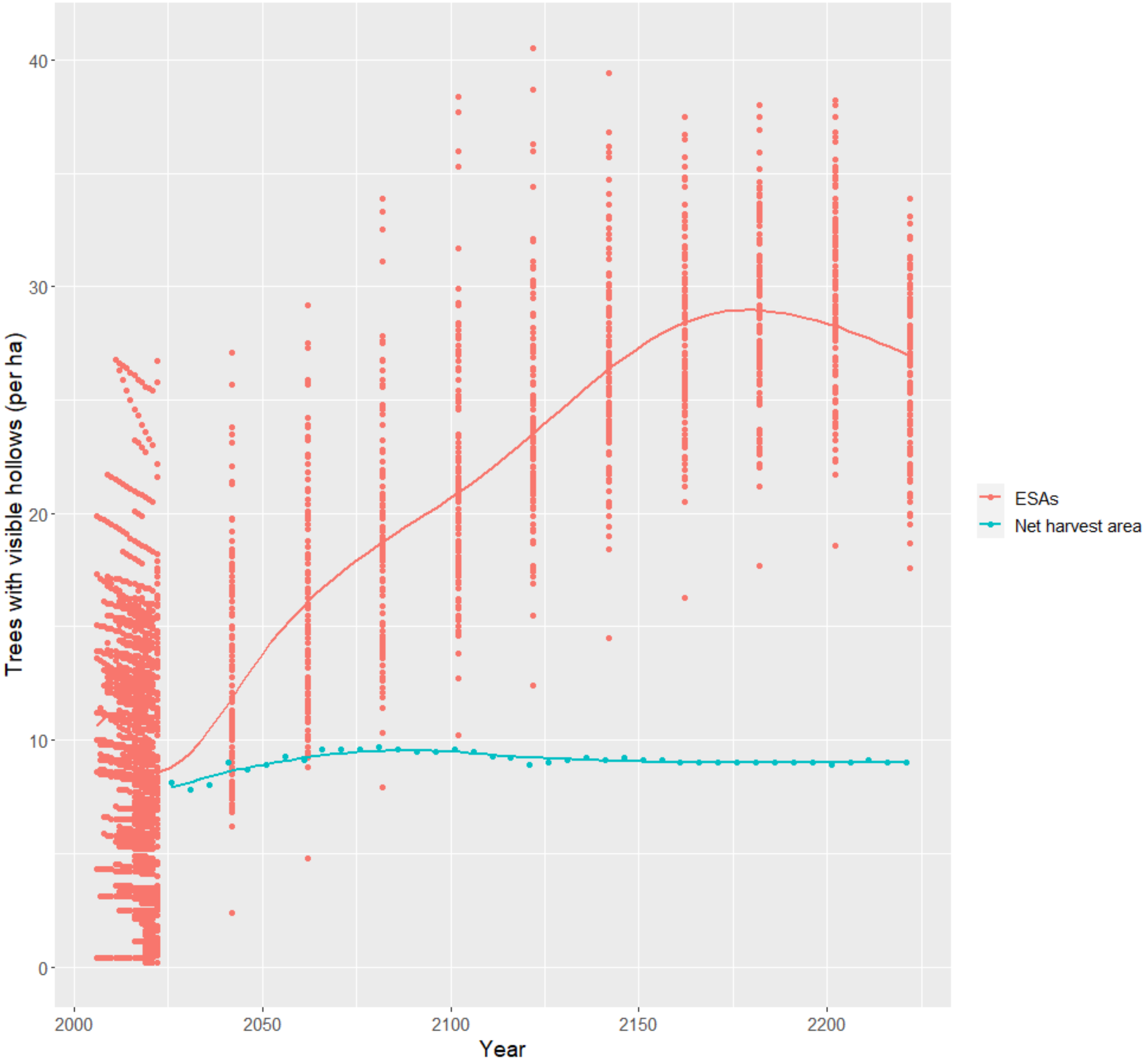

Figure 4. Predicted numbers of trees with visible hollows under scenarios of no further harvesting (ESAs) and ongoing harvesting (net harvest area) for the Coffs Harbour Timber Zone. Predictions are as simulated in FRAMES (v12.01). Trend lines are fitted with a loess smoother.

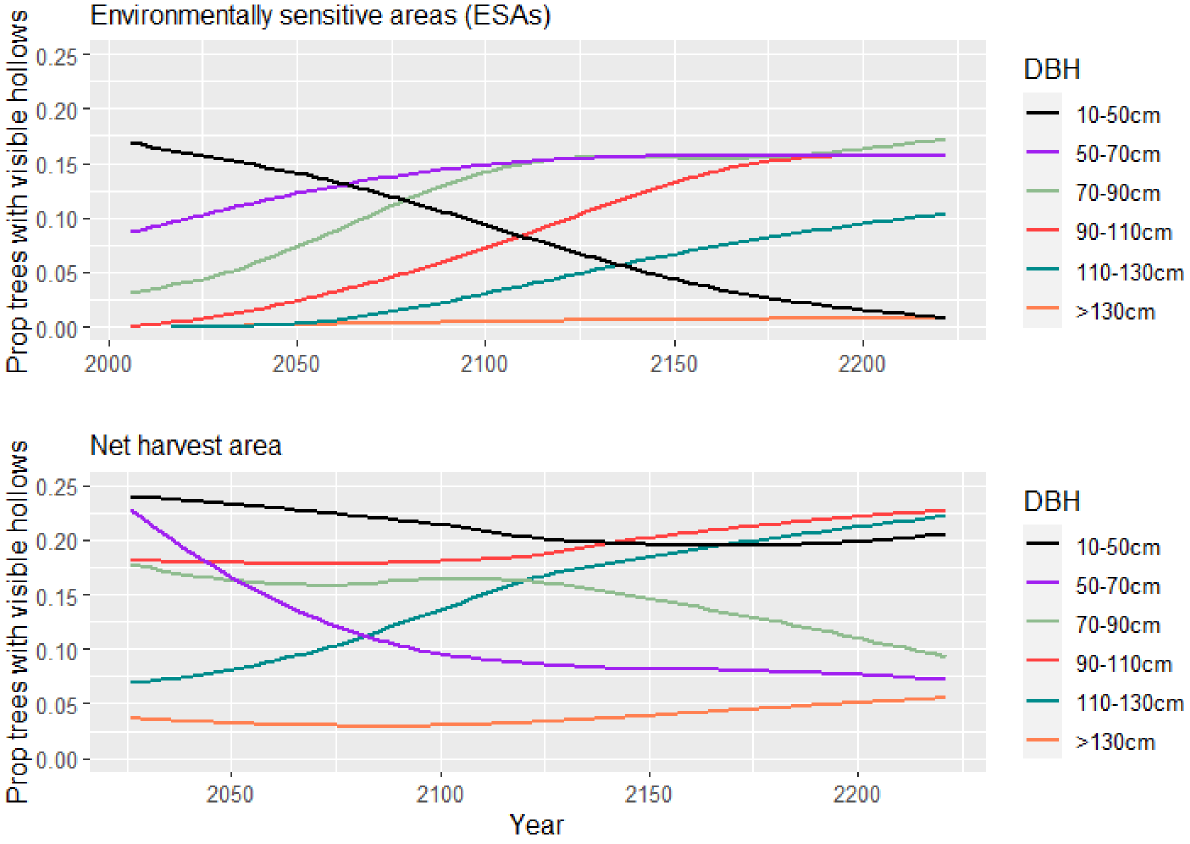

Figure 5. The proportions of all trees with visible hollows in each DBH class for ESAs and the net harvest area based on predictions from FRAMES (v12.01). Trend lines are fitted with a loess smoother.

Predicting the number of trees with hollows suitable for occupancy by vertebrate fauna over time

The previous predictions of trees with hollows are based on data collected from inventory plots in which a hollow-bearing tree is defined as one with at least one apparent hollow visible from the ground. Published studies from Australia indicate that 28% to 57% of trees with visible or apparent hollows measured from the ground contain hollows suitable for occupancy by vertebrate fauna (reviewed by Gibbons and Connolly-O'Donnell 2023). The predicted numbers of trees with visible hollows reported in the previous section will therefore over-estimate the number of hollow-bearing trees suitable for occupancy by vertebrate fauna.

I therefore developed a method to predict how many hollow-bearing trees are likely to be suitable for occupancy by vertebrate fauna. The largest and most relevant database to inform this part of the analysis is 842 trees with at least one hollow visible from the ground that were subsequently felled and inspected as part of the Pacific Highway upgrade in northern NSW (Sandpiper Ecological 2016, Sandpiper Ecological 2017, Sandpiper Ecological 2020). Using 102 living trees for this database that contained sufficient information on DBH, tree species and evidence of current or previous occupancy by vertebrate fauna (e.g., animal within or exiting the hollow, nest material, feathers, eggs or egg shells, obvious wear), I developed a logistic regression model to predict the proportions of trees with visible hollows that are suitable for occupancy by vertebrate fauna by DBH and tree species group. For tree species groups not represented in this dataset (SPG, BBX, SBG, SBK, NEG, NCO – see Appendix 1 for definitions) I used predictions obtained for the nearest species group taxonomically according to (Brooker 2000).

