Tasmanian wedge-tailed eagle nest monitoring project 2007–12

Nest site use, timing of breeding, and a review of the nesting habitat model

Amy Koch, Jason Wiersma and Sarah Munks

Hobart

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Glossary

Activity status (nest)**:** Whether a nestling was hatched and raised (to an age of at least four weeks) in a nest or not. Nests containing a nestling were classified as 'successful' and nests without a nestling were classified as 'unsuccessful'.

Active nest: A nest which was known to produce a chick (i.e. be successful) on at least one occasion during this study.

Breeding chronology: The timing of the five breeding phases: courtship; incubation; nestling; fledging; post-nest dependence.

Breeding territory: The area over which a single breeding pair forage in a given breeding season.

Courtship: The first phase of breeding, during which the adults reaffirm pair bonds, commence territorial defence and displays, mate, furbish the nest(s) and prepare to lay eggs.

Disturbance: Any human activity which has or might have a negative impact on the behaviour or reproductive output of wedge-tailed eagles.

Fledging: The time when the fully-feathered nestlings voluntarily first leave the nest.

Incubation: The time period from when the adult starts incubating (sitting on the eggs) until the egg(s) hatch.

Inactive nest: A nest which was surveyed, but not observed to produce a chick during this study. It should be noted that some nests classified as 'inactive' may still be in use some years (e.g. may be maintained).

Maintained: A nest that is visited by an adult bird before or during the breeding season but is not actually used for breeding. These nests show signs of use such as whitewash, green leaves, recently added brown sticks or bark.

Managed (nest): A nest or area subject to forestry activities and current wedge-tailed eagle nest management prescriptions.

Nesting habitat: An area that has qualities suitable for the establishment of a nest by wedge-tailed eagles.

Nest attrition: A decrease in nest quality, mass or form, culminating in nest loss.

Nest loss: Nest attrition is complete, or the nest is destroyed due to collapse or damage of the tree or limb.

Nest success: See Activity status.

Nestling: A chick that cannot yet fly and is confined to the nest.

Not successful (nest): A nest that did not produce a chick in a particular breeding season. This includes nests that were not visited by a breeding adult, and nests that were maintained but no breeding attempt was made or a breeding attempt was made but a chick was not produced.

NVA: The Natural Values Atlas (NVA) is a government database of Tasmanian plant and animal records managed by DPIPWE.

Productivity: Whether at least one nestling was produced in a nest or not.

Post-fledging dependence The time from when the chick first leaves the nest, until the chick is fully independent and not fed by the parents. The dependence period will vary considerably with the hunting skills of the chick, the quality of the territory and availability of prey (Olsen 1995).

Raptor nest database: A subset of data hosted within the NVA, comprised of locality records and observations of known raptor nests.

Recruitment tree: A tree that does not currently contain a nest but is located in an area and has qualities such that it may be suitable for nest establishment in the future.

Semi-natural: areas not subject to forest practices within 1 km of the nest according to GIS information.

Successful: A nest in which at least one nestling was produced.

Whitewash: White faecal matter that can accumulate on and near nests or roosting trees.

Windthrow: Tree collapse due to strong winds.

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Summary

- The Tasmanian wedge-tailed eagle *Aquila audax fleayi* is listed as endangered under state and federal legislation due to a low number of successful breeding pairs, loss and disturbance of breeding habitat, and high mortality due to persecution and human-related accidents. Tasmanian wedge-tailed eagles nest in large old-growth trees and are sensitive to disturbance. Current management in areas covered by the forest practices system includes pre-harvest surveys for nests, establishment of reserves around nests, and restrictions on nearby forestry activities during the core breeding season (which is from the later stages of courtship up until the time when most chicks have fledged). The number of known nests has increased over time, and it has been suggested that this is because disturbed birds abandon existing nests and build new nests in other locations. To help conserve this species it is important to determine if current management is effective in mitigating adverse effects of forestry activities.

- This report summarises the first five years of a project evaluating the effectiveness of current management prescriptions in mitigating adverse effects of activities covered by the forest practices system on the breeding success of Tasmanian wedge-tailed eagles. The results of this project will assist in the ongoing development of management actions. The information in this report addresses the activities outlined in the project description and funding agreement (Appendix A). This project also contributes to recovery action 6.1 detailed in the Recovery Plan for Threatened Eagles (Threatened Species Section 2006).

- A selection of eagle nests has been monitored annually (2007–2012) from a fixed-wing aircraft for the presence of wedge-tailed eagle nestlings. Nest success (i.e. the presence or absence of a nestling(s)) is naturally very variable so it is difficult to determine what factors affect it. This issue was explored using mixed-effects models to relate nest success (n = 145 nests, with one to four successful surveys conducted for each nest during the first four years of the study) to habitat composition and disturbance from forestry activities near the nest. Although overall the models explained little of the variation in the data and had low predictive ability, the results indicated that:

    - The rate of nest success was variable between years.

    - Nests were more likely to be successful if they had been used in the previous breeding season, were at higher altitude, on steeper slopes, in smaller patches of forest (<10 ha = 6 nests; 10-30 ha = 17 nests; > 30 ha = 122 nests) and in areas with greater amounts of agricultural land within 4 km of the nest. The relationship between nest success and smaller patch sizes suggest that the size of nest reserves (10 ha) is adequate. However, nest success was only considered in three broad groups and further study is required to more closely examine whether 10 ha is the optimal reserve size. Other studies have indicated that reserve design is important as well as reserve size. This study did not examine the relationship between reserve design and nest success, but guidelines are provided to forest planners on how to design eagle nest reserves.

  - Nests were more likely to be successful if there was no forestry operation within 1 km of the nest during the 12 months prior to the breeding season. However, this result is confounded by the inclusion of inactive nests. Inactive nests have a greater incidence of forest operations occurring within the 1 km zone, and possibly a greater legacy of being inactive due to their less optimal site location. Examination of the raw data found that nests known to be used in one year were used at a similar rate in the following year regardless of whether a forest operation occurred within 1km of the nest or not. It is uncertain whether the occurrence of forestry operations around inactive nests is preventing future use by breeding birds. Further study is required to assess whether specific activities, which were not adequately sampled in the current study, affect breeding eagles.
  - Overall, the results of this study found **no** evidence that forestry activities conducted under current management prescriptions are having a significant impact on the nest success of wedge-tailed eagles. However there were limitations to this study (e.g. this study was observational not experimental so it is difficult to make strong conclusions on causal effects) and it is recommended that nest success continues to be monitored over time (particularly in relation to specific forest management activities such as aerial activities) and that behavioural research be conducted.

- Management prescriptions require that forestry activities are restricted near eagle nests during the breeding season. To be effective, it is important that the management period coincides with the core breeding season. The timing of various breeding activities in each of the five years of study was estimated from data on nestling age and knowledge of the duration of various aspects of breeding for this species. Nestling age was estimated confidently for between 12 and 34 nestlings in any one breeding season. The results showed that the duration of breeding remains relatively consistent, but the timing can vary between years. It is therefore noted that the management period may need to be extended during some years where breeding activities are later than normal.

- When a proposed forestry operation may contain eagle habitat it is recommended that nest searches are conducted prior to harvesting. Details of the site characteristics and types of trees in which nests are found will help guide nest searches. Given that forestry activities are only restricted near active nests, it would also be useful if forest planners could differentiate between active and inactive nests. To explore these issues ground-based surveys were conducted for 103 eagle nests. The results confirmed the conclusions from previous studies that eagle nests were usually located on moderate slopes (largely 20-35°), on easterly aspects, in large diameter native trees. No significant difference was found between active and inactive nests in terms of physical attributes of the trees.

- In order to determine whether a proposed forest operation may contain eagle nesting habitat, and therefore require a pre-harvest nest search, it is useful to have a spatial model predicting where nests may be located. While a spatial model currently exists, it is based on a small number of nests in eastern Tasmania. A large number of nests have been found since the previous modelling, and modelling techniques have advanced considerably. Therefore the model predicting nesting habitat for the wedge-tailed eagle was reviewed

using data from the NVA. Three models were produced: one for low altitude areas (<850 m), one for high altitude areas (> 700 m) and one for the north-west of the state. In low altitude areas the best predictors were morphological protection index (MPI, i.e. degree of topographic dominance or enclosure), aspect and mature crown density. In areas of high altitude the best predictors were slope, aspect, mature crown density and wind exposure. In the north-west the best predictors were altitude, mature crown density and wind exposure, with a small contribution made by landform. These three revised, regionalised models were found to perform better at locating known nests than two other models. These new models can be used by forest planners to plan more efficient eagle nest searches.

- Current management prescriptions were developed as result of previous research (Mooney and Taylor 1996) and expert opinion. This study suggests that current management of forestry activities is effective at minimising impacts on breeding wedge-tailed eagles and helping ensure nesting success. However, there were limitations to this study and it is important that this or equivalent monitoring is continued. To further increase our understanding of the effectiveness of eagle nest management it is also recommended that future research examine how eagle behaviour changes in relation to disturbance, and that abundance trends in the eagle population are better monitored.

1 General introduction

The Tasmanian wedge-tailed eagle *Aquila audax fleayi* is listed as endangered under state and federal legislation due to a low number of successful breeding pairs, loss and disturbance of breeding habitat, and high mortality due to persecution and human-related accidents (Gaffney & Mooney 1992; Mooney 1997; Mooney & Holdsworth 1991). In more recent years, the total population for Tasmania was variously estimated at 1196–1524 free-flying birds in 457 territories (Mooney 2005) to 1000–1500 birds in 426 breeding territories (Threatened Species Section 2006). A population viability analysis for eagles in north-eastern Tasmania predicted a decline in the eagle population over the next 160 years if unnatural mortality and nest disturbance continue at the rates modelled (5–40% mortality per annum, and identified coupes are harvested on an 80 year rotation with some plantation conversion) (Bekessy et al. 2009). Wedge-tailed eagles are the second most disturbance-prone (when breeding) raptor in Australia (Marchant & Higgins 1993), and the Tasmanian subspecies seems more sensitive than mainland subspecies (Mooney & Holdsworth 1991; Mooney & Taylor 1996). Maintaining a viable wedge-tailed eagle breeding population is an ongoing challenge for land managers.

Wedge-tailed eagles hunt over a wide range of habitats, but nest primarily in old growth trees on sheltered sites in native forests (Mooney & Holdsworth 1991). Wedge-tailed eagle breeding pairs have been known to nest as close as 700 m apart during rabbit plagues on mainland Australia, but active nests are usually 6–12 km (range 3–20 km) apart with nest density varying according to habitat quality (Forest Practices Board 2000; Mooney & Holdsworth 1991; Olsen 1995). Breeding pairs may maintain more than one nest within a territory but only one is used for breeding in any given year. Breeding failure often promotes a change of nest in the next year (Mooney 2005; Mooney & Taylor 1996).

1.1 Management of eagle nests

Current management prescriptions in production forestry areas require that surveys for new nests are conducted in areas containing potential habitat within two years of the operation commencing. A reserve (minimum size 10 ha) must be established around all nests found, regardless of whether the nest has been recently used by breeding birds or not. Guidelines are provided on how reserves should be designed to maximise the protection they provide to eagles (FPA 2006). In addition, forestry activities are restricted within 500m or 1km line-of-sight of active nests during the core breeding season (FPB 2002).

Current management prescriptions have been developed from previous research and expert opinion. The recommended minimum nest reserve size was determined from published data demonstrating that nests in forest patches less than 10 ha in size are less successful than those in larger forest patches (Mooney & Holdsworth 1991). The recommendation for the 500 m / 1km line-of-sight management recommendation was based on recommendations made in the published literature (Mooney & Holdsworth 1991), although the data on which these recommendations were based was not included in the publication. Similarly, the breeding period for wedge-tailed eagles in Tasmania, and the sensitivity of the birds during the breeding season, was published in the literature but the data on which this information is based was not published (Mooney & Holdsworth 1991). Therefore, while the best available

information has been used in developing these prescriptions, it is important that the implementation and effectiveness of management is assessed and monitored over time.

A study looking at the implementation of eagle management prescriptions found that application of eagle nest management was generally of a high standard (although at a slightly lower standard on private land compared to public land) (Mooney 2000). Some of the concerns raised were that delays may occur between locating and reporting nests, that nest searches are critical and it would be useful to have tools to facilitate nest searches, and appropriate search techniques need to be used when conducting nest searches.

Only one published study has examined whether current management of eagle nests in Tasmania is effective. Nests found were classified as ‘undisturbed’ (n = 15), ‘protected’ (n = 22) if at least 8 ha of forest was left around the nest and heavy disturbance had not occurred within 500 m of the nest for more than two consecutive days during the breeding season, and ‘unprotected’ otherwise. Breeding success after disturbance was higher for nests that were protected than those that were unprotected (Mooney & Taylor 1996), indicating the eagle nest management is effective.

Despite the research that has gone in to developing and monitoring eagle nest management, further study is still required. While previous work indicates that 10 ha reserve size and the 500 m/1 km line-of-sight management should effectively minimise disturbance to breeding eagles, further monitoring is required to confirm this conclusion and whether this remains true over time despite changes in industry practices and additional stressors (e.g. variable climate or prey availability). Similarly, in order to be effective management must be applied during the appropriate time period. It is therefore important to confirm the timing of the breeding season and how this varies between years.

Eagle nest management has a considerable impact on the forest industry, by way of planning costs, areas retained for nest protection, and costs associated with changes to planned operations when nests are found during an operation rather than before. Streamlining the planning process where possible will reduce costs to industry, while potentially improving the application of nest management prescriptions. For example, providing tools to help locate eagle nests will reduce the cost of nest surveys and help ensure management prescriptions are applied around these nests. Forestry activities are only restricted around *active* nests during the breeding season, so it would be useful to be able to differentiate between active and inactive nests if possible. Nest reserves are applied regardless of whether the nest is known to be used or not. Examining rates of nest use and re-use over time will provide information on whether long-unused nests are expected to be re-used again in the future if they are managed appropriately.

1.2 Aims of the current study

The overall aim of the current study is to increase our understanding of eagle breeding ecology, and evaluate the effectiveness of current management prescriptions in mitigating any adverse effects of activities covered by the forest practices system on the breeding success of wedge-tailed eagles (Wiersma 2010; Wiersma et al. 2009).

Many different research projects are needed to comprehensively examine the effectiveness of current management. Population trends in particular, but also mortality rates (or survivorship) and recruitment, need to be monitored to examine the cumulative impact of numerous disturbance agents. Studies need to be conducted to determine how disturbing agents influence the behaviour and nest selection of breeding pairs, and whether they continue to be used under current management. To conduct all of these studies was beyond the capacity of the FPA. Consequently, the current research program focussed on issues that were most strongly aligned with the forest practices system.

The specific aims of the study were:

- examine the degree to which known nests are used and re-used over time (Section 2);
- examine the relationship between nest site characteristics (including degree of disturbance and protection measures) and nest productivity (Section 2);
- determine variation in the timing of breeding events between years (Section 3);
- determine if active and inactive nests have different attributes (Section 3);
- review wedge-tailed eagle nesting habitat models (Section 4).

1.3 Study outline and report structure

This study was initiated in 2007. The current report provides an overview and synthesis of the first 5 years of this study.

- **Section 2** reports on modelling that investigates the relationship between attributes of the broader landscape and the production of nestlings in eagle nests. This includes examining the relationship between nest success and the size of the forest patch in which the nest is located, and the occurrence of a forestry operation within 1 and 4 km of the nest.
- **Section 3** provides data on the timing of breeding activities, and the success of nests in relation to attributes of the nest trees.
- **Section 4** outlines a study that uses the raptor nest database to model areas that may contain eagle nests. The product of this study is a map predicting the location of eagle nesting habitat.

2 Relationship between nest success and habitat variables

2.1 Introduction

It is well established that human activities can affect the reproductive success of raptors (e.g. Dennis et al. 2011; Newton 1979). Past research into the effects of disturbance on Tasmanian wedge-tailed eagles has focussed largely on disturbance events in the vicinity of nest sites (Mooney 1988a; Mooney 1997; Mooney & Holdsworth 1991; Mooney & Taylor 1996). While critical, the disturbance at individual nest sites is only one of the factors that may influence breeding success. Factors that influence prey availability and foraging energetics are also important for breeding success. Gathering data on nests and relevant environmental parameters over successive years will help us to understand trends in nest success, and the relationship between land-use, environmental conditions and nest success.

The aim of the current section is to examine if the successful production of a nestling in wedge-tailed eagle nests is related to the habitat or disturbance in the landscape around a nest.

Adult wedge-tailed eagles in territories usually maintain several nests within that territory, but only one of these nests can be used for breeding in a given season. Therefore most eagle nests are not used for breeding in any given year. To establish the location of all nests within a breeding territory can be difficult (and potentially disturbing for the birds). To establish the location of all nests each year for a large number of breeding pairs (sufficient to conduct robust statistical analysis) would be an extremely large undertaking.

Individual nests are at a fixed location. Examining the use or non-use of a random selection of nests over time allows the relationship between nest success and environmental attributes to be modelled for a considerably lower effort. While surveying a random selection of nests means that reproductive rates for particular breeding pairs cannot be determined, the lower survey effort per nest means that more nests can be sampled given limited resources, which will capture a greater diversity of habitats and disturbing agents and have more widely-applicable results.

2.2 Methods

2.2.1 Nest selection and monitoring

Nest sites, located on State forest and private land, were selected from the raptor nest database (DPIW 2007). In 2007 GIS techniques were used to randomly select 80 nests which were located in areas potentially subject to forestry activities and current wedge-tailed eagle nest management prescriptions (referred to as 'managed' nests). A further 80 nests were selected from areas not subject to forest practices within 1 km (referred to as 'semi-natural' nests). GIS techniques and aerial imagery were used to randomly select these 'managed' and 'semi-natural' sites. Of these 160 nests, 76 were not examined because they did not meet their designated management category, they no longer existed, or ground-based data were unavailable. Therefore, 84 nest sites were assessed in the first year of survey (2007–08

breeding season). Of the original 84 nest trees, one had fallen and 22 could not be located in 2008–09. Consequently 61 nests were monitored in 2008–09, and a further 90 nests were selected from the raptor nest database for monitoring in 2009–10. A total of 95 nests were surveyed in 2010–11 and 12 of these had not previously been surveyed. 139 nests were surveyed in 2011–12.

Nests examined were at least 3 km apart, and are assumed to belong to different breeding pairs and therefore be independent. The 3 km threshold was used because this is the minimum known distance between nests from different territories (B. Brown pers. comm.). However it is acknowledged that territories can be larger than 3 km and it is possible that some of the study nests were actually from the same breeding pair. A large proportion of the nests in the raptor nest database were found during surveys conducted as part of the Forest Practices Plan planning process, but for the purposes of this study we assume nests were independent and from a stratified-random population of sites.

The activity status of nests was assessed from a fixed-wing aircraft (usually Cessna 206 or 172) during November of each year of the study, when the nestlings were likely to be 4–6 weeks old and large, white, downy and highly visible (Mooney 1988b). Not all nests could be surveyed each year due to weather conditions, issues with locating the nest, visibility into the nest and the occurrence of adult birds near or on the nest. Overall, 170 nests sites were assessed between one and five times, with 145 nests assessed during the first four years of the study. 47 nests were assessed in 2007–08, 47 in 2008–09, 105 in 2009–10, 104 in 2010–11 and 116 in 2011–12. Nests containing a nestling were classified as 'successful' and nests without a nestling (including nests that were maintained) were classified as 'unsuccessful'.

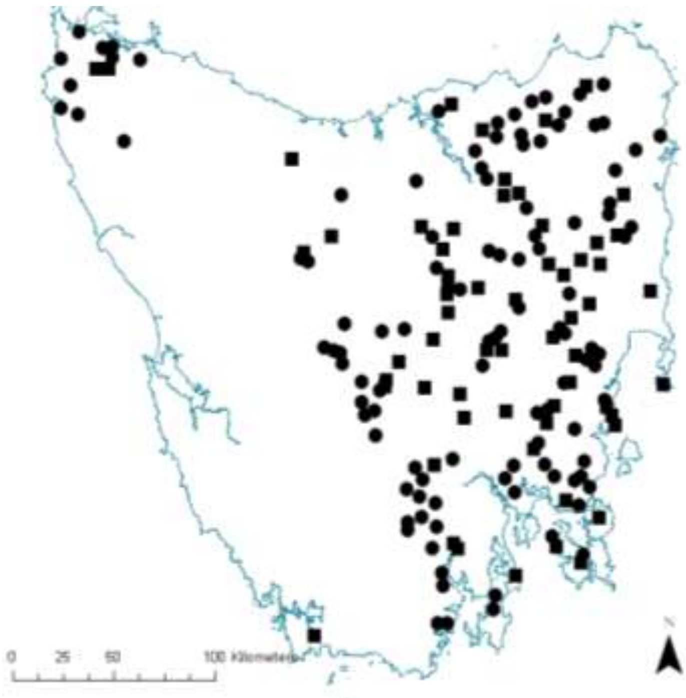


Figure 1. The location of wedge-tailed eagle nest sites included in the current study (circles indicate sites that were never observed with a nestling and squares indicate sites where a nestling was observed at least once). No indication is provided of the number of times each nest was surveyed.

2.2.2 Habitat variables

The attributes of the area surrounding each of the nest trees were determined using GIS techniques in the program ArcMap 10 (ESRI 2010). Variables selected were those thought most likely to influence breeding activity and for which GIS information was available, including a large range of disturbance categories and vegetation covers (see Table 1 for the final variables used). Data were obtained from DPIPWE's Natural Values Atlas (NVA), FPA's databases, and under licence from Forestry Tasmania, Gunns LTD, Private Forests and Norske Skog.

The distributions of all continuous variables were examined. Where required to improve normality, data were log transformed ($\log_e x + 1$), standardized (mean subtracted from the value and the result divided by the standard deviation), square root transformed, or logged and then standardised. Of the initial variables considered, some lacked variability (were highly zero-inflated) and so were removed. Pearsons' correlations among all remaining variables were examined and some variables were excluded if they were strongly correlated with other variables (expert opinion was used to decide which of two correlated variables was to be excluded). Many variables were initially considered at a range of spatial scales, (180 m, 500 m, 1 km, 4 km radius around the nest), but the different spatial scales of a variable were generally highly correlated. Consequently variables were only examined at a 1 km radius as this scale was considered the most relevant to current management. The amount of agricultural land was assessed at a 4 km radius because the 1 km radius was strongly correlated with other variables but the 4 km radius was not. Details of the final 20 variables considered, including any transformations done, are outlined in Table 1.

2.2.3 Data analysis

We analysed data from the first four years of survey using mixed-effects models with a binomial error structure to determine whether a nest supporting a nestling or not was related to any of the habitat or disturbance variables. NestID and Year were included as random effects, but Year was also considered as a fixed effect to determine if nests were more successful in some years than others.