Of the 102 trees with at least one hollow visible from the ground in the database from the Pacific Highway upgrade in northern provided by Sandpiper Ecological, 45% contained hollows with evidence of occupancy by vertebrate fauna (Table 1). The mean DBH of hollow-bearing trees with evidence of occupancy by vertebrate fauna was 80cm DBH and the range 40-120cm DBH. Using the logistic model fitted to these data, the mean predicted proportions of hollow-bearing trees that are suitable for occupancy by vertebrate fauna ranged from 0.12-0.28 for trees from 10-50cm DBH, to 0.29-0.55 for trees >130cm DBH. Predictions by species group and DBH class are provided in Appendix 3. It should be noted that predictions from this model have a high degree of uncertainty (Appendix 5). This is discussed later in the report.

Table 1. Vertebrate taxa positively identified to occupy hollow-bearing trees felled as part of the Pacific Highway upgrade and used in this study. Occupied trees were also identified from the presence of nest material, feathers, eggs or egg shell, or obvious wear at the entrance. Data provided by Sandpiper Ecological.

Common name	**Taxon name**
Graceful tree frog	*Litoria gracilenta*
Green tree frog	*Litoria caerulea*
Skink	*Cryptoblepharus* sp.
Skink	*Eulamprus* sp.
Bar-sided skink	*Eulamprus* (*Coccinnia*) *tenuis*
Pink-tongued skink	*Cyclodomorphus gerrardii*
Blackish blind snake	*Anilios nigrescens*
Lace monitor	*Varanus varius*
Carpet python	*Morelia spilota*
Common tree snake	*Dendrelaphis punctulatus*
Australian owlet-nightjar	*Aegotheles cristatus*
Sacred kingfisher	*Todiramphus sanctus*
Lorikeet	*Trichoglossus* sp.
Antechinus	*Antechinus* sp.
Feathertail glider	*Acrobates pygmaeus*
Sugar glider	*Petaurus breviceps*
Common ringtail possum	*Psuedocheirus peregrinus*
Bat	Microchiroptera

A comparison between the predicted numbers of trees with visible hollows and trees with hollows suitable for occupancy by vertebrate fauna for ESAs and the net harvest area in the Coffs Harbour Timber Zone is illustrated in Figure 6. Whereas the number of trees with visible hollows was predicted to increase from 8-10 to approximately 26 per ha over 200 years in unharvested ESAs, the number of trees with hollows suitable for occupancy by vertebrate fauna was predicted to increase from a mean of approximately 3 per ha to a mean of approximately 10 per ha. In the net harvest area, the mean number of trees with visible hollows was predicted to range from 8-10 per ha over the simulation period (200 years), while the mean number of trees with hollows suitable for occupancy by vertebrate fauna ranged from 2.3-2.7 per ha over the same period. On average, the predicted number of trees with hollows suitable for occupancy by vertebrate fauna is 26% of the predicted number of trees with visible hollows.

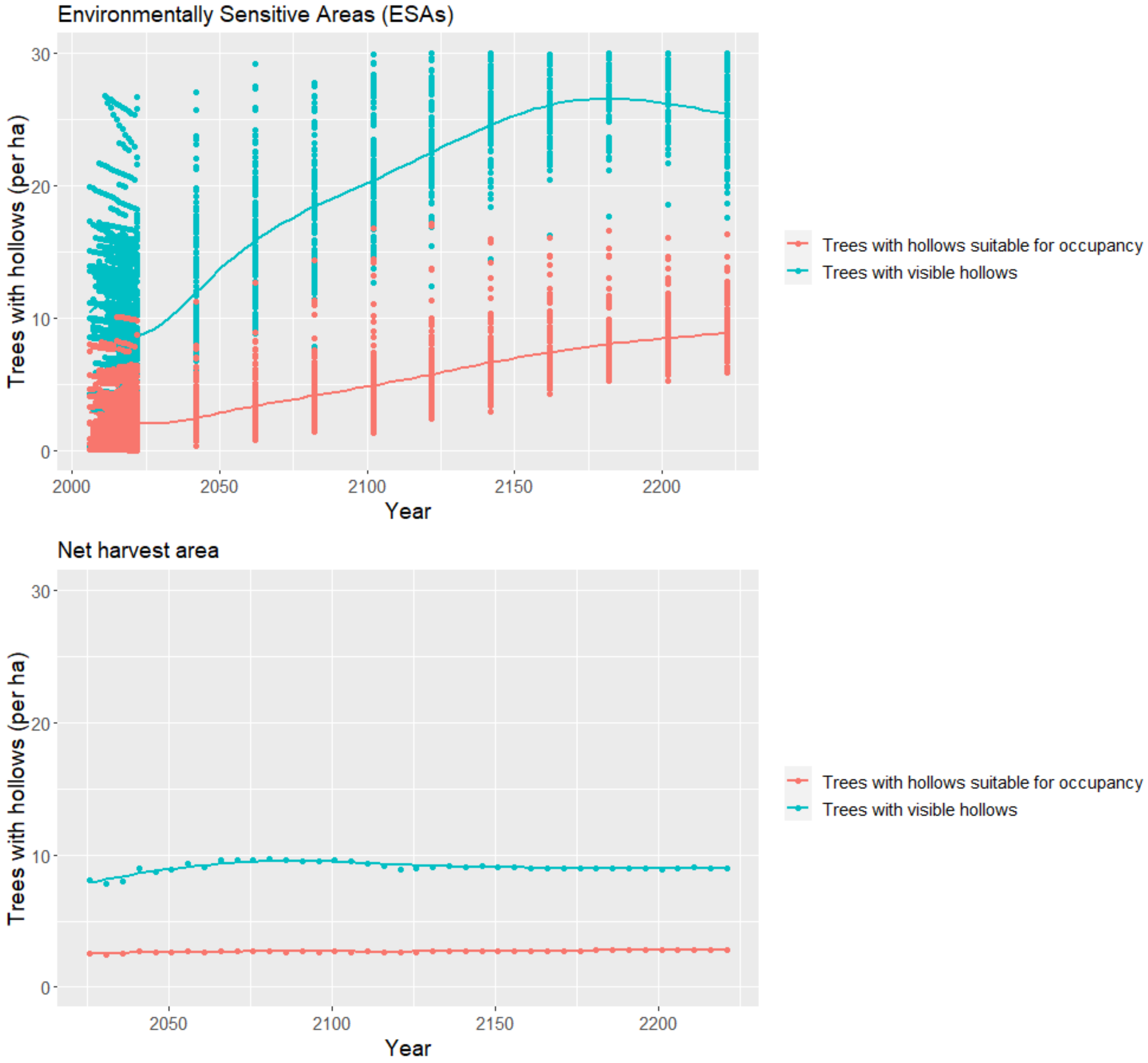

Figure 6. Predicted numbers of trees with visible hollows and trees with hollows suitable for occupancy by vertebrate fauna under scenarios of no further harvesting (ESAs) and ongoing harvesting (net harvest area) for the Coffs Harbour Timber Zone. Predictions of trees with visible hollows are as simulated in FRAMES (v12.01) and trees with hollows suitable for occupancy by vertebrate fauna are modelled using the predicted numbers of stems per ha for each DBH class produced by FRAMES. Trend lines are fitted with a loess smoother.

Spatial predictions

Simulations from FRAMES can be used to provide spatially explicit predictions for hollow-bearing trees at a moderate resolution. To spatially predict the number of hollow-bearing trees in ESAs (i.e., areas that are permanently protected from harvesting), I used generalised linear mixed models and Akakie's Information Criterion (AIC) to identify variables that are available spatially and for which the predicted numbers of trees with visible hollows are associated. This analysis was limited to variables recorded in the FRAMES simulation output. Models were fitted using plot number as a random effect since there are predictions every 20 years per plot and thus these data are nested. Of the spatial variables available, predicted numbers of trees with visible hollows were associated with the last year harvesting occurred, the severity of the 2019 fire and the Yield Association Group (YAG) (a grouping of tree species and productivity classes used by FCNSW) (Appendix 6). Given these variables are available spatially, numbers of hollow-bearing trees can be predicted using these variables in spatial models (Figure 7). The same variables could be used to predict trees with hollows suitable for occupancy by vertebrate fauna. Predictions from the net harvest area from FRAMES were not supplied separately by covariates such as forest type, fire severity or harvesting history and thus the predictions must be averaged across the entire net harvest area, which results in predictions with a coarse spatial resolution (Figure 7). Thus, predictions from FRAMES for the net harvest area would be more suitable for spatial prediction if provided with the same covariates as provided for predictions across ESAs. A spatial layer of hollow-bearing trees can be used to help spatially predict the occurrence of hollow-dependent species for which there are species distribution models (SDMs).