To determine the contribution of the random effects, a full model was fitted that included all random and fixed effects components and the variance components were estimated with restricted maximum likelihood. Each random effect was deleted in turn and the full and reduced models were compared. The change in model deviance was compared to the χ^2 distribution to determine if the random effect made a significant contribution to model fit.

We used forward-stepwise procedures to determine the fixed effects (Table 1) that helped explain nest success, with a decrease in AIC value indicating support for the addition of a variable. No interaction terms were considered due to the large number of variables considered relative to the amount of nest survey data. The modelling was also done using only nest-years for which a result was available in the previous year, and including 'previous success' as an additional variable. Variance components were estimated with maximum likelihood when comparing models with similar random effects but different fixed effects (Crawley 2002).

Wedge-tailed eagles usually maintain several nests within a territory but only one of these nests can produce a nestling in a given year. The nests surveyed in this study were randomly chosen and so some nests may have been classed as unsuccessful because the breeding pair used another nest in their territory in that particular year. To partially account for this the modelling process outlined above was repeated including only ‘active’ nests that were successful at least once during the study (territories known to have a successful breeding pair of eagles). (Note: the number of years of survey varied greatly between nests and so the ability to identify ‘active’ nests was variable).

To test the predictive ability of the models, we re-constructed them without any random effects and without including the variable ‘year’. We used these models to compare the observed and expected success for the 116 nests with monitoring results in 2011–12.

All analyses were conducted in the statistical package R (R Development Core Team 2010) and the mixed-effects models were fitted using the R library ‘lme4’ (Pinheiro & Bates 2000; Bates & Sarkar 2006).

Table 1. Variables used in wedge-tailed eagle habitat modelling, with details of any data transformations done.

Variable	Description	Transformation
Patch size	The size (ha) of the forest patch in which the eagle nest tree was located. This was subjectively estimated by drawing polygons over connected forested areas on Google Earth imagery, and then determining the area of the polygon. The boundaries to the patch include non-forest land, young regenerating forest, plantations and large roads. Where a large patch narrowed considerably and then expanded again, the patch size did not include the narrow bands of forest and areas of forest connected through these narrow bands. For example, if a nest was located in a large intact patch of forest joined by a streamside reserve to another large forest patch, the streamside reserve and second forest patch would not be included in the estimate of patch size. Patch size was reduced to three categories; less than 10 ha (the minimum required size of an eagle reserve), 10–30 ha, or greater than 30 ha.	Log-transformed
Managed	A subjective bi-part classification of land management in a 1km radius around each nest, as determined from Google Earth. Semi-natural: area comprised of intact relatively homogenous forest with no visual indication of harvest disturbance, such as distinct changes in forest age (note: areas of cleared or agricultural land can be located within 1km of a nest classified as ‘semi-natural’). Managed: area contains heterogeneous forest canopy, with adjacent areas showing distinctly different age classes suggesting changes in forest age and potential forestry activities.	-
prevFON1 prevFON4	A bi-part classification of whether a forest operation was recorded within 1 km (prevFON1) or 4 km (prevFON4) of the nest during the twelve month period (June–May) prior to the breeding season. This was established for each breeding season separately. Data were available for public land and for private property managed by large landowners (e.g. Gunns, Norske Skog etc). Gunns data were only available for within 2 km of each nest. No data were available for any small private forest operations that may have occurred. It is assumed that the number of small operations was minimal.	-
bredFON1 bredFON4	A bi-part classification of whether a forest operation was recorded within 1 km (bredFON1) or 4 km (bredFON4) of the nest during the breeding season but prior to the nest check period (June–November). This was established for each breeding season separately. Data were available for public land and for private property managed by large landowners (e.g. Gunns, Norske Skog etc). Gunns data were only available for within the 2 km of each nest. No data were available for any small private forest operations that may have occurred. It is assumed that the number of small operations was minimal.	-
Road1	Total length of road (m) within a 1 km radius around the nest, estimated using ‘the List 2011’ Transport layer as maintained by the Department of Infrastructure, Energy and Resources. This includes all roads, from highways to small unsealed roads.	Square-root transformed
DistEdge	Distance (km) to closest non-native forest land. Non-native forest land were areas classified on the TASVEG 2.0 (2010) layer as ‘agricultural, urban and exotic vegetation’, ‘saltmarsh and wetland’, ‘scrub heathland and coastal complexes’, ‘highland treeless vegetation’, ‘moorland sedgeland rushland and peatland’, ‘native grassland’, ‘other natural environments’.	Log-transformed and standardised
DistMod	Distance to the nearest land classified as ‘agricultural, urban and exotic vegetation’ on the TASVEG 2.0 (2010) layer.	Log-transformed and standardised

DistClearGE	Distance to the nearest modified land (road, agricultural area, plantation, non-forest vegetation etc but not including native forestry) as determined from Google Earth.	Log-transformed
Mature1	Area (ha) within a 1 km radius of each nest tree defined as having a predominantly 'mature or senescing' canopy, as defined in the PI-type growth stage data (Stone 1998).	Square-root transformed
Regrowth1	Area (ha) within a 1 km radius of the nest tree defined as having a predominantly 'young regeneration' or 'regrowth' canopy, as defined in the PI-type growth stage data.	Square-root transformed
Open1	Area (ha) within a 1 km radius of each nest tree classified in the TASVEG 2.0 (2010) layer as 'dry eucalypt forest and woodland' or 'non eucalypt forest and woodland'.	-
Nonforest1	Area (ha) within a 1 km radius of each nest tree classified as 'moorland, sedgeland, rushland and peatland', 'native grassland', 'saltmarsh and wetland', 'scrub, heathland and coastal complexes' or 'highland treeless vegetation' (TASVEG 2.0 2010).	Square-root transformed
Ag4	Area (ha) within a 4 km radius of each nest tree classified in the TASVEG 2.0 (2010) layer as 'agricultural, urban and exotic vegetation', but excluding areas of plantation (i.e. 'plantations for silviculture' and 'plantations unverified'). (Note: unlike the other variables a 4 km radius was used because the 1 km radius was correlated with other variables).	Log-transformed and standardised
Plantation1	Area (ha) within a 1 km radius of each nest tree classified in the TASVEG 2.0 (2010) layer as 'plantations for silviculture' or 'plantations unverified'.	Log-transformed
Altitude	Approximate altitude at nest site (m^{ASL}) as estimated using spline interpolation from Tasmanian 10 m contour data (Tasmap data, DPIPWE).	Standardised
Slope	Approximate slope at nest site (^{o}) extracted from Tasmanian 10 m contour data (Tasmap data, DPIPWE).	-
Aspect	The aspect of the site on which the nest tree is located as extracted from DPIPWE's Tasmap data. Aspect was grouped into classes: 0 = flat; 1 = north-west (292° – 337°); 2 = north or west (249° – 291° or 338° – 22°); 3 = north-east or south-west (23° – 67° or 203° – 248°); 4 = east or south (68° – 112° or 158° – 202°) ; 5 = south-east (113° – 157°) (Nunez 1983).	-
SIMP1 SIMP4	Simpson's diversity index within a 1 km (SIMP1) and 4 km (SIMP4) radius of the nest tree. The area of each different vegetation community is divided by the total land area within the specified radius, the results of which are squared and then summed to provide the index. A low Simpson index value indicates high diversity and a high value indicates low diversity. The area of each vegetation community was determined using TASVEG 2.0, and the vegetation communities considered were: 'agricultural, urban and exotic vegetation', 'dry eucalypt forest and woodland', 'highland treeless vegetation', 'moorland, sedgeland, rushland and peatland', 'native grassland', 'non-eucalypt forest and woodland', 'other natural environments', 'rainforest and related scrub', 'saltmarsh and wetland scrub', 'heathland and coastal complexes', 'wet eucalypt forest and woodland'.	-

2.3 Results

2.3.1 All nests

The proportion of nests surveyed that were observed to have a nestling varied between years (Table 2). No nests were successful in all years, and of the fifteen nests surveyed four times only three were found to support a nestling in three of the four years of surveys (Table 3).

Table 2. The percentage of study nests that produced a nestling over the five breeding seasons surveyed.

Breeding season	Number of nests surveyed	Percentage of nests observed with a nestling
2007–08	47	40%
2008–09	47	9%
2009–10	105	28%
2010–11	104	19%
2011–12	116	17%

Table 3. A summary of nest success in relation to survey effort for data used in the following modelling (first four years of survey).

Number of surveys conducted	Number of years when nests were successful					Total
	Four	Three	Two	One	None	
Four	0	3	3	5	4	15
Three		0	4	8	14	26
Two			8	10	41	59
One				10	35	45

The random effects NestID (χ^2 = 2.3, DF = 28, P = 0.13) and Year (χ^2 = 3.1, DF = 28, P = 0.08) did not contribute significantly to model fit. Year was the most important fixed effect and so was included as a fixed effect rather than a random effect for the results presented. Model selection including Year as a random effect rather than a fixed effect (results not presented) found the same variables were important as indicated below (unless otherwise stated). We examined models with the random effect NestID (Table 5) and without (Figure 2).

The production of a nestling was related to the year of survey, with nests more likely to contain nestlings in 2007 and least likely to in 2008 (Table 5). (Note: the stated year indicates the starting year of the breeding season, so year 2007 indicates the 2007–08 breeding season). Nests were less likely to be successful if a forest operation had occurred within 1km of the nest during the 12 months prior to the breeding season (Table 5, Figure 3, Appendix B). Nests were more likely to be successful if they were at higher altitude (Figure 3), had more agricultural land within 4 km of the nest (Figure 4), were on steeper slopes (Figure 5), and if

they were in smaller patches of forest (Figure 3). However, these variables explain very little of the model deviance (Table 5) and the final model has poor predictive ability (Figure 2).

To explore the issue of forest operations in more detail we examined the raw data. Over the five years of the study, there were 56 instances in which a nest was observed with a nestling in one year and a nest survey result (success or no success) was obtained for the following year. There was no evidence that nests were less likely to be used if a forestry operation occurred in the 12 months prior to breeding when considering nests known to have been successful in the previous breeding season (Table 4a). Forest operations occurred around a greater proportion of inactive nests (nests never observed with a nestling during the study: 57%) than active nests (44%) (Table 4b). (However it should be noted that the level of survey was typically higher for active nests, with 18% of active nests surveyed only once but 42% of inactive nests surveyed only once).

Table 4 a) The number of nests that were known to be successful in one breeding season and a survey result was obtained for the following breeding season, according to whether the nest was successful or not in the second season and whether a forest operation occurred within 1km of the nest in the 12 months prior to the second breeding season.

b) The number of nests according to activity status (active nests were observed with a nestling at some stage during the five years of study and inactive nests were not) and whether a forest operation occurred within 1 km of the nest at some stage during the study.

Activity status for year following a known successful breeding event	Forestry operation		
	No	Yes	Total
Successful	10	9	19
Not successful	21	16	37
Total	31	25	56

Activity status	Forestry operation		
	No	Yes	Total
Active	34	27	61
Inactive	47	62	109
Total	81	89	170

Table 5. Select models for GLMM for nest success. The sign and significance of the coefficient for each variable is indicated in brackets, with '-' indicating a negative coefficient, '+' indicating a positive coefficient, and '*', '**', '*' and '.' indicating *P*-values of <0.001, <0.01, <0.05 and <0.1 respectively. 'ns' indicates *P* > 0.1. N = 301, with 145 nests and 4 years. DEM indicates altitude. The model highlighted in grey is the final model.**

Model #	Variables							ΔAIC	Random NestID VAR	Model deviance	Model deviance (%)
0	-							23.4	1.54	323.5	
1	Year [a]							11.6	2.13	305.7	5.5
2	Year [b]	PrevFON1 (-*)						9.1	1.91	301.2	6.9
3	Year [b]	PrevFON1 (-*)	DEM (+*)					5.4	1.67	295.5	8.7
4	Year [b]	PrevFON1 (-**)	DEM (+**)	Ag4 (+*)				3.3	1.46	291.4	9.9
5	Year [c]	PrevFON1 (-**)	DEM (+**)	Ag4 (+*)	Slope (+.)			1.6	1.39	287.7	11.1
6	Year [c]	PrevFON1 (-**)	DEM (+**)	Ag4 (+*)	Slope (+*)	Patch size [10–30ha] (-ns)	Patch size [>30ha] (-*)	0	1.11	282.1	12.8

[a] Year 2008 (-***), Year 2009 (-ns), Year 2010 (- **)

[b] Year 2008 (-**), Year 2009 (-ns), Year 2010 (- *)

[c] Year 2008 (-**), Year 2009 (-ns), Year 2010 (- .)

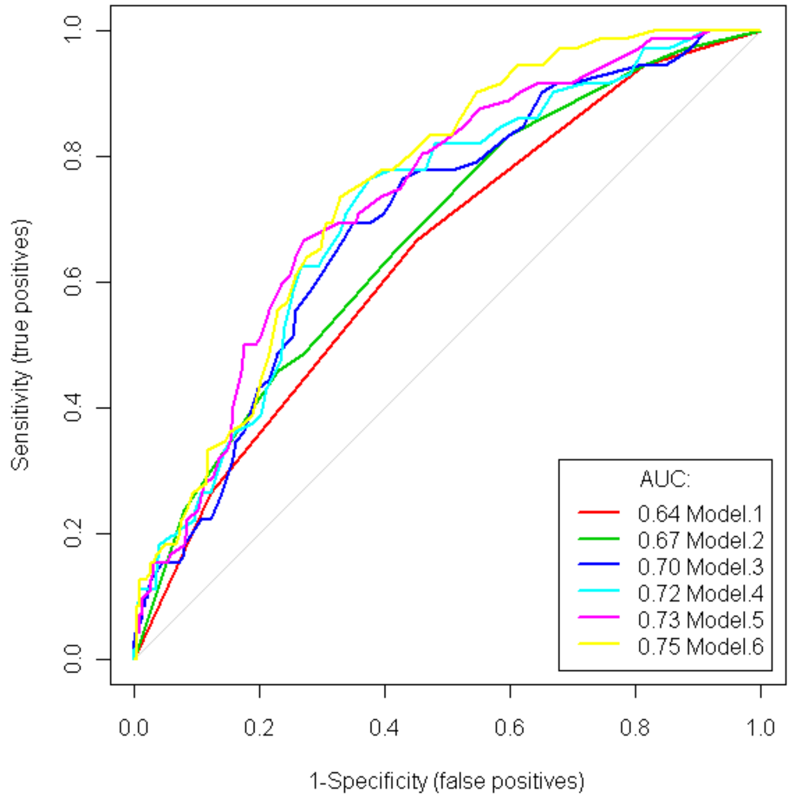


Figure 2. ROC curves for six GLM models examining nest success (i.e. models excluding random factors). ROC curves are a plot of the proportion of positive results that are correctly predicted (sensitivity) against the proportion of negatives that are incorrectly predicted (1 − specificity), as the discrimination threshold is varied. The AUC value indicates the classifier performance of the model and an AUC of 1 indicates perfect predictive ability and an AUC of 0.5 indicates the model is no better than random.

Model 1 = logit(-0.39 – 1.99 × Year2008 – 0.56 × Year 2009 – 1.04 × Year 2010),

Model 2: logit(-0.22 – 1.75 × Year2008 – 0.39 × Year 2009 – 0.85 × Year 2010 – 0.71 × prevFON1),

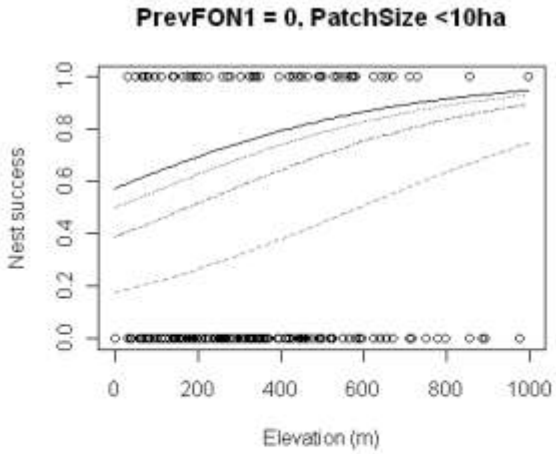
Model 3: logit(-0.14 – 1.73 × Year2008 – 0.33 × Year 2009 – 0.80 × Year 2010 – 0.93 × prevFON1 + 0.42 × ((DEM – 380)/233)),

Model 4: logit(-0.19 – 1.79 × Year2008 – 0.33 × Year 2009 – 0.77 × Year 2010 – 1.00 × prevFON1 + 0.55 × ((DEM – 380)/233) + 0.42 × (((log(Agriculture4 +1) -6)/2)),

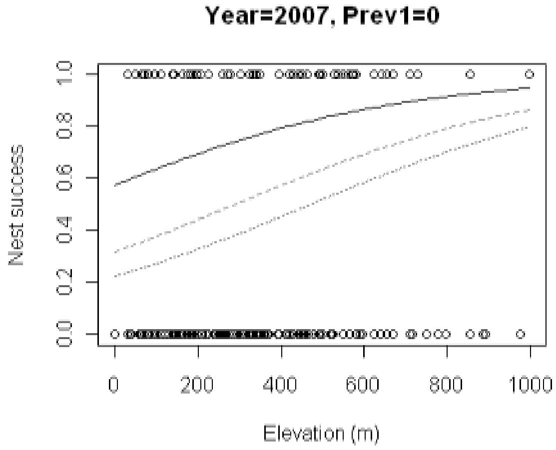
Model 5: logit(-0.93 – 1.82 × Year2008 – 0.29 × Year 2009 – 0.72 × Year 2010 – 0.95 × prevFON1 + 0.52 × ((DEM – 380)/233) + 0.44 × (((log(Agriculture4 +1) -6)/2) + 1.89 × Slope),

Model 6: logit(-0.40 – 1.84 × Year2008 – 0.30 × Year 2009 – 0.75 × Year 2010 – 0.99 × prevFON1 + 0.61 × ((DEM – 380)/233) + 0.48 × (((log(Agriculture4 +1) -6)/2) + 2.07 × Slope – 1.05 × PatchSize[10-30ha] – 1.53 × PatchSize[>30ha]).

a)



b)



c)

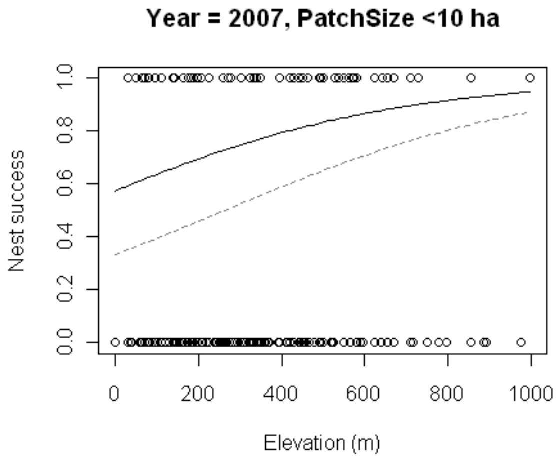


Figure 3. The predicted likelihood that a nestling will be successfully raised in relation to the altitude (m) at the nest site, when the continuous variables in the model are kept at their median value, and the level of two categorical variables is indicated in the figure title while the third categorical variable is varied as indicated by the lines on the graph. The varying variables are:

> **(a) Year (black solid line is 2007–08, grey dashed line is 2008–09, dotted grey line is 2009–10, dashed dark grey line is 2010–11),**
>
> **(b) size of the forest patch in which the nest is found (black solid line is <10 ha, grey dashed line is 10–30 ha and dotted grey line is >30 ha),**
>
> **(c) whether a forest operation occurred within 1 km of the nest in the 12 months prior to the breeding season (black solid line is no forest operation, grey dashed line is a forest operation).**

The raw data are indicated by the circles in the graphs. Model 6: logit(-0.40 – 1.84 × Year2008 – 0.30 × Year 2009 – 0.75 × Year 2010 – 0.99 × prevFON1 + 0.61 × ((DEM – 380)/233) + 0.48 × (((log(Agriculture4 +1) -6)/2) + 2.07 × Slope – 1.05 × PatchSize[10–30ha] – 1.53 × PatchSize[>30ha]).

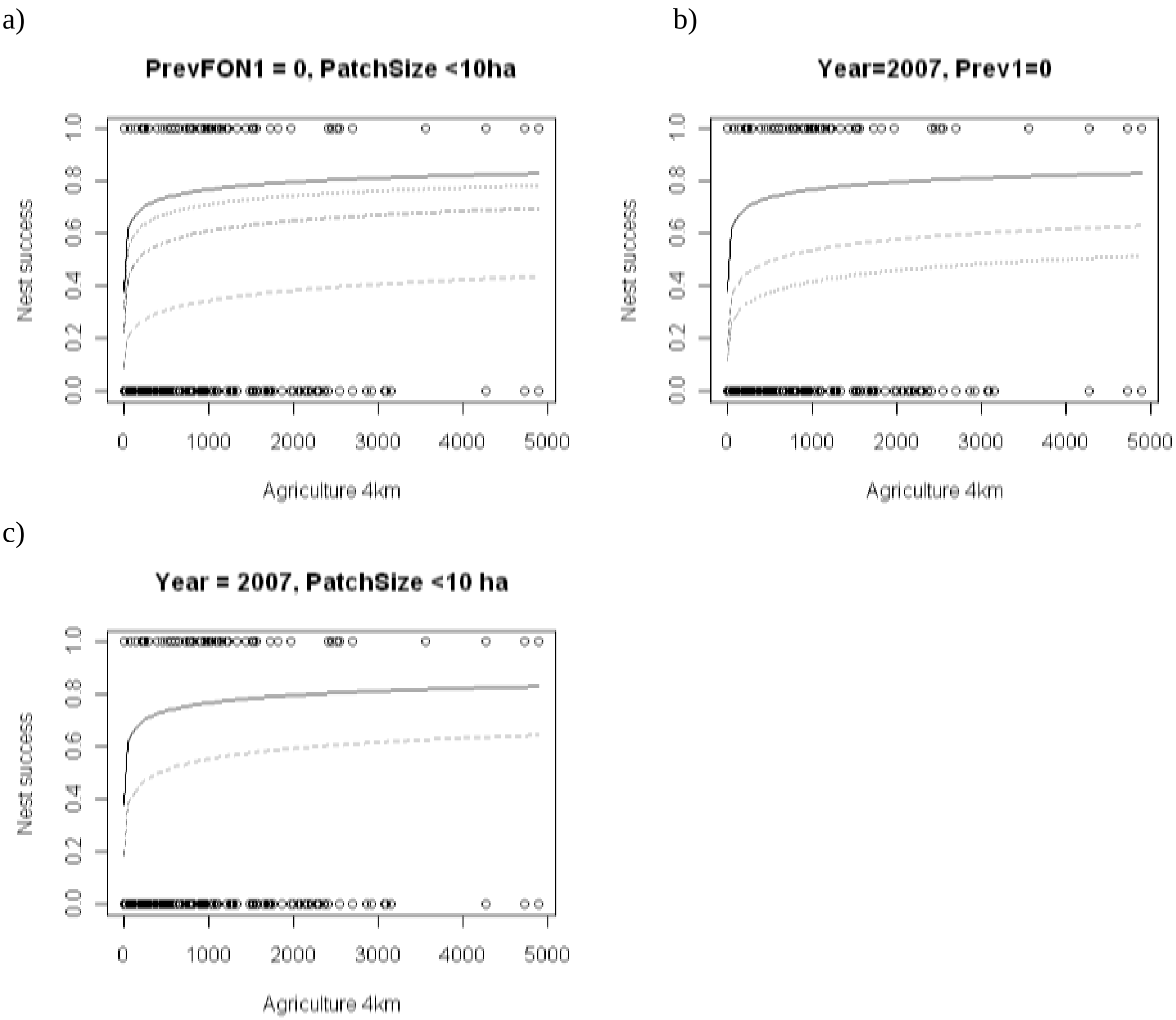
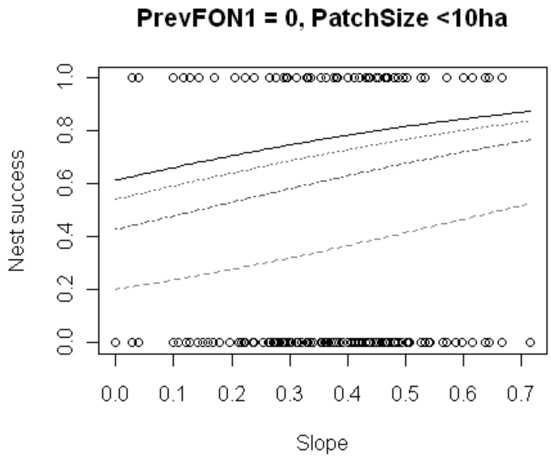