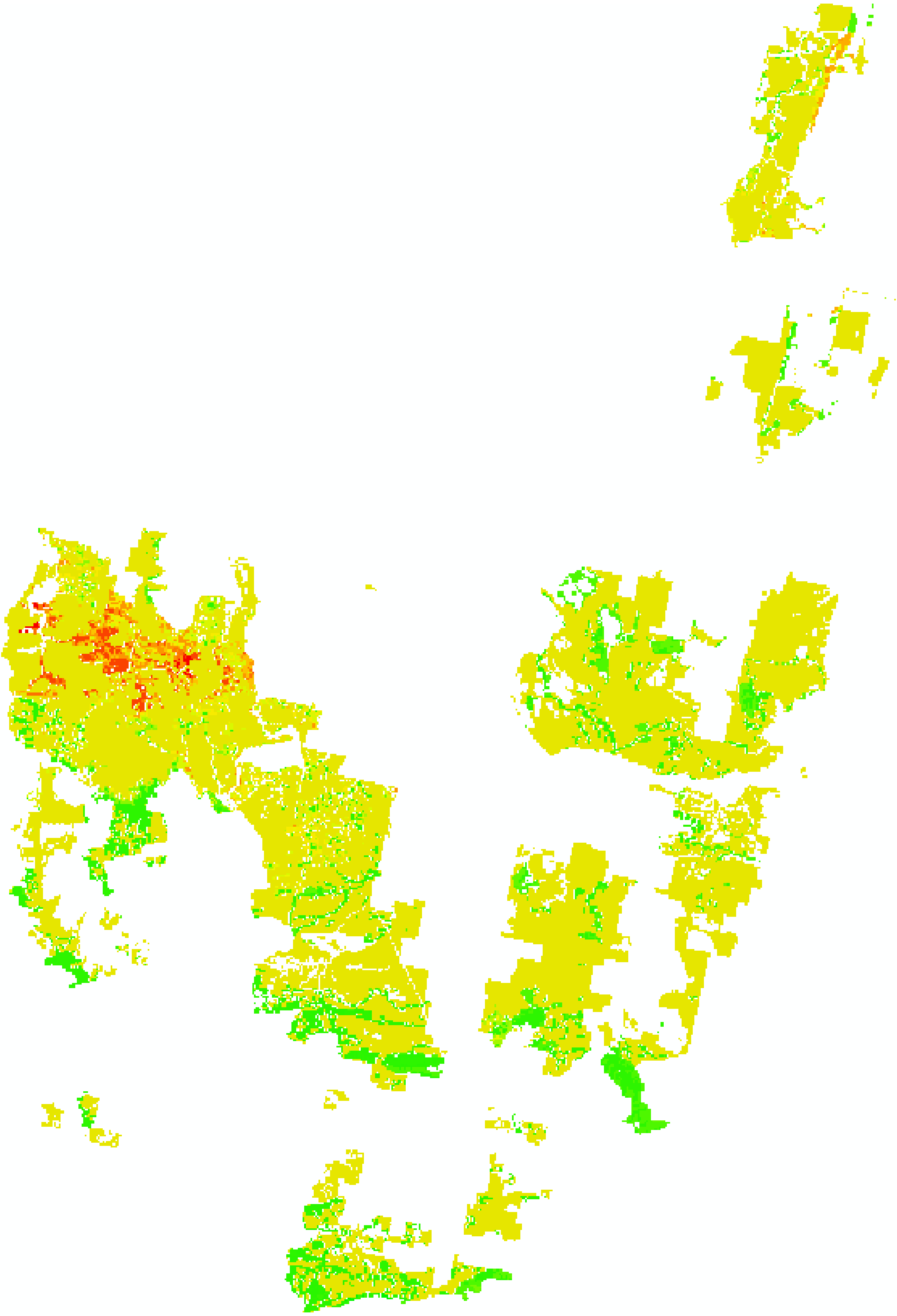

Figure 7. The predicted numbers of trees with visible hollows in the study area in the year 2022 grading from relatively low numbers per ha (red) to relatively high numbers per hectare (green). Only predictions for Forest Management Zones 1, 2, 3A, 3B and 4 are illustrated.

Effects of the IFOA on hollow-bearing trees

A key spatial variable that affects the number of hollow-bearing trees that occur in different parts of the study area is different conditions imposed under the Coastal IFOA. A breakdown of the net harvest area and ESAs for the Coffs Harbour Timber Zone is provided in Table 2. I have excluded plantations, non-forest uses and unclassified areas from all subsequent calculations. Although these areas will contain hollow-bearing trees, they may be managed for different land uses (e.g., powerline easements) and thus the assumptions underpinning our modelling may not be valid for these areas.

Excluding plantations, non-forest uses and unclassified areas, the net harvest area represents approximately 52% of the Coffs Harbour Timber Zone. However, further exclusions that are identified prior to harvesting (e.g., tree retention clumps) have yet to be applied across the entire study area. Tree retention clumps must occupy ≥5% of the base net area in the regrowth zone and ≥8% of the base net area in the non-regrowth zone (State of NSW and Environment Protection Authority 2018). I did not have access to the base net area, nor areas of the regrowth and non-regrowth zones across the study area, so I can only estimate the area likely to be occupied by tree retention clumps. Assuming tree retention clumps will occupy 6.5% (i.e., the average of 5% and 8%) of the net harvest area reported in Table 2 (i.e., the net harvest area not including all IFOA conditions), the net harvest area will occupy approximately 49% of the study area (excluding plantations, non-forest uses and unclassified areas), although additional wildlife habitat clumps and areas <30 degrees slope but not accessible by machinery may reduce this area further. Areas permanently excluded from harvesting therefore represent approximately 51% of the study area.

Based on these area estimates, approximately 49% of the study area (excluding plantations, non-forest uses and unclassified areas) (i.e., the area over which Protocol 23 of the IFOA applies) is predicted to support, on average, 2-3 hollow-bearing trees per ha suitable for vertebrate fauna over the long-term (200 years). Approximately 51% of the study area (ESA's) will support 3 to 10 hollow-bearing trees suitable for vertebrate fauna. When averaged over the duration of the simulation (200 years), the net harvest area (i.e., Protocol 23 of the IFOA) is predicted to provide 35% and 37% of all trees with visible hollows and all trees suitable for occupancy by vertebrate fauna respectively; and ESA's are predicted to provide 65% and 63% of all trees with visible hollows and all trees with hollows suitable for occupancy by vertebrate fauna respectively (Figure 8). Tree retention clumps (i.e., Protocol 22 of the Coastal IFOA) are predicted to provide 4.4% and 4.2% of hollow-bearing trees with visible hollows and hollow-bearing trees suitable for occupancy by vertebrate fauna respectively. A breakdown of the percentages of all trees with visible hollows and hollows suitable for occupancy by vertebrate fauna in ESAs within the Coffs Harbour Timber Zone is provided in Figure 9.

Table 2a. Breakdown of different Forest Management Zones within the Coffs Harbour Timber Zone (Source: FCNSW).

Area Component	Forest	Area Category	SubTotal	Proportion
Net Harvest Area[1]	FMZ 4	Available for harvesting	26,151	52%
Dedicated Formal Reserves	FMZ 1	Permanent Exclusion	1,222	2%
Informal Reserves	FMZ 2		7,408	15%
Broad Area Harvest Exclusion	FMZ 3A		6,654	13%
Exclusions within Harvest Zones[2]	FMZ 3B and 4		8,377	17%
Subtotal of permanent exclusions			26,390	48%
Gross area of State Forest considered in this study			**49,812**	**100%**
Plantation	FMZ 5	Plantation	**5,500**	
No classification	Unclassified	May include other land uses	2,436	
Non-forestry Uses	Unclassified		293	
Subtotal of other areas			**8,229**	
Gross area of State Forest			**58,041**	

[1] Does not include all IFOA exclusions (i.e., some IFOA exclusions are identified on the ground prior to harvesting)

[2] Does not include all exclusions within harvest zones as some are identified on the ground prior to harvesting

Table 2b. Breakdown of exclusions within harvest zones in the study area. Does not including all exclusions that are identified on the ground prior to harvesting (Source: FCNSW).

Primary Exclusion Types within Harvest Zones	Hectares	Proportion
Riparian Exclusions	5,115	49%
Slope Exclusion	1,401	13%
Owl Landscape	586	6%
Ridge & Headwater	233	2%
Wildlife Habitat Clumps	263	3%
TEC Exclusion	385	4%
Ecology Exclusion	177	2%
Rainforest	102	1%
Rest (OG/Buffers etc)	115	1%
Total	**8,377**	**100%**

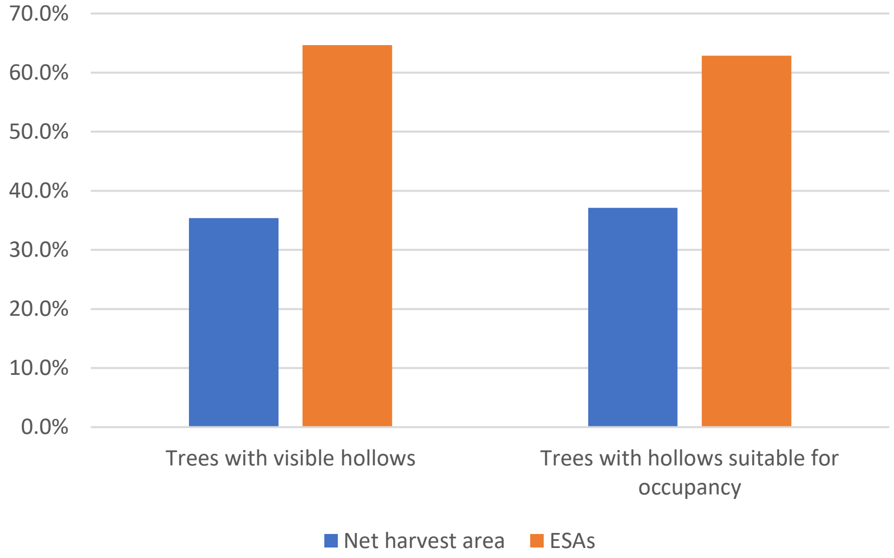

Figure 8. Percentages of all predicted trees with visible hollows and trees with hollows suitable for occupancy by vertebrate fauna in the net harvest area (blue) and ESA's (orange) within the Coffs Harbour Timber Zone (excluding plantations, areas not classified and areas designated non-forestry uses).

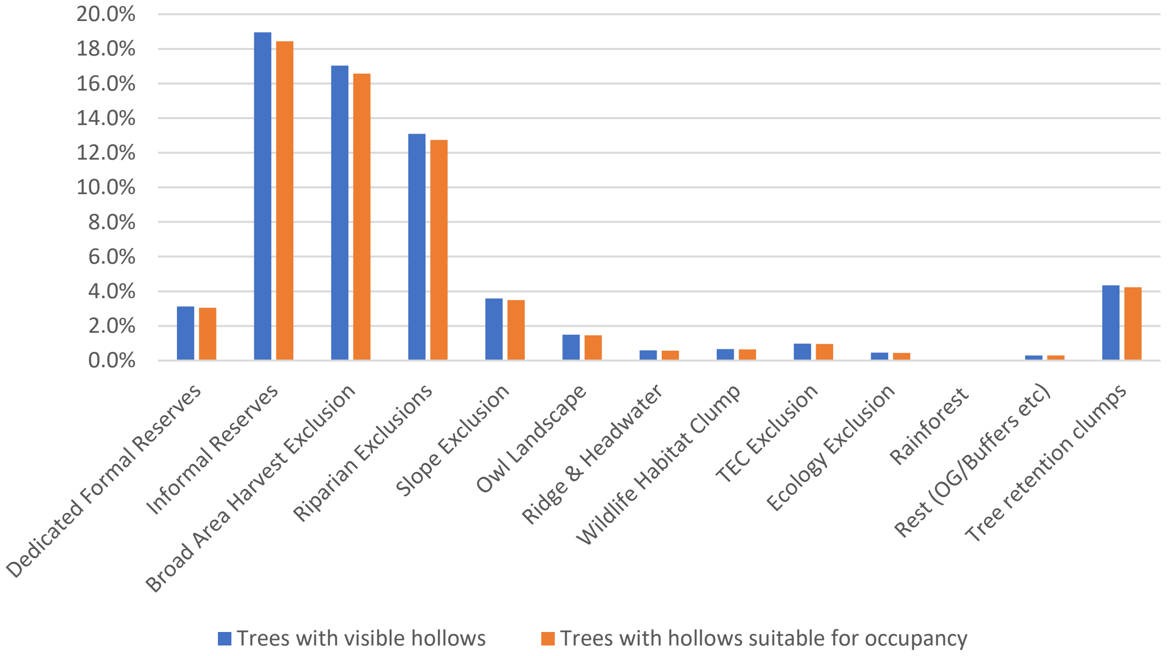

Figure 9. Percentages of all predicted trees with visible hollows (blue) and all trees with hollows suitable for occupancy by vertebrate fauna (orange) within the Coffs Harbour Timber Zone (excluding plantations, areas not classified and areas designated non-forestry uses) that are provided by different ESAs defined in the IFOA. The area of tree retention clumps has been estimated based on assumptions provided in the text.

Discussion

Simulations in the pilot study area (Coffs Harbour Timber Zone) indicated that forests within the net harvest area (36% of the total area) will support, on average, 2-3 hollow-bearing trees per ha suitable for occupancy by vertebrate fauna over the long-term (200 years) under the Coastal IFOA. Hollow-bearing trees suitable for occupancy by vertebrate fauna are predicted to increase from a current mean of approximately 3 per ha to 10 per ha over the same period in areas set aside permanently from harvesting (ESAs) under the Coastal IFOA (48% of the total area).

Differences between trees with visible hollows and trees with hollows suitable for occupancy by vertebrate fauna

Predicted numbers of trees with hollows suitable for occupancy by vertebrate fauna were considerably less than numbers of trees with visible hollows predicted in FRAMES. The reasons for these differences is because most hollows visible from the ground are not suitable for occupancy by hollow-dependent fauna. The models used in FRAMES to predict trees with hollows are based on trees with at least one visible hollow observed from the ground within inventory plots. In a review of Australian studies undertaken for the NSW Natural Resources Commission, Gibbons and Connolly-O'Donnell (2023) reported that 28% to 57% of trees with visible or apparent hollows measured from the ground contain hollows suitable for occupancy by vertebrate fauna. Studies indicate that all hollows suitable for occupancy by fauna are typically utilised by hollow-dependent fauna (Gibbons and Lindenmayer 2002). Forty-five per cent of trees with at least one visible hollow felled as part of the Pacific Highway upgrade on the north coast of NSW contained evidence of prior occupation by vertebrate fauna (Sandpiper Ecological, unpublished). While hollow-dependent fauna have been observed using trees with hollows as small as 16cm DBH (Goldingay 2009), the probability a hollow-bearing tree is suitable for occupancy by hollow-dependent fauna increases with DBH. In the data obtained from the Pacific Highway upgrade in northern NSW, the smallest living hollow-bearing tree in which vertebrate fauna were observed was 40cm DBH and the proportion of hollow-bearing trees that contained evidence of occupancy by vertebrate fauna increased with DBH (Gibbons and Connolly-O'Donnell 2023). In wet sclerophyll forest in East Gippsland, Victoria, only hollow-bearing trees >140cm DBH had a probability of occupancy >50% (Gibbons, Lindenmayer et al. 2002). Given a large proportion of predicted trees with visible hollows are in the smallest DBH class (10-50cm)—particularly in the net harvest area (Figure 5)—the predicted number of trees with hollows suitable for occupancy by vertebrate fauna is likely to be considerably below the predicted number of trees with visible hollows.

I overcame this issue by developing a model to predict the proportions of trees with at least one visible hollow that are likely to be suitable for occupancy by fauna. As illustrated in Appendix 5, the model used to predict which trees with visible hollows are suitable for occupancy by hollow-dependent fauna had wide confidence limits, and thus the predictions come with a reasonable degree of uncertainty. Thus, improving these models should be a priority if more reliable predictions are sought. There are few existing suitable data sources available for NSW forests that can be used to make these estimates (Gibbons and Connolly-O'Donnell 2023) and therefore the priority should be given to: (a) identifying further unpublished data (e.g., additional data collected from the Pacific Highway Upgrade); and (b) collecting new data to inform these models. This research should be used, in turn, to identify the variables that should be collected in forest inventories for developing improved predictions of trees with hollows that are likely to be suitable for occupancy by vertebrate fauna and guidelines for selecting trees with hollows in the field.

Comparisons with other studies

The simulations indicated that the numbers of trees with visible hollows will, on average, increase over time in ESAs in the study area from a current predicted mean number of approximately 10 per ha to approximately 26 per ha. The latter figure is within the range of the number of trees with visible hollows in relatively unmodified forests in south-eastern Australia (Gibbons and Lindenmayer 2002, McLean, Bradstock et al. 2015).

Simulations indicated that the number of trees with visible hollows and hollows suitable for occupancy by vertebrate fauna will remain stable at 8-10 per ha and 2-3 per ha respectively in the net harvest area over 200 years. Although the tree retention condition and protocol under the Coastal IFOA does not specify that recruitment trees or potential hollow-bearing trees must be retained in addition to existing hollow-bearing trees, simulations from FRAMES indicate that sufficient recruitment occurs to maintain these numbers through time from trees retained for other purposes (e.g., seed trees, retained basal area where Australian Group Selection harvesting is practiced, giant trees).

Other studies have observed (Ross 1999, McLean, Bradstock et al. 2015) or predicted (Gibbons, McElhinny and Lindenmayer 2010) a decline in the number of trees with visible hollows with the number of cutting cycles in forests of eastern Australia. Gibbons et al. (2010), Gibbons et al. (2008) and Le Roux et al. (2014) found that the number of mature trees or hollow-bearing trees perpetuated over the long-term is very sensitive to mortality among older trees in the stand—a common finding for any long-lived organism (Jennings, Reynolds and Mills 1998, Norse, Brooke et al. 2012, Turkalo, Wrege and Wittemyer 2017). In FRAMES, tree mortality is a function of tree size, competition with surrounding trees and locality (Tim Parkes, pers. comm.). Maximum annual mortality rates of approximately 1.5% are applied to trees up to approximately 100cm DBH and maximum mortality rates up to approximately 4% are applied for trees that are 150cm DBH (Figure 8). The mortality estimates employed in FRAMES are based on observations in the long-term permanent growth plot (PGP) network managed by FCNSW between 1970 and 2010 (T. Parkes pers. comm.). Approximately 20% of the plots in this network have a recorded fire event and 4% had a high-severity fire preceding re-assessment and thus the mortality estimates are averaged across stands with different fire histories. However, higher rates of annual mortality or collapse of large and hollow-bearing trees have been recorded in a number of studies immediately after fire. In south-eastern NSW, Gibbons et al. (2000) observed an annual mortality rate of 3-7% among trees in all DBH classes retained in harvested stands treated with a low-intensity slash burn in the Eden region of NSW over 2-5 years. In East Gippsland, Victoria, Bluff (2016) observed that 19% of hollow-bearing trees within the boundary of fuel-reduction burns collapsed within the first year after fire, rising to 27% for hollow-bearing trees that were directly impacted by fire. In northern NSW, Milledge and Soderquist (2022) observed that 11% of trees >60cm DBH and 19% of trees >100cm DBH were killed or collapsed in the year after the 2019 wildfires. Higher rates of collapse than simulated in FRAMES among mature or hollow-bearing trees have also been observed in woodlands, ash-type forests of Victoria and forests in Tasmania (Lindenmayer and Wood 2010, Parnaby, Lunney et al. 2010, Stojanovic, nee Voogdt et al. 2016).