Figure 4. The predicted likelihood that a nestling will be successfully raised in relation to the amount of agricultural land within 4 km of the nest (ha), when the continuous variables in the model are kept at their median value, and the level of two categorical variables is indicated in the figure title while the third categorical variable is varied as indicated by the lines on the graph. The varying variables are:

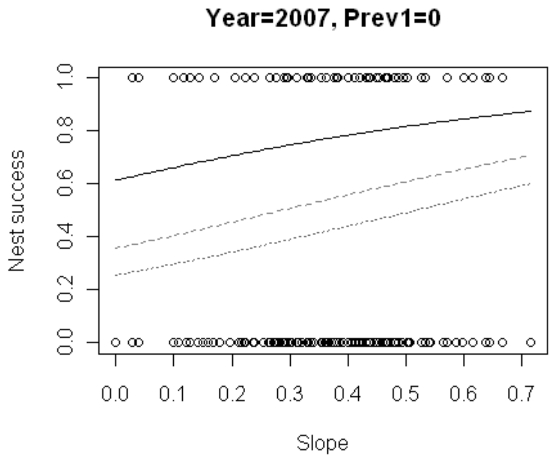
> **(a) Year (black solid line is 2007–08, grey dashed line is 2008–09, dotted grey line is 2009–10, dashed dark grey line is 2010–11),**
>
> **(b) size of the forest patch in which the nest is found (black solid line is <10 ha, grey dashed line is 10–30 ha and dotted grey line is >30 ha),**
>
> **(c) whether a forest operation occurred within 1 km of the nest in the 12 months prior to the breeding season (black solid line is no forest operation, grey dashed line is a forest operation).**

It should be noted that the shape of the curve is related to the transformation done on the agricultural data to meet model assumptions and no other model structures were used. Therefore while the model indicates an increase in likelihood of nest success with amount of agricultural land, it is uncertain if there is a threshold above/below which this is not the case. The raw data are indicated by the circles in the graphs. Model 6: logit(-0.40 – 1.84 × Year2008 – 0.30 × Year 2009 – 0.75 × Year 2010 – 0.99 × prevFON1 + 0.61 × ((DEM – 380)/233) + 0.48 × (((log(Agriculture4 +1) -6)/2) + 2.07 × Slope – 1.05 × PatchSize[10–30ha] – 1.53 × PatchSize[>30ha]).

a)



b)



c)

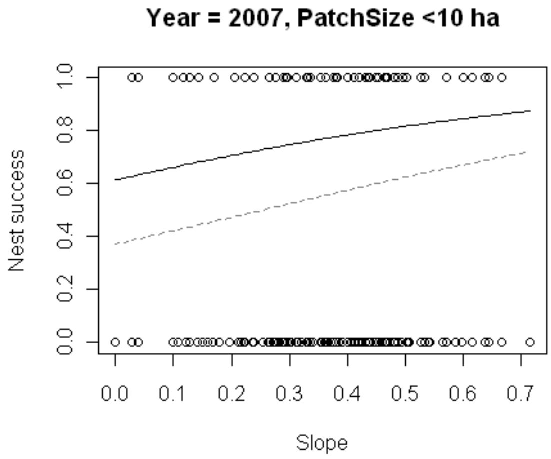


Figure 5. The predicted likelihood that a nestling will be successfully raised in relation to the slope (radians) at the nest site, when the continuous variables in the model are kept at their median value, and the level of two categorical variables is indicated in the figure title while the third categorical variable is varied as indicated by the lines on the graph. The varying variables are:

> **(a) Year (black solid line is 2007–08, grey dashed line is 2008–09, dotted grey line is 2009–10, dashed dark grey line is 2010–11),**
>
> **(b) size of the forest patch in which the nest is found (black solid line is <10 ha, grey dashed line is 10–30 ha and dotted grey line is >30 ha),**
>
> **(c) whether a forest operation occurred within 1km of the nest in the 12 months prior to the breeding season (black solid line is no forest operation, grey dashed line is a forest operation).**

The raw data are indicated by the circles in the graphs. Model 6: logit(-0.40 – 1.84 × Year2008 – 0.30 × Year 2009 – 0.75 × Year 2010 – 0.99 × prevFON1 + 0.61 × ((DEM – 380)/233) + 0.48 × (((log(Agriculture4 +1) -6)/2) + 2.07 × Slope – 1.05 × PatchSize[10–30ha] – 1.53 × PatchSize[>30ha]).

2.3.2 Previous use

There were 142 nest-years (i.e. survey result for a particular nest in a particular year) for which nest success data were collected and the nest had been surveyed in the previous year. For these nest-years the model showed that nests were more likely to be successful if they had produced a nestling in the previous year. Nests were less likely to be successful in the 2008–09 season (2007–08 season data were not available as this was the first year of survey), and more likely to be successful if they were further from modified land and there was less mature forest within 1km (Table 6). If year was not included as a variable then the best model included only previous success (Model 1).

Table 6. Select models for GLMMs for nest success. The sign and significant of the coefficient for each variable is indicated in brackets, with '-' indicating a negative coefficient, '+' indicating a positive coefficient, and '*', '**', '*' and '.' indicating *P* values of <0.001, <0.01, <0.05 and <0.1 respectively. 'ns' indicates *P* > 0.1. N = 142, with 94 nests and 3 years. The model highlighted in grey is the final model selected because all variables are significant.**

Model #	Variables	ΔAIC	Random NestID VAR	Random Year VAR	Model deviance	Model deviance (%)
0	-	15	0.42	0.19	148.0	
1	PrevSuc (+**)	7.6	<0.001	0.78	138.6	6.4
2	PrevSuc (+***) Year [a]	3	<0.001	<0.001	130	12.2
3.1	PrevSuc (+***) Year [a] DistMod (+.)	2	<0.001	<0.001	127	14.2
3.2	PrevSuc (+***) Year [b] Regrowth (+.)	2	<0.001	<0.001	127	14.2
4	PrevSuc (+***) Year [b] DistMod (+*) Mature1 (-*)	0	<0.001	<0.001	123	16.9
5.1	PrevSuc (+**) Year [b] DistMod (+**) Mature1 (-*) Ag4 (+ns)	-0.5	<0.001	<0.001	120.5	18.6
5.2	PrevSuc (+***) Year [b] DistMod (+*) Mature1 (-*) Slope (+ns)	-0.5	<0.001	<0.001	120.5	18.6
6	PrevSuc (+**) Year [a] DistMod (+**) Mature1 (-*) Slope (+.) Ag4 (+ns)	-1.6	<0.001	<0.001	117.4	20.7

[a] Year 2009 (+**),Year 2010 (+ns)

[b] Year 2009 (+**),Year 2010 (+.)

2.3.3 Nests that were successful at least once during the study

Of the 145 nests surveyed at some point during the first four years of the study, 51 produced a nestling on at least one occasion. Of these 51 nests, nestlings were more likely to be produced in some years than others (2007 and 2009 were the better years) and nests at higher altitudes produced nestlings more regularly (Table 7). No other variables were related to nest success for these 51 nests.

Table 7. Model selection for GLMMs examining the factors related to nest success when using only nests that were successful at least once during the study. The sign and significant of the coefficient for each variable is indicated in brackets, with '-' indicating a negative coefficient, '+' indicating a positive coefficient, and '*', '**', '*' and '.' indicating *P* values of <0.001, <0.01, <0.05 and <0.1 respectively. 'ns' indicates *P* > 0.1. N = 126, with 51 nests and 4 years. The model highlighted in grey is the final model selected.**

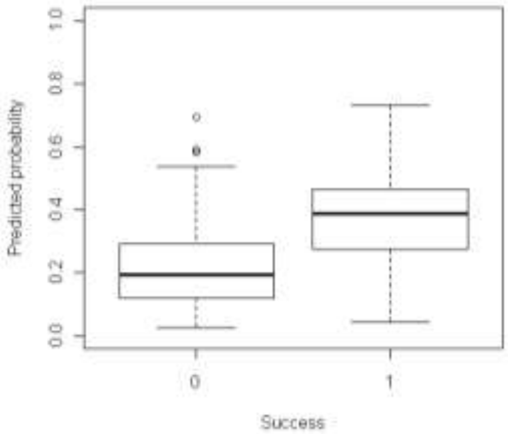
Model #	Variables		ΔAIC	Random NestID VAR	Random Year VAR	Model deviance	Model deviance (%)
0	-		9.7	<0.01	0.87	160.7	
1	Year [a]		4.2	<0.01	<0.01	149.2	7.2
2	Year [a]	Altitude (+*)	0	<0.01	<0.01	143.0	11.0

[a] Year 2008 (-***), Year 2009 (-ns), Year 2010 (- *)

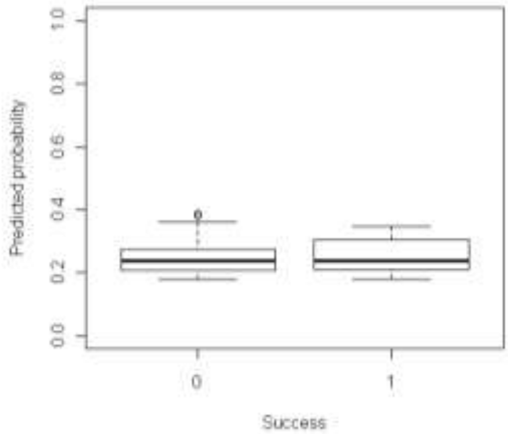
2.3.4 Predictions

The models above were used to make predictions to compare with the actual results observed for 2011. The model using all nests (the complete data set, Table 5) best identified nests likely to be successful (Figure 6a). These results indicate that this model has some predictive ability, but has low precision. The other models (previous use and nests used at least once during the study, Table 6 and Table 7) have no predictive ability (Figure 6b and c).

a)



b)



c)