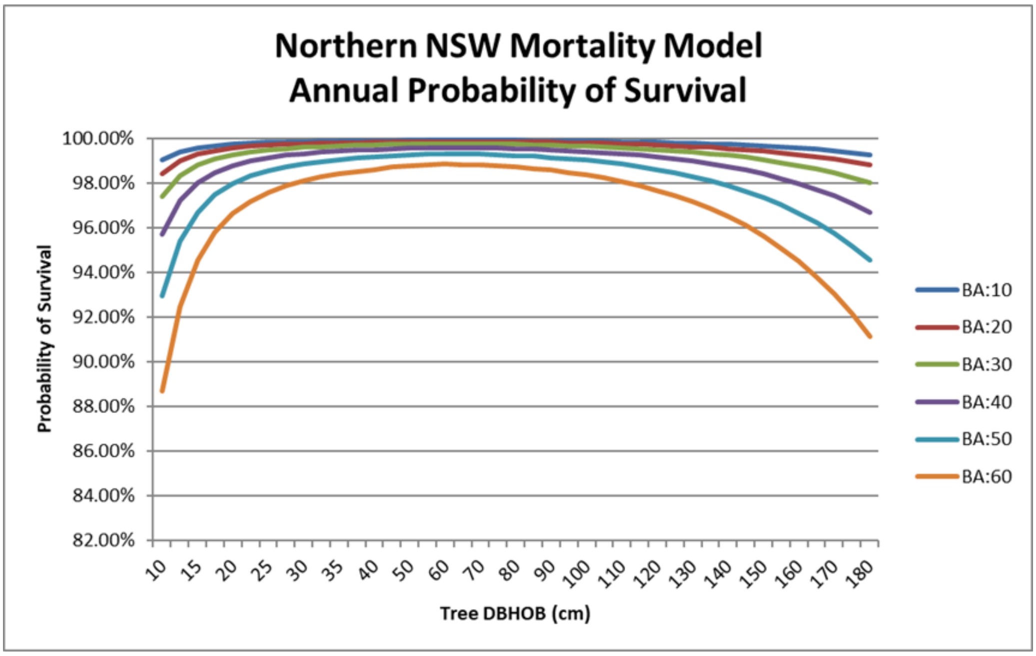

Figure 8. Annual mortality rates applied to trees in FRAMES according to DBH and basal area of the stand (supplied by Tim Parkes FCNSW).

Given a pulse in mortality and/or collapse among hollow-bearing trees has been recorded after fire events, it is recommended that FRAMES be modified so it has the capacity to introduce fires (planned and unplanned) stochastically, and a higher rate of mortality among hollow-bearing trees is associated with these events.

While there is an acceleration in the collapse of hollow-bearing trees after fire, fire is also an agent for hollow creation. Fire can damage or kill trees predisposing them to decay and hollow formation, cause limbs to break thus exposing hollows in decayed heartwood and/or excavate hollows by burning decayed heartwood (Inions, Tanton and Davey 1989, Gibbons and Lindenmayer 2002). Thus, a pulse in mortality and/or collapse among trees after fire could be offset by an increase in the rate at which hollows form in trees. In a study within the IFOA in northern NSW, McLean et al. (2015) observed that the number of trees with hollows was positively associated with the number of fires that had occurred in the stand, but only where the stand did not have a history of intensive harvesting. Refining models predicting the occurrence of hollows in trees to determine if the rate of hollow formation changes with time since last fire, and then incorporating these results into the simulation is therefore recommended.

Definitions of hollow-bearing trees

The definitions of “hollow-bearing tree” used in this study vary from the definition in the IFOA (State of NSW and Environment Protection Authority 2020) and (non-binding) guidance for selecting hollow-bearing trees in the field provided by the NSW Environment Protection Authority (2020) and FCNSW (2021) (Table 3). This makes it difficult to compare or translate predictions from this study to operational practice or validate the predictions in the field. One way to overcome this is to ensure that the same variables for each hollow-bearing tree are recorded or used: (a) in inventory plots measured by FCNSW; (b) in models used within FRAMES to predict how many hollow-bearing trees occur and; (c) when hollow-bearing trees are selected in the field. This suite of variables should include the best predictors of visible hollows and hollows used by vertebrate fauna. Sourcing all suitable data and fitting such a model is a recommendation of this report (see next section).

Table 3. A comparison of definitions of "hollow-bearing tree" used in the IFOA and this study.

IFOA[1]	**FCNSW inventory data used for this study**[2]	**This study**	**This study**	**EPA guidance**[3]	**FCNSW guidance**[4]
A tree that is alive	Living trees	Living trees	Living trees	A tree that is alive	A tree that is alive
Visible hollows	Hollows [likely to be] suitable for animal or bird nesting are visible	Visible hollows [likely to be] suitable for animal or bird nesting occur	Hollows suitable for vertebrate fauna occur	Includes any hollow large enough to be visible	Visible to a ground observer and suitable for providing important shelter habitat to vertebrate species
Clearly inferred hollows in older growth stage tree (in particular senescent tree) with one or more obvious deformities	Trees considered likely to contain hollows (but hollows are not visible)	NA	NA	A deformity associated with a burl, large protuberance or broken limb and a senescent growth stage (late mature or over mature)	Hollows are easily expected, highly likely to occur or unambiguous (additional guidelines are provided) and occur in mature trees where ageing is well-advanced or exacerbated by disease or injury, or occur in senescent trees

[1] State of NSW and Environment Protection Authority (2020)

[2] FCNSW (undated)

[3] NSW Environment Protection Authority (2020)

[4] FCNSW (2021)

Using the results to inform forest management in NSW

I have demonstrated that FRAMES can be used to predict how many trees with visible hollows and trees with hollows suitable for occupancy by vertebrate fauna will be perpetuated over long time-frames under different conditions and protocols specified in the IFOA. With relatively minor changes and some additional analyses, FRAMES can also be used for the following:

1. Simulate any proposed changes to the IFOA on the hollow resource

In this pilot study, FRAMES was employed to simulate numbers of trees with visible hollows and numbers of trees with hollows suitable for occupancy by vertebrate fauna over time under two broad scenarios: no harvesting and harvesting. Thus, changing the area or configuration of harvesting exclusions or the net harvest area can be readily simulated. FRAMES can also be configured to simulate the long-term outcomes of retaining different numbers of hollow-bearing trees and/or recruitment trees within the net harvest area. In addition to changes to the hollow resource, outputs from FRAMES can be used to estimate impacts of these measures on the timber resource.

2. Simulate impacts of changing fire regimes on tree hollows in state forests of NSW

With relatively minor changes, FRAMES can be configured to simulate the effects of fire on the hollow resource. This is relevant given a recent study identified a decrease in the mean interval between wildfires across forested areas of NSW from 69 years in the 1980s to 44 years in the 2010s (Canadell, Meyer et al. 2021) and a study from forests in northern NSW reported a (negative) interaction between fire and harvesting on the number of hollow-bearing trees (McLean, Bradstock et al. 2015). Simulating the effect of fire can be achieved by introducing fires stochastically into the model at different average fire intervals. However, the introduction of fire must be accompanied by the change in mortality and collapse of trees that occurs after fire and the associated change in the rate at which hollows form in trees as discussed previously.

3. Identify variables that should be collected to improve the information base for managing hollow-bearing trees

As indicated previously, higher rates at which trees die and collapse after fire have been reported in the literature than used in FRAMES. Similarly, there is some evidence that hollow formation can be accelerated after fire. Thus, determining rates of mortality and collapse among hollow-bearing trees with time since fire (and fire severity) and the effects of time since fire on the occurrence of hollows from the current inventory data will improve the predictions, particularly if implemented alongside the introduction of stochastic fires within FRAMES.

When predicting which trees contain hollows suitable for occupancy by vertebrate fauna, we are currently constrained by variables recorded in forest inventories undertaken by FCNSW, variables that can be simulated within FRAMES and the availability of data on the types of trees used by hollow-dependent fauna. In a separate study undertaken for the NRC, Gibbons and Connolly-O'Donnell (2023) identified that, in addition to DBH and tree species, the number of visible hollows in a tree (not the presence/absence of hollows) is an additional variable that will improve predictions for which trees contain hollows suitable for occupancy by vertebrate fauna (see recommendation in next section).

4. Spatially map hollow-bearing trees across areas subject to the IFOA.

The predicted numbers of hollow-bearing trees obtained from FRAMES can potentially be mapped spatially (Figure 7). Spatial maps of hollow-bearing trees can be used to calculate area estimates for hollow-bearing trees across NSW and can be used to improve, or spatially enable, species distribution models for hollow-dependent fauna.

Recommendations

FRAMES is a suitable platform to evaluate the effectiveness of the Coastal IFOA for perpetuating hollow-bearing trees and habitat for hollow-dependent fauna. However, I recommend the following before FRAMES is used more broadly to simulate hollow-bearing trees:

- Source all available data on hollow-bearing trees occupied by vertebrate fauna (e.g., any additional data held by Sandpiper Ecological), develop an improved model to predict which trees are suitable for occupancy by vertebrate fauna and incorporate this model into FRAMES as it will provide a better indicator of how many trees suitable for hollow-dependent fauna occur in forests managed under the IFOA.
- Use the above model to identify a common set of variables that is recorded: (a) when selecting hollow-bearing trees for retention; (b) in inventory plots; and (c) is used in FRAMES that can predict which trees contain hollows suitable for occupancy by vertebrate fauna. This will enable

predictions from FRAMES to be more easily verified in the field and translated into operational practice.
- Introduce fires—and the associated mortality and collapse of trees and any change in the rate of hollow formation in existing trees—stochastically into FRAMES as there is some evidence that hollow-bearing trees experience higher rates of mortality after planned and unplanned fires than the mean mortality rates used for large trees in FRAMES and there is evidence that fire may increase the rate at which hollows form in trees. This will allow FRAMES to be used to simulate changing fire regimes in NSW forests.
- Provide predictions for the net harvest area with accompanying covariates such as forest type (or YAG), fire severity of the 2019/20 fires and previous harvest year. This will enable the predictions to be spatially mapped at a more useful spatial resolution for fauna modelling.
- Compare predictions from FRAMES with data collected through a field-based pilot study. This will require data on hollow-bearing trees to be collected in a sample of the net harvest area and areas permanently protected from harvesting, all stratified (if feasible) by the years since last harvest, YAG (or tree species group), 2019 fire severity and the number of harvesting events, as the number of hollow-bearing trees appears to be sensitive to these variables.

By including these changes, FRAMES can be used routinely to simulate conditions and protocols in the IFOA and any proposed changes to it and potentially generate data that can add value to species models predicting the distributions of hollow-dependent fauna.

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Appendices

Appendix 1

Definitions of tree species groups used in FRAMES.

Species_Group_Code	Tree_Species_Code	Species_CommonName
BBT	BBT	Blackbutt
SPG	SPG	Spotted Gum
BBX	BBX	Brush Box
TWD	TWD	Tallowwood
SBG	SBG	Sydney blue Gum/Blue Gum
DUR	BMY	Broadleaved white Mahogany
DUR	GBX	Grey Box
DUR	GIB	Grey Ironbark
DUR	GYG	Grey Gum
DUR	IBK	Ironbark group
DUR	NMY	Narrowleaved white Mahogany
DUR	QBX	Whitetopped Box
DUR	RIB	Mugga Ironbark/Red Ironbark
DUR	SBX	Steel Box
DUR	TRP	Turpentine
DUR	WMY	Mahogany, white (group)
RED	BLW	Bloodwood group
RED	FLG	Flooded Gum
RED	FRG	Forest red Gum
RED	PBW	Pink Bloodwood
RED	RBW	Red Bloodwood
RED	RMY	Red Mahogany
SBK	ASB	Blueleaved Stringybark
SBK	BAN	Bangalay
SBK	BLB	Broad leaved stringybark
SBK	BSB	Brown Stringybark
SBK	CBX	Coast grey Box
SBK	ESB	New England Stringybark
SBK	OSB	Narrowleaved Stringybark
SBK	RSB	Red Stringybark
SBK	SBK	Stringybark group
SBK	STA	Silvertop Ash/Black Ash/Coast Ash
SBK	TSB	Thin leaved stringybark
SBK	WSB	White Stringybark
SBK	YSB	Yellow Stringybark
NEG	BPM	Broadleaved Peppermint
NEG	DSB	Diehard Stringybark
NEG	DWG	White Gum
NEG	EPM	New England Peppermint
NEG	FAS	Brown barrel/Cuttail
NEG	MAG	Manna Gum/Ribbon Gum

NEG	MKG	Monkey Gum/Mtn Grey Gum
NEG	MMT	Messmate
NEG	MTG	Mountain Gum
NEG	NEB	New England Blackbutt
NEG	NPM	Narrowleaved Peppermint
NEG	PPM	Peppermint group
NEG	RLG	Roundleaved Gum
NEG	RPM	River Peppermint
NEG	SCG	Scribbly Gum
NEG	SMY	Swamp Mahogany
NEG	SPM	Sydney Peppermint
NEG	SSB	Silvertop Stringybark
NEG	WHG	Whitegum/Ribbongum
NCO	ABX	Apple Box
NCO	BBW	Brown Bloodwood
NCO	BCP	Black Cypress pine
NCO	BOK	Bull Oak
NCO	BSA	Black Sallee
NCO	BWD	Brushwood group
NCO	CCP	Coast cypress pine
NCO	CWD	Coachwood
NCO	EUC	Eucalyptus spp.
NCO	FOK	Forest Oak
NCO	HPP	Hoop Pine
NCO	KUR	Kurrajong
NCO	MBX	Western grey Box
NCO	MCP	Mallee Cypress pine
NCO	MEL	Paperbark
NCO	NCE	Non-commercial Eucs
NCO	NCO	Non-commercial others
NCO	NSB	Needlebark Stringybark
NCO	OAK	Oak group
NCO	RAP	Roughbarked Apple
NCO	RCD	Red cedar
NCO	RRG	River red Gum
NCO	SAP	Smoothbarked Apple
NCO	SNG	White Sallee/Snow Gum
NCO	TBX	Appletopped Box
NCO	TEA	Tea tree
NCO	TRG	Tumbledown red Gum
NCO	UBX	Rudders Box
NCO	UNK	Unknown species
NCO	WAT	Wattle group
NCO	YBX	Yellow Box

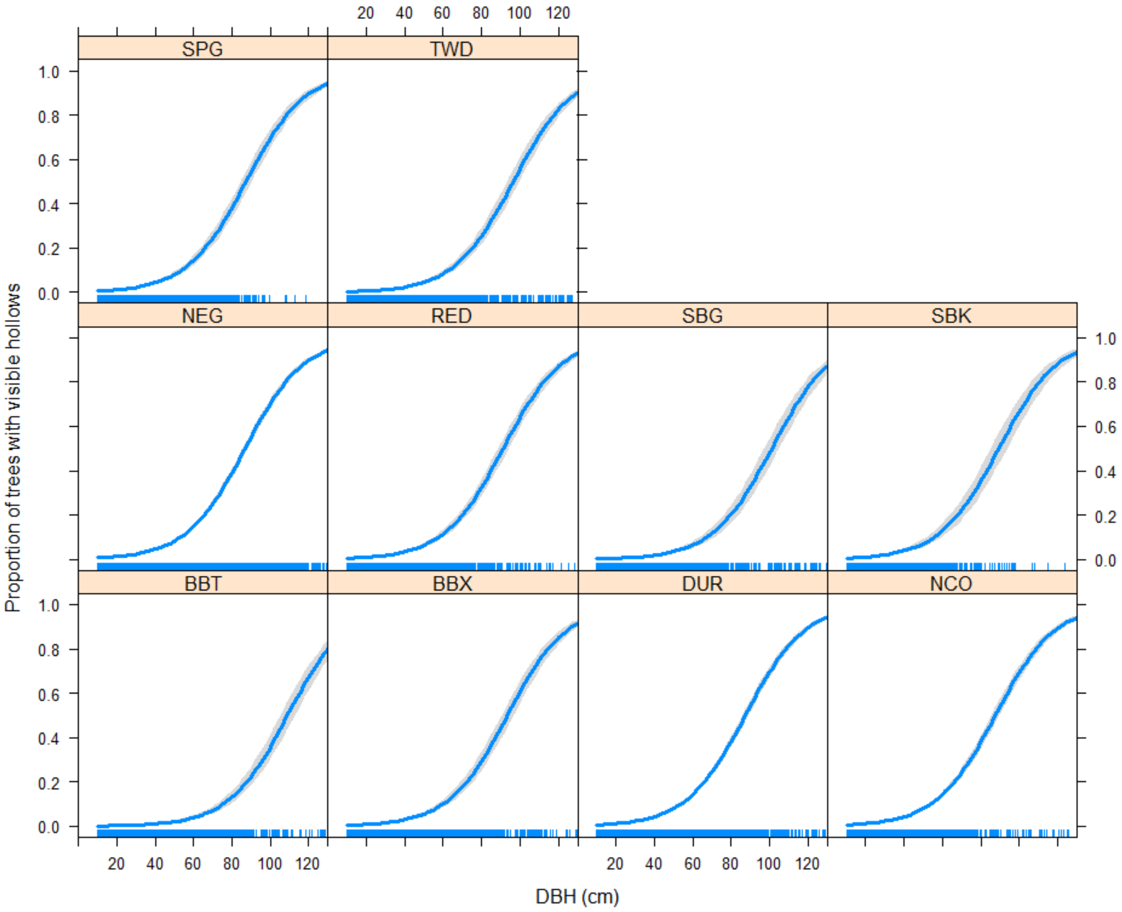
Appendix 2

The logistic regression model used to predict the proportion of trees with at least one visible hollow by DBH and species group. Species groups are defined in Appendix 2.

	Estimate	Std. Error	z value	p-value
(Intercept)	-7.118	0.135	-52.804	< 2e-16
DBHob_cm	0.065	0.001	76.227	< 2e-16
Species_groupBBX	1.012	0.160	6.320	0.000
Species_groupDUR	1.414	0.130	10.861	< 2e-16
Species_groupNCO	1.399	0.135	10.332	< 2e-16
Species_groupNEG	1.450	0.130	11.172	< 2e-16
Species_groupRED	1.156	0.149	7.747	0.000
Species_groupSBG	0.517	0.176	2.946	0.003
Species_groupSBK	1.278	0.185	6.912	0.000
Species_groupSPG	1.414	0.154	9.186	< 2e-16
Species_groupTWD	0.817	0.158	5.166	0.000

Table A3. The logistic regression model used to predict the proportion of trees with at least one visible hollow by DBH (i.e., across all species groups).

	Estimate	Std. Error	z value	p-value
(Intercept)	-5.785	0.042	-136.160	<2e-16
DBHob_cm	0.064	0.001	82.820	<2e-16



Predicted proportions (mean ± 95% confidence interval) of trees with at least one hollow visible from the ground by DBH and tree species group using the model in Table A2. Species groups are defined in Appendix 1.