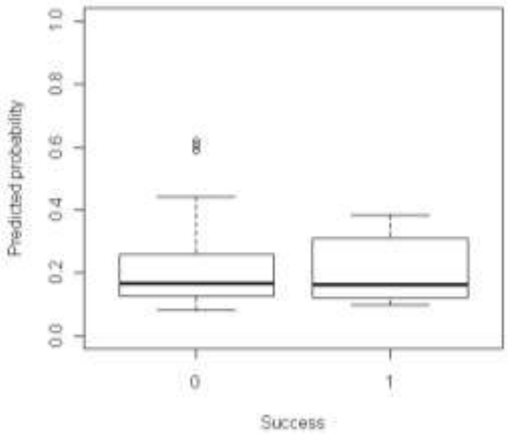


Figure 6. The observed versus predicted presence of a nestling in a nest using the 2011 data (N = 116). For observed success, '1' indicates a nestling was produced and '0' indicates no nestling was observed. On the y-axis a probability of '1' indicates a nestling is highly likely to be observed and a probability of '0' indicates a nestling is highly unlikely to be observed. The predictive models excluded year and had no random effects. The box length is the interquartile range and the circles are outliers.

a) **logit(-0.16 –1.12 × prevFON1 + 0.59 × ((DEM – 380)/233) + 0.45 × (((log(Agriculture4 +1) -6)/2) + 2.05 × Slope – 0.94 × PatchSize[10–30ha] – 1.46 × PatchSize[>30ha]). N = 116.**

b) **logit(-1.14 +0.26 × ((DEM – 380)/233)). N = 116.**

c) **logit(-0.84 –1.08 × prevSuc[1] + 0.49 × ((DistMod – 0.6)/0.4) – 0.07 × sqrt(Mature1). N = 83.**

2.4 Discussion

2.4.1 Rates of nest success

Rates of nest success found during this study were highly variable between years, with no indication of an increasing or decreasing trend (see Appendix C for a summary of other studies examining rates of nest success). The most successful year for eagle nest productivity was 2007–08, followed by 2009–10. The least successful year was 2008–09. Nest use and success can vary with a range of attributes, including prey availability (McIntyre & Schmidt 2012) and climatic conditions (Bionda & Brambilla 2012). A subjective examination of climatic data (annual temperature and rainfall) suggests that the breeding season was warmer than average in 2007 (and to a lesser degree in 2009, Figure 7). Warmer conditions could affect the abundance or activity of prey species, or the amount of food available may be influenced by other activities (e.g. pest management). Further study is required to determine how climatic conditions relate to the nest success of wedge-tailed eagles.

Nest use was variable. Many nests were never observed with a nestling during the study (some of these were maintained, but not used for breeding). Nests were more likely to support a nestling if they had been used the previous year, with up to three consecutive successful breeding attempts observed. Many nests were successful in some years but not others, including nests that produced nestlings in alternate years and nests where a successful breeding attempt preceded or followed several unsuccessful years. These results suggest that nests vary in how important they are for breeding eagles, but also that a lack of use during one or two breeding seasons does not mean that a nest will not be used in the future by breeding eagles.

Lack of nest success in our study cannot be used to infer the breeding success of a nesting pair. Breeding pairs maintain several nests and we did not survey all nests within a territory. When nests were not successful it is uncertain whether alternative nests were used within the territory, or if the birds made no breeding attempt that particular year. It has been proposed that wedge-tailed eagles are physically capable of breeding in numerous consecutive years (Olsen 2005), but it is thought that they do not generally breed every year (Mooney & Holdsworth 1991). A study examining the success of 16 territories (i.e. each with multiple nests) between 1983 and 1989 found rates of breeding success were consistent across years, with approximately half of territories being successful in any given year (Mooney & Holdsworth 1991).

2.4.2 Nest success and landscape composition

Nest use is likely to be correlated with nest success but the current study cannot differentiate between factors that are associated with a failed breeding attempt and those where an attempt was not made. The landscape variables related to nest success were altitude, slope, and amount of agricultural land. Altitude and slope are two of the variables that influence where Tasmanian wedge-tailed eagles are likely to construct nests (Chapter 4, Brown & Mooney 1997) and potentially relate to how protected a nest is from the wind, how well the birds can access the nest, and the ability for birds to detect predators and territorial intruders (Speiser & Bosakowski 1988). (Note: nests at higher altitudes and on steeper slopes were no more likely to have a forest

operation nearby than other nests, Figure 31). Steeper slopes may also mean flight energetics are more favourable for large soaring raptors (Speiser & Bosakowski 1988). A study on golden eagles in Alaska found that altitude did not influence nest success, but that nesting territories at higher altitudes exhibited slightly higher probabilities of occupancy (McIntyre and Schmidt 2012). The positive relationship between nest success and amount of agricultural land may relate to foraging opportunities, with birds preferring more heterogeneous landscapes. It is also possible that birds using areas with a lot of agricultural activity may be less sensitive to disturbance than those found in largely forested landscapes. However, it should be noted that further study is required to ascertain the ‘optimal’ amount of agricultural land around an eagle nest for maximising nest success. Only one model structure was examined in the current study, and so it is uncertain if there is an amount of agricultural land above or below which there is no benefit to eagles, or at which breeding success declines. More study is also required to determine the degree to which individuals are sensitive to disturbance.

The current study found that nests were more likely to be successful if they were in smaller patches of forest than larger patches. This is in contrast to a study conducted by Mooney and Holdsworth (1991) which showed that nests were less likely to be used if they were in smaller patches of oldgrowth forest (< 10 ha). In the current study only six nests were in patches of forest smaller than 10 ha, which is the minimum patch size for a nest reserve as recommended by the Forest Practices Authority. (Patch size data were taken from Google Earth imagery, and the quality and amount of imagery for each nest was highly variable. Therefore patch size data are approximate only and the accuracy of the data will vary greatly between nests and these results should be interpreted with caution). Of these six nests in patches of forest < 10 ha, two were in formal reserves, one was in state forest and three were on private land. Two of these nests did not have nestlings at any stage during the study. Of the four nests in small patches that were observed with a nestling on at least one occasion, three were located in very sheltered sites and all are subject to the 1km line-of-sight exclusion zone during the breeding season (FPA 2006). For these particular nests a reserve slightly smaller than 10 ha may have been adequate due to the topography of the area (J. Wiersma pers. comm.). Tasmanian wedge-tailed eagles vary considerably in their tolerance of disturbance (Brown pers. comm.; Olsen 2005) and by chance these four nests could be used by birds that are more resilient to disturbance. Alternatively the importance of small patches may be explained by the proximity of small remnant patches of forest to areas of open and productive land (e.g. agricultural land) where prey availability and accessibility may be higher than in other landscapes. Being closer to these areas means the energetic cost of transporting prey is less. The current modelling found that nests were more successful if they had more agricultural land within the home range. Regardless of why nests in smaller patches were modelled as having greater success than nests in larger patches, this result supports earlier conclusions (Mooney & Taylor 1996) that the current 10 ha reserve size is adequate for minimising the impact of forest operations on breeding eagles given adjunct conservation measures are undertaken. However patch size was examined in three broad categories (<10 ha, 10-30 ha, >30ha) which limits the sensitivity of this analysis for assessing the adequacy of a 10 ha reserve. To assess this issue in greater detail (i.e. examine if the optimal reserve size is just slightly larger or smaller than 10 ha), future nest surveys would need to target nests located in forest patches between 5 and 20 ha in size.

2.4.3 Nest success and disturbance

The number of known wedge-tailed eagle nests has increased considerably in the last 12 years (DPIPWE, NVA). It has been proposed that current management practices are causing birds to move from established nests more frequently than would occur without human disturbance (B. Brown pers. comm.), with forestry known to impact breeding birds if not managed appropriately (Mooney & Holdsworth 1991). The current study found that nest success was lower if a forest operation occurred within 1 km of a nest site *during the 12 months prior* to the breeding season. The occurrence of a forest operation *during the breeding season* was not found to influence nest success, potentially indicating that current management during the breeding season is effective, or disturbance affects future breeding attempts rather than current ones. To try and better understand how forestry operations affect nest success we qualitatively examined the type, timing and duration of disturbance in relation to nest success (Appendix B). The required level of information was not available for all operations, and no formal analysis was conducted and so strong conclusions cannot be drawn. Nevertheless, the data showed no strong influence of harvesting operations on nest success (Figure 32). Burning and aerial operations appeared slightly more likely to influence nest success (although sample sizes were relatively low), with these operations occurring more around April–May than other times of the year (Figure 33, Figure 34). The data also suggests that the occurrence of a forest operation within 1 km during the breeding season may influence future nesting attempts more than current nesting attempts (Figure 35). Finally, the data suggests that the longer the duration of the disturbance, the less likely a nestling will be produced (Figure 39), supporting work done by Mooney and Holdsworth (1991) who found that disturbance has a cumulative effect.

There is some indication that operations occurring during the previous breeding season may have the biggest impact (Figure 35). The majority of forest operations involve harvesting (Figure 30), but the monthly results (Appendix B, Figure 35, Figure 36) also potentially suggest that other forest operations have a greater impact on nest success than harvest operations alone. Almost no burning occurs during the breeding season (Figure 30). However, aerial spraying of plantations for pesticides, herbicides and fertilisers does occur during the breeding season (Figure 30). (Not all of the operations classified as 'aerial' will have been conducted by air, but it was not possible to completely differentiate between aerial and ground work for the current study). Survey of nests using small, fixed-wing aircraft has been described as the best combination of efficiency and low-disturbance for Tasmanian wedge-tailed eagles (Mooney 1988b).The theory is that eagles perceive aircraft as competitors. If a breeding bird displays aggressively and the aircraft leaves immediately (as occurs during nest surveys), then this may be seen as a successful territory defence. During industry operations the aircraft may remain in the area for extended periods which may cause greater stress to the birds. Furthermore, the majority of industry aerial operations are done by helicopter while nest breeding surveys are done by light plane, and helicopters have been shown to have a greater disturbance impact on raptors than light aircraft (Andersen et al. 1989; Watson 1993). Further study is required to determine if industry aerial operations near nests reduce the chance of nest success in future breeding seasons.

While the data in Appendix B suggests forest operations may have a slight impact on the breeding success of Tasmanian wedge-tailed eagles, there is little evidence at the nest-level that forestry activities are reducing breeding success (unless an inactive nest is actually a failed attempt to breed!). Of the 37 instances where a nest was successful in one year and not in the following, 43% had a forestry operation within 1km during the 12 months prior to the second breeding season. Of the instances where a nest was successful in one year and again in the following year (n = 19), 47% had a forestry operation within 1 km. The hypothesis that forest operations are reducing breeding success is not supported by the higher occurrence of forest operations around nests that had successive use than did not have successive use.

The results found in this study may be confounded by a higher incidence of forest operations around inactive nests. During the 5 years of monitoring, a slightly higher proportion of inactive nests (57%) had a forest operation nearby than active nests (44%). The higher incidence of operations around inactive nests may be promoted by current management which prescribes that forest operations should not occur during 500 m or 1 km line-of-sight of active nests, but they are permissible around inactive nests. Including inactive nests (that have more forestry activities around them) in the modelling may have resulted in forest operations being identified as an explanatory factor even if there was no causal relationship. When this modelling was repeated using only nests that were active at some stage during the study, forest operations did not affect nest activity. Therefore, there is no strong evidence that the occurrence of forestry operations under current species management restrictions is reducing the breeding success of active nests. It is recommended that further study is conducted, including continued nest monitoring and behavioural research, to confirm this result.

Although there is little evidence to suggest that forestry operations reduce breeding attempts of nests that have been recently used for breeding, it is uncertain whether the occurrence of forestry operations discourages birds from using currently inactive nests. Nests that were not successful in one year were more likely to be successful in the following year if there was no forest operation (Table 8). Further study is required to determine whether forestry activities around currently inactive nests mean nests are more likely to remain inactive.

Table 8. The percentage of all nest-years that were successful in producing a nestling in relation to the occurrence of a forest operation in the 12 months prior to the breeding season, and in relation to nest success in the previous year. Sample sizes are indicated.

	No previous forest operation	Previous forest operation
Nest successful in previous year	32% (n = 31)	36% (n = 25)
Nest not successful in previous year	20% (n = 83)	11% (n = 87)

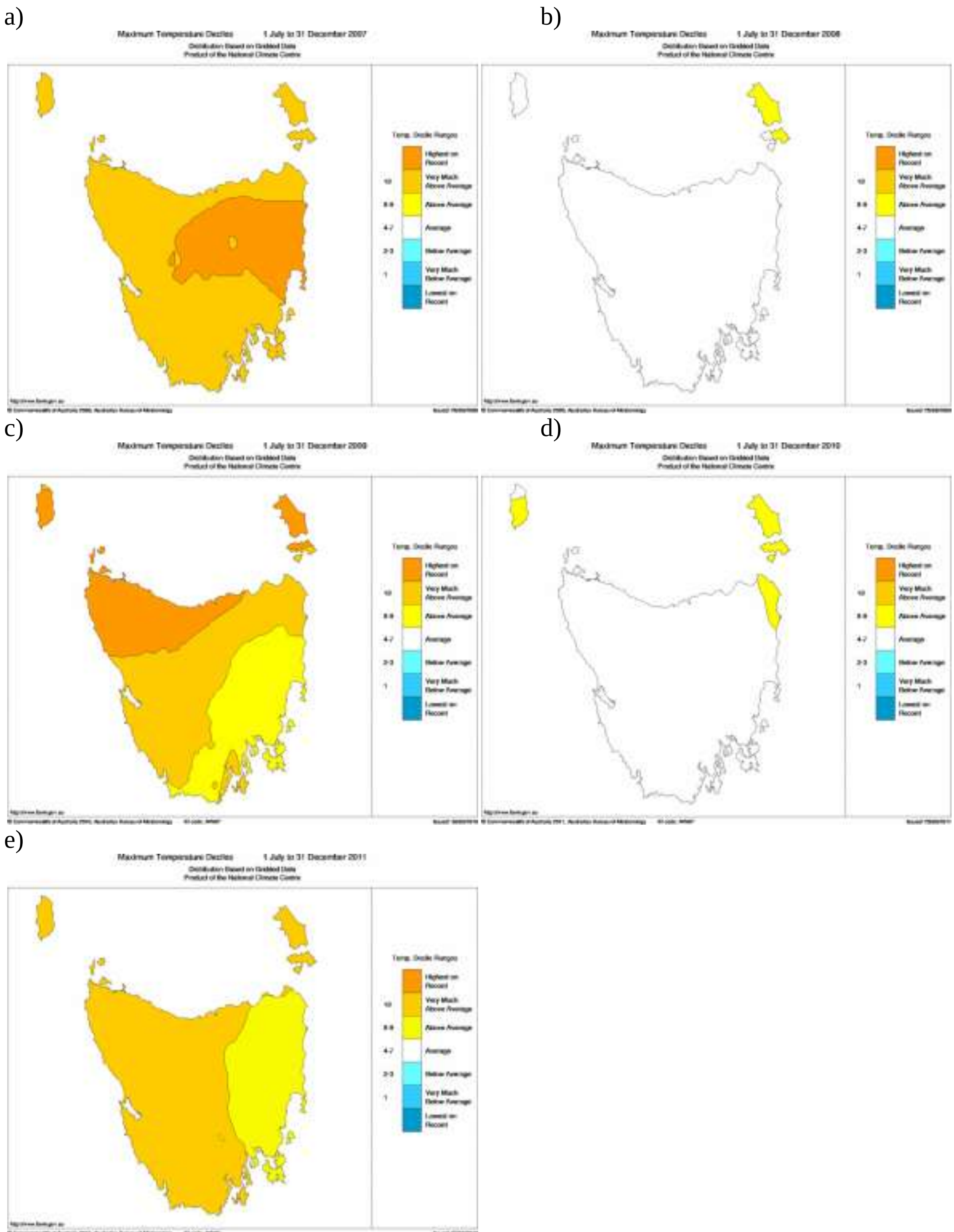


Figure 7. The maximum temperatures during six months of the breeding season in relation to the long-term average in (a) 2007, (b) 2008, (c) 2009, (d) 2010 and (e) 2011. Data obtained from the Bureau of Meteorology.

2.4.4 Management implications

Current management of eagle nests entails retaining a minimum 10 ha reserve around the nest site, and applying restrictions on activities within 500 m or 1km line-of-site from the nest during the breeding season (FPB 2002). These management prescriptions were based on recommendations made from previous research on the breeding success of eagles in relation to disturbing activities (Mooney & Holdsworth 1991). We found that nest success was greater in smaller reserves, with all except six nests being located in patches of forest greater than 10 hectares. Therefore the results of the current study support earlier findings (Mooney & Taylor 1996) that the size of nest reserves is adequate if reserves are designed appropriately (to maximize shelter from prevailing winds, see FPA 2006) and other adjunct conservation requirements are followed. The results of this study also confirm the need to manage inactive nests, because as has been found in other areas (Kochert & Steenhof 2012), nests can be re-used even after many years of inactivity.

The results also appear to suggest that current management of forestry operations near active nests is effective at minimizing disturbance to birds that have committed to breeding. However, there is some uncertainty around this conclusion and it is recommended that monitoring continue into the long-term so it can be more clearly ascertained how usage patterns of particular nests vary in relation to disturbing activities. In particular, future work needs to consider further how the type, duration and timing of disturbing activities affect wedge-tailed eagles. It is also important that the monitoring continue to help determine whether industry activities around inactive nests are reducing the likelihood that these nests will be used in the future.

3 Nest site use and timing of breeding

3.1 Introduction

The Tasmanian wedge-tailed eagle is a forest-dependant breeder. Courtship generally commences in June when eagles can be seen displaying and carrying sticks to refurbish nests. Breeding pairs usually maintain several nests in large, old native trees (Mooney & Holdsworth 1991; Olsen 2005). The large nest platforms are the focal points of eagle territories, irrespective of whether nests are used each year for breeding (Mooney 2000; Mooney & Holdsworth 1991; Olsen 2005; Wiersma et al. 2009). Both adults incubate the one or two eggs that are laid, but more time is spent on the nest by the female while the male is the primary hunter. After the nestlings hatch they spend about 12 weeks on the nest before they fledge. Nestlings are dependent on the adults for a period after fledging and some can even be seen with adults the following breeding season (Brown pers. comm.). Once fledged, it is estimated that approximately 60% of young die before reaching breeding age (Olsen 2005). Males of the mainland subspecies reach sexual maturity at about five years and females at four years (Olsen 2005) and it is assumed the same applies to the Tasmanian subspecies.

Eagles usually maintain several nests within a territory and most pairs do not breed every year so most eagle nests are not used for breeding in any given year. Nests found to be inactive in a particular breeding season may be never used by breeding birds, or may not be used in that particular breeding season but will be used in later years. Eagles are known to be sensitive to disturbance during the breeding season, and can abandon or change nests as a result of disturbance (Mooney & Taylor 1996). It is therefore important to get an understanding of the factors that influence the use and re-use of a particular nest, and to ensure that the timing of management activities coincides with the timing of eagle breeding.

The specific aims of the current section are:

- Determine the timing and duration of breeding events for each year of study and examine whether this varies between years.
- Examine the characteristics of the trees in which eagle nests are found.

3.2 Methods

3.2.1 Breeding chronology

The age of wedge-tailed eagle nestlings can be estimated from their size, colour and covering of down or feathers (Debus et al. 2007). Nestlings can be aged from direct observation, or from photographs (e.g. as sent in by forest planners). For all nests with a nestling that could be aged with confidence (irrespective of the data source), the timing of four distinct breeding phases were extrapolated using known developmental periods (Table 9). Graphs of the breeding chronology are presented for each breeding season during the study.

Table 9. The four phases of breeding recognised in the current study, and the expected duration of each phase

Breeding phase	Description	Duration
Courtship	Adults furbishing nests and preparing to lay eggs.	Estimated at 6 weeks (Wiersma pers. obs.).
Incubation	The time from when the egg(s) are laid and the adult starts incubating the eggs, until the egg is hatched.	Estimated at 43–45 days (6.4 weeks) (Debus et al. 2007).
Nestling	The time from when the egg hatches, until the nestling is fully feathered and leaves the nest for the first time.	Estimated at 12 weeks (Debus et al. 2007; Olsen 1995).
Post-fledging dependence	The time from when the nestling first leaves the nest, until the nestling is fully independent and not fed by the parents. The nest dependence period can be expected to vary considerably with the hunting skills of the nestling, the quality of the territory and availability of prey (Olsen 1995).	Highly variable but estimated at 6 weeks (Mooney and Wiersma, pers. obs.).

3.2.2 Nest tree attributes

Between 2007 and 2011, 103 trees were surveyed from the ground (Figure 8). The nests, trees and surrounding area were surveyed for a range of attributes, as per Table 10. Summary data are provided for the attributes of the nest trees and surrounding area.

Between 2007 and 2012, a selection of nests were surveyed from a fixed-wing aircraft for the presence of nestlings (see Section 2). Surveys were conducted during the end of November or start of December when the nestlings were likely to be 4–6 weeks old and large, white, downy and highly visible.

A total of 84 nests had data for both tree and site attributes and the activity status for the nest in at least one year (Figure 8). To determine if active nests (those that produced a nestling in at least one breeding season) differed in site and tree level attributes from nests not known to be active (i.e. were surveyed but never observed to produce a nestling), we conducted a series of tests. Chi-square tests were used for categorical attributes. Kruskal-Wallis tests were used for continuous variables due to the unbalanced sample sizes. Results were considered significant at $P = 0.05$ and analyses were conducted using the statistical program R.

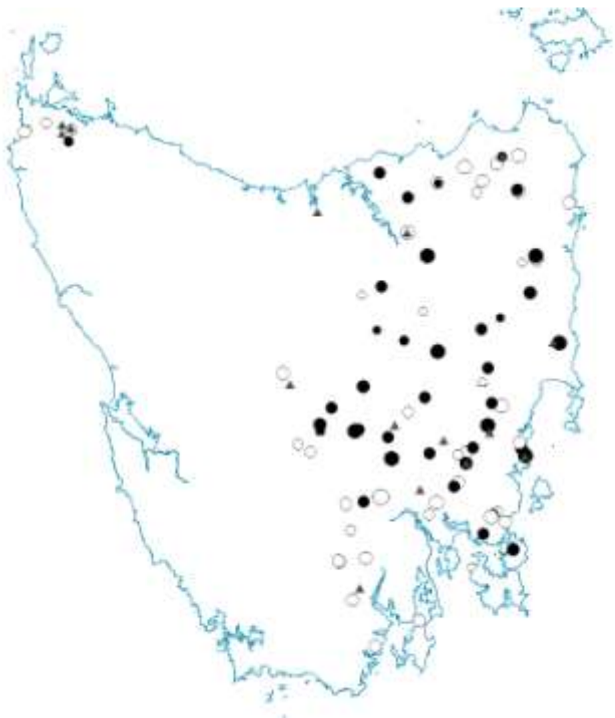


Figure 8. Location of nests around Tasmania, with circles indicating nests included in aerial surveys and triangles indicating nests not included in aerial surveys. For the nests included in the aerial surveys, black circles indicate the nest was active (i.e. successful on at least one occasion, n = 38) and black circles indicate that the nest was inactive (i.e. was surveyed but never observed with a nestling, n = 46). The size of the circles indicates the number of aerial surveys conducted, with larger circles having been surveyed more times. (Note: 3 of the 103 trees surveyed were not included in this figure because no locality data were available).