Appendix 3

Predicted proportions of trees with visible hollows and hollows suitable for occupancy by vertebrate fauna by tree species group (Appendix 1) and DBH class.

Species group	DBH_class	Median DBH (used for prediction)[1]	Proportion of trees with visible hollows[2]	Mean proportion trees with visible hollows occupied by fauna[3]	Standard error[3]	Mean proportion of all trees suitable for occupancy by vertebrate fauna[4]
BBT	10-50cm	17	0.002	0.192	0.117	0.000
BBT	50-70cm	57	0.032	0.257	0.089	0.008
BBT	70-90cm	78	0.117	0.296	0.082	0.035
BBT	90-110cm	98	0.328	0.336	0.090	0.110
BBT	110-130cm	118	0.643	0.378	0.115	0.243
BBT	>130cm	143	0.902	0.434	0.152	0.392
SPG	10-50cm	17	0.010	0.277	0.140	0.003
SPG	50-70cm	57	0.121	0.356	0.095	0.043
SPG	70-90cm	78	0.352	0.402	0.085	0.142
SPG	90-110cm	98	0.667	0.448	0.096	0.299
SPG	110-130cm	118	0.881	0.494	0.123	0.435
SPG	>130cm	143	0.974	0.551	0.158	0.537
BBX	10-50cm	17	0.007	0.115	0.083	0.001
BBX	50-70cm	57	0.084	0.158	0.088	0.013
BBX	70-90cm	78	0.267	0.186	0.098	0.050
BBX	90-110cm	98	0.573	0.216	0.117	0.124
BBX	110-130cm	118	0.832	0.249	0.146	0.207
BBX	>130cm	143	0.962	0.294	0.183	0.283
TWD	10-50cm	17	0.006	0.173	0.129	0.001
TWD	50-70cm	57	0.071	0.233	0.128	0.018
TWD	70-90cm	78	0.230	0.269	0.135	0.068
TWD	90-110cm	98	0.525	0.307	0.151	0.176
TWD	110-130cm	118	0.803	0.348	0.176	0.304
TWD	>130cm	143	0.954	0.402	0.209	0.414
SBG	10-50cm	17	0.010	0.277	0.140	0.003
SBG	50-70cm	57	0.121	0.356	0.095	0.043
SBG	70-90cm	78	0.352	0.402	0.085	0.142
SBG	90-110cm	98	0.667	0.448	0.096	0.299
SBG	110-130cm	118	0.881	0.494	0.123	0.435
SBG	>130cm	143	0.974	0.551	0.158	0.537
DUR	10-50cm	17	0.010	0.115	0.083	0.001
DUR	50-70cm	57	0.121	0.158	0.088	0.019
DUR	70-90cm	78	0.352	0.186	0.098	0.065
DUR	90-110cm	98	0.668	0.216	0.117	0.144
DUR	110-130cm	118	0.881	0.249	0.146	0.219
DUR	>130cm	143	0.974	0.294	0.183	0.287
RED	10-50cm	17	0.008	0.277	0.140	0.002

RED	50-70cm	57	0.096	0.356	0.095	0.034
RED	70-90cm	78	0.296	0.402	0.085	0.119
RED	90-110cm	98	0.608	0.448	0.096	0.272
RED	110-130cm	118	0.851	0.494	0.123	0.420
RED	>130cm	143	0.967	0.551	0.158	0.533
SBK	10-50cm	17	0.009	0.192	0.117	0.002
SBK	50-70cm	57	0.107	0.257	0.089	0.028
SBK	70-90cm	78	0.322	0.296	0.082	0.095
SBK	90-110cm	98	0.637	0.336	0.090	0.214
SBK	110-130cm	118	0.866	0.378	0.115	0.327
SBK	>130cm	143	0.971	0.434	0.152	0.421
NEG	10-50cm	17	0.010	0.277	0.140	0.003
NEG	50-70cm	57	0.125	0.356	0.095	0.045
NEG	70-90cm	78	0.360	0.402	0.085	0.145
NEG	90-110cm	98	0.675	0.448	0.096	0.302
NEG	110-130cm	118	0.885	0.494	0.123	0.437
NEG	>130cm	143	0.975	0.551	0.158	0.538
NCO	10-50cm	17	0.010	0.277	0.140	0.003
NCO	50-70cm	57	0.120	0.356	0.095	0.043
NCO	70-90cm	78	0.349	0.402	0.085	0.140
NCO	90-110cm	98	0.664	0.448	0.096	0.297
NCO	110-130cm	118	0.880	0.494	0.123	0.434
NCO	>130cm	143	0.974	0.551	0.158	0.537

[1] Median DBH values for each species group and DBH class used in FRAMES were taken from n=103,036 trees recorded in 0.1ha plots from the north coast of NSW.

[2] Predictions are based on logistic regression models described in the body of this report developed from n=103,036 trees recorded in 0.1ha plots from the north coast of NSW.

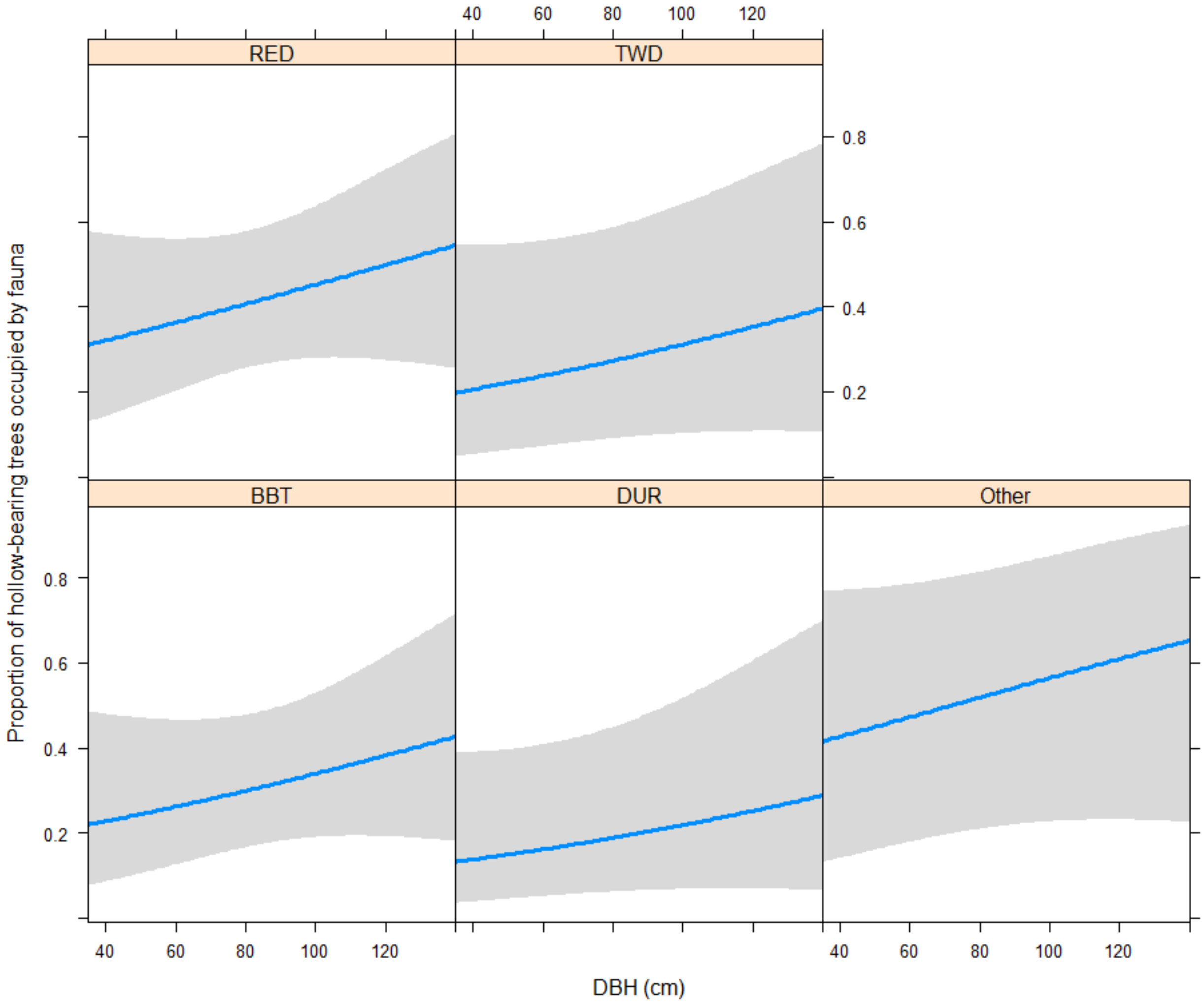
[3] Mean (and standard error) predicted proportions of trees with hollows visible from the ground that were occupied by vertebrate fauna were taken from n=102 hollow-bearing trees that were felled and inspected as described in the main body of this report.

[4] Mean proportions of all trees suitable for occupancy by hollow-dependent fauna were calculated by multiplying the mean proportion of trees with visible hollows x the mean proportion of trees with visible hollows that were occupied by fauna.

Appendix 4

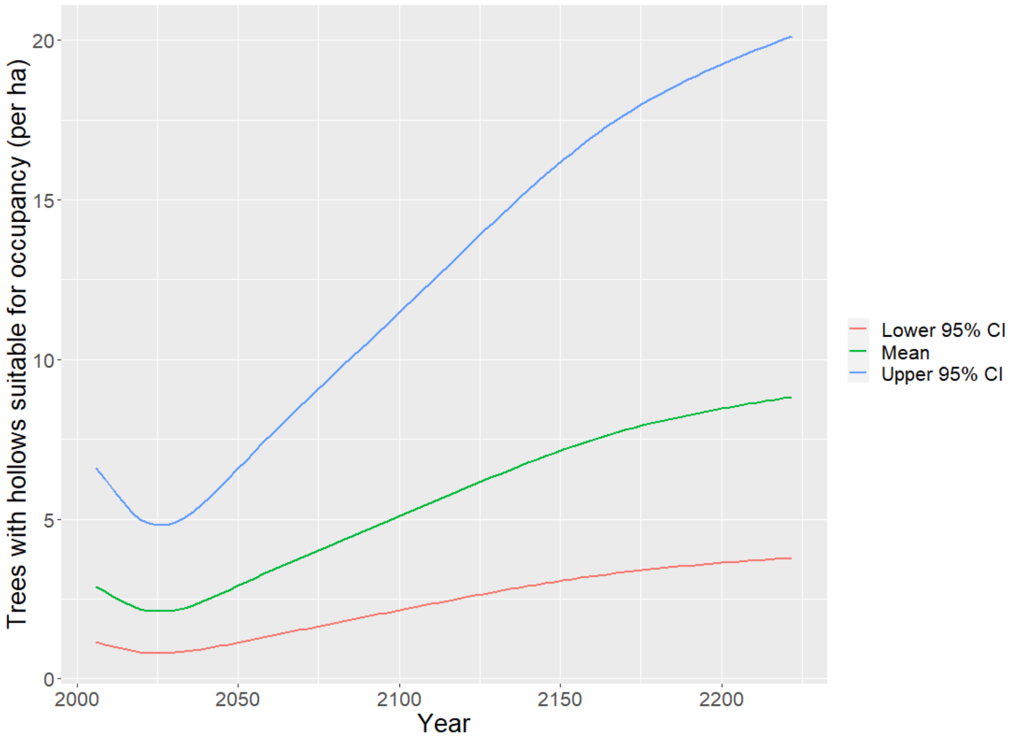
The logistic regression model used to predict the proportion of trees that are suitable for occupancy by vertebrate fauna.

	Estimate	Std. Error	z value	p value
(Intercept)	-1.59179	0.8959	-1.777	0.0756
DBH_cm	0.009273	0.009278	0.999	0.3176
Species_group_codeDUR	-0.60885	0.756633	-0.805	0.421
Species_group_codeOther	0.9256	0.820591	1.128	0.2593
Species_group_codeRED	0.472355	0.520994	0.907	0.3646
Species_group_codeTWD	-0.12962	0.782755	-0.166	0.8685



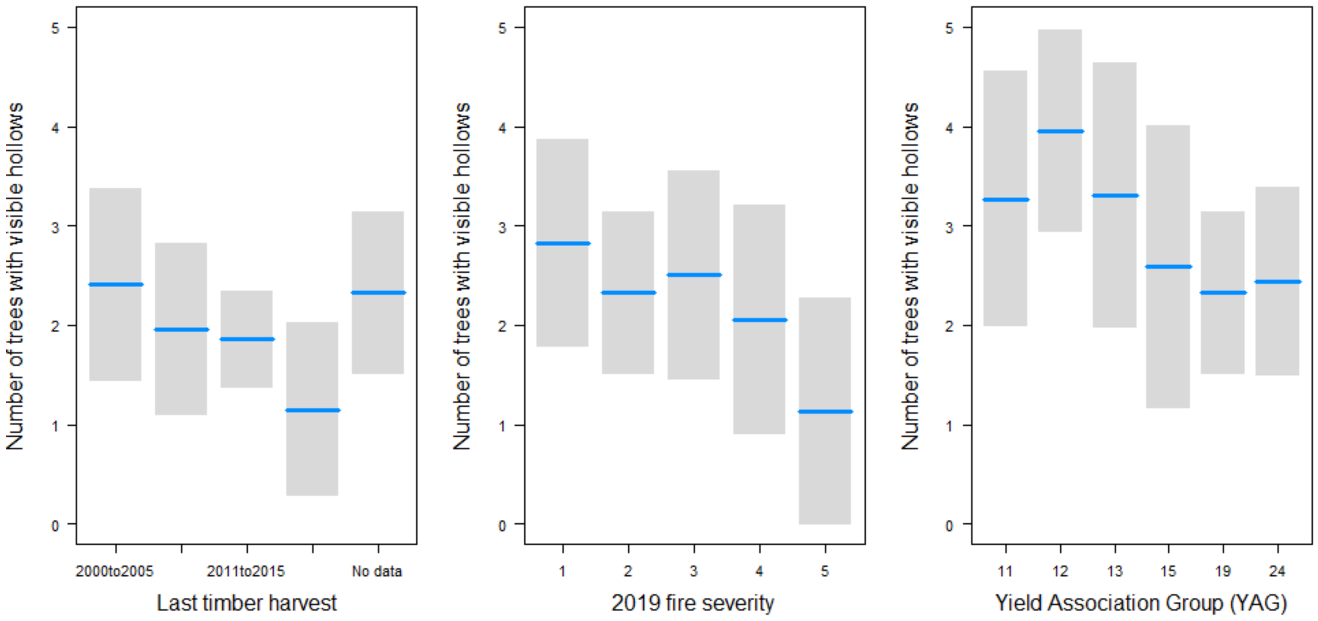
Predicted proportions (mean ± 95% confidence interval) of hollow-bearing trees that are suitable for occupancy by vertebrate fauna. Species groups are defined in Appendix 1.

Appendix 5



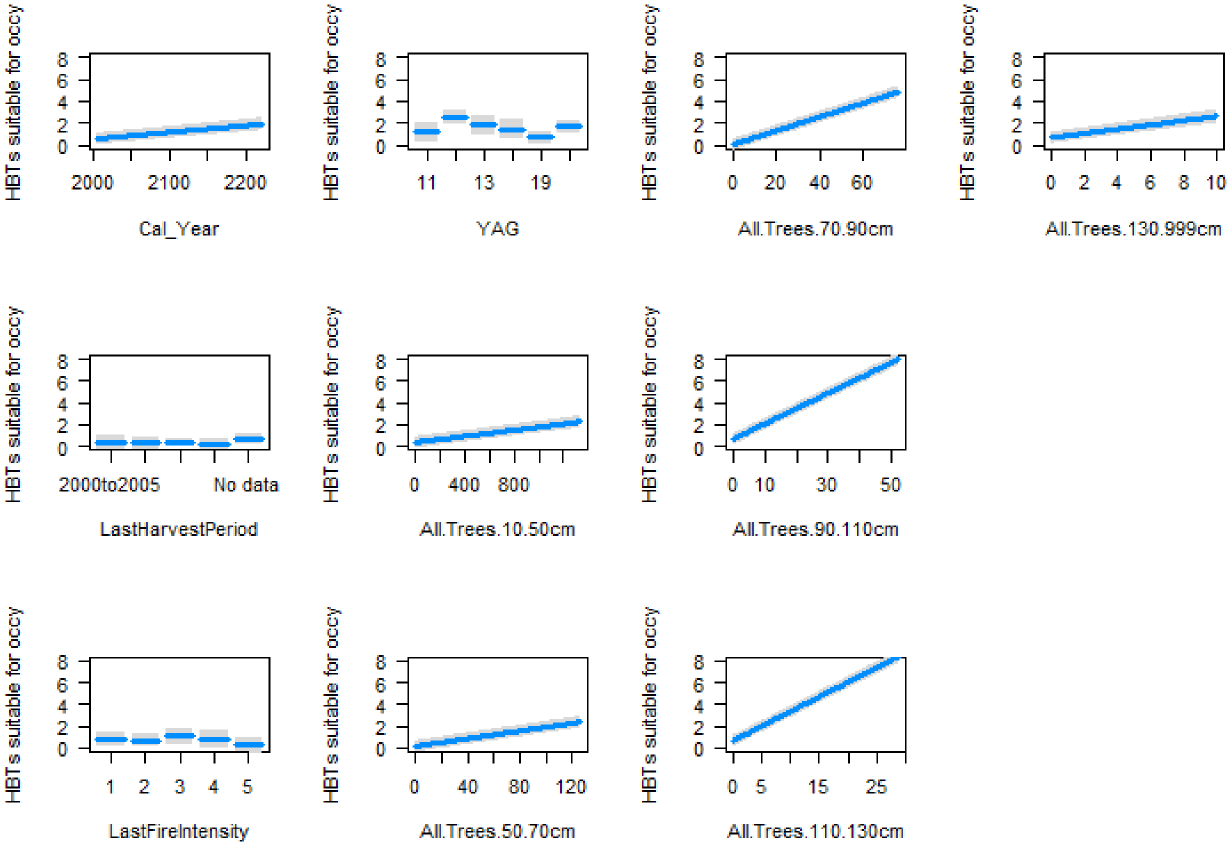
The predicted number of trees with hollows suitable for occupancy by vertebrate fauna for ESAs in the Coffs Harbour Timber Zone based on proportions of trees with hollows suitable for fauna derived from the mean, lower 95% confidence interval and upper 95% confidence interval.

Appendix 6



Variables available spatially for which predictions for the numbers of trees with hollows suitable for occupancy were most sensitive. Predictions are illustrated with the year fixed at 2022.

Appendix 7



Relationships between the predicted mean number of hollow-bearing trees suitable for occupancy and variables in FRAMES for the unharvested scenario (ESAs).