Table 10. Nest tree and site attributes

Attribute	Details
Floristic community	The classification of the forest immediately surrounding the nest tree as a wet or dry forest type, according to the FPA Forest Botany Manual (Forest Practices Authority 2005).
Forest type	Forest type as determined from the TasVeg mapping layer, classified as: wet forest, dry forest, plantation, scrub/non-forest, non-eucalypt forest.
Basal area	The basal area of the forest surrounding the nest tree, as estimated from three locations using a factor 4 Basal Wedge.
Slope	The slope of the site (°) on which the nest tree was located, as measured using a clinometer.
Aspect	The aspect directly downslope from the nest tree, as measured from a compass in magnetic degrees.
Tree species	The species of tree in which the nest was found.
Crown senescence	An estimate of the percentage of the crown volume that is comprised of dead branches.

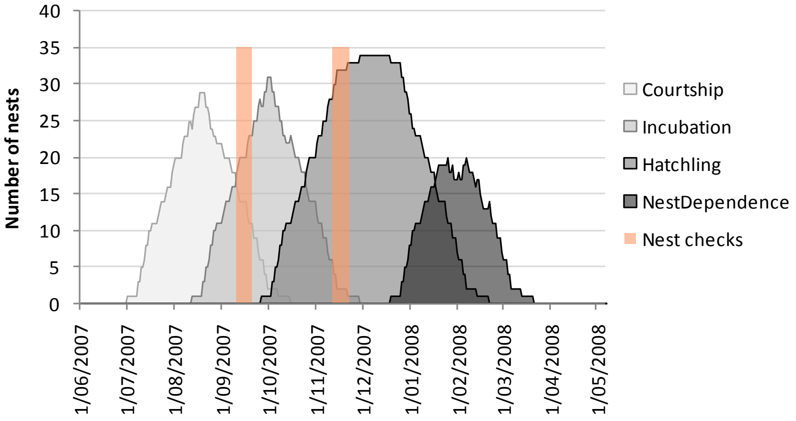
Attribute	Details
Fire damage category	The amount of fire damage observed on the nest tree using the following categories: 1) None visible. 2) Charcoal on the trunk. 3) Fire scarring, where the bark has burnt off and wood is exposed. 4) The base of the tree has burnt through and is hollow.
Nest tree diameter	The diameter at breast height (dbh) of the nest tree, as measured in centimetres using a diameter tape.
Nest tree height	The height of the nest tree (m) as determined by a laser rangefinder (most cases), or visually estimated when the rangefinder could not be used due to visual obstruction.
Nest height above ground	The height of the nest above the ground (m) as determined by a laser rangefinder.
Nest height as proportion of tree height	The height of the nest above the ground as a proportion of the total height of the nest tree.
Nest location	The location of the nest in the tree, with categories being; a fork in the trunk, a fork in a primary branch, or a fork in a secondary branch.
Canopy above nest	A visual estimate of the density of the canopy cover above the nest, where zero is no canopy and 100% is a solid canopy. Categories used were: 1) <10% 2) 10 – 25% 3) 25 – 50% 4) 50 – 75% 5) >75%
Canopy below nest	A visual estimate of the canopy density below the nest, using the same categories as for 'Canopy above nest'.

3.3 Results

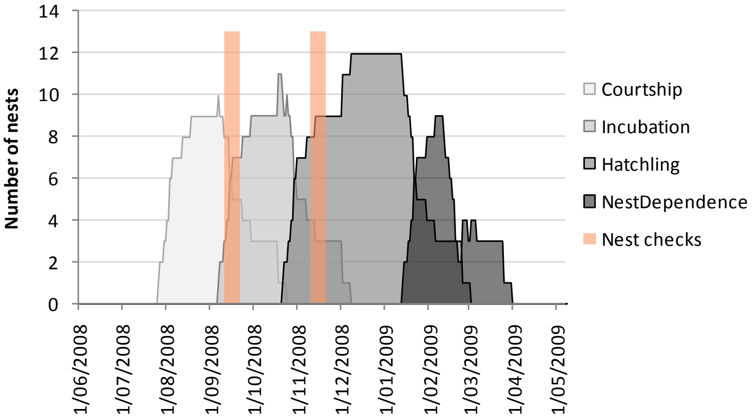
3.3.1 Breeding chronology

A comparison of the first five breeding seasons shows that the 2008–09 season and the 2010–11 season started and ended later than the other years (Figure 2). [It should be noted that the 2008–09 data were based on only 12 nests]. Incubation was initiated over 8 weeks for the nests examined in 2007–08, over 7 weeks in 2008–09, five weeks in 2009–10, eight weeks in 2010–11 and eight weeks in 2011–2012. The total duration over which breeding activity occurred was estimated to be 39 weeks in 2007–08, 36 weeks in 2008–09, 33 weeks in 2009–10, 36 weeks in 2010–11 and 36 weeks in 2011–12 (Figure 9). Over all years combined breeding occurred between the first week of July and the last week of March.

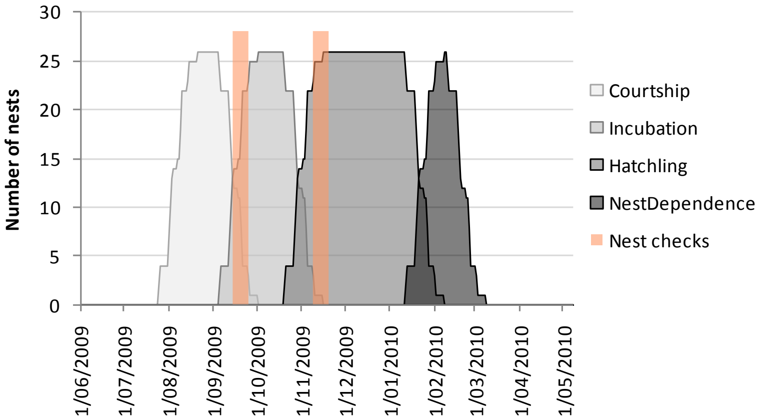
2007–08 (34 breeding pairs)



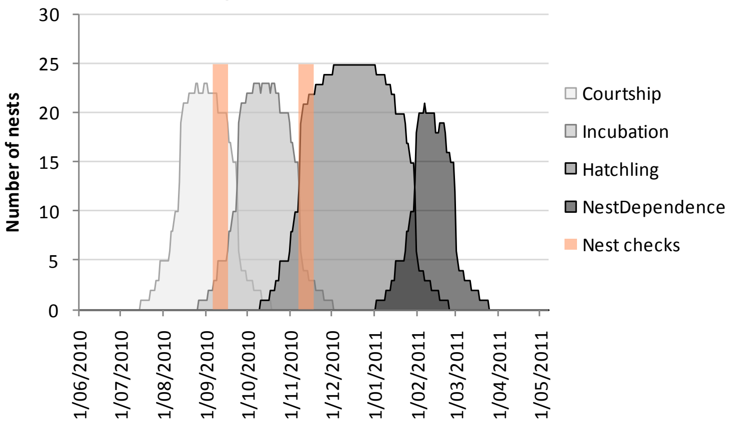
2008–09 breeding season (12 breeding pairs).



2009–10 breeding season (27 breeding pairs).



2010–11 breeding season (25 breeding pairs).



2011–12 breeding season (21 breeding pairs).

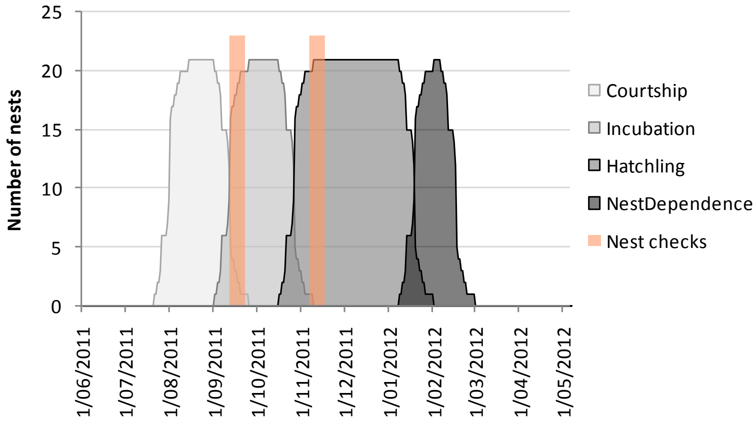


Figure 9. Chronology of breeding activities as extrapolated from the estimated age of nestlings observed in the nest for (a) 2007–08, (b) 2008–09, (c) 2009–10, (d) 2010–11 and (e) 2011–12. The number of breeding pairs on which the figures are based are 34, 12, 27, 25 and 21 respectively. The orange vertical lines indicate the timing of standard industry nest checks (second weeks of September and November).

3.3.2 Nest site attributes

Of the 103 nest trees surveyed from the ground, 45 were located in dry forest, 52 in wet forest, and 6 were unclassified at the time this report was written. The eagle nest trees visited were located on an average slope of 24.5º ± 16 SD on predominantly easterly facing slopes (Figure 10).

a) b)

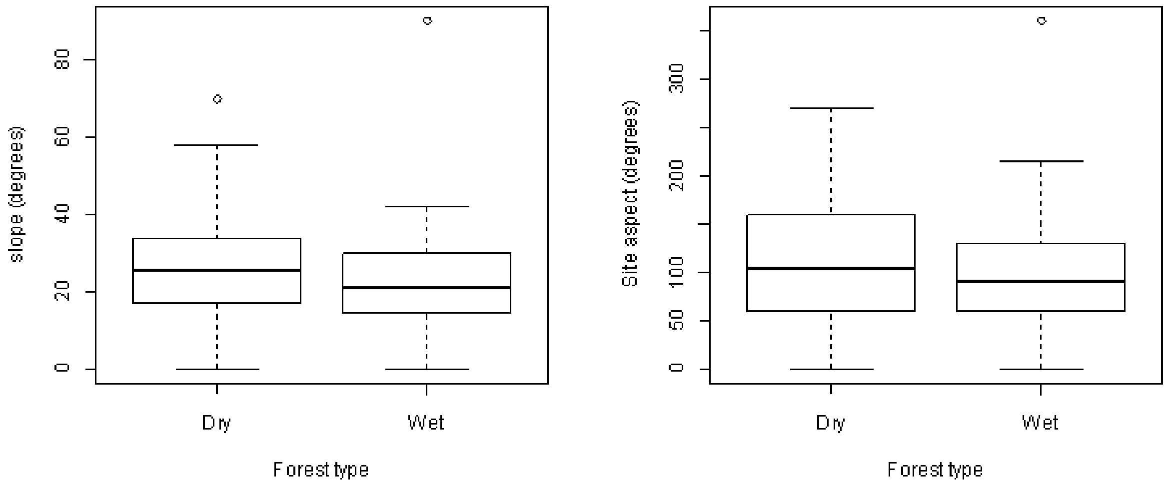


Figure 10. Boxplots of the (a) slope and (b) aspect of the site on which eagle nest trees were found in dry (n = 45) and wet (n = 52) forest types. The box length is the interquartile range and the circles are outliers.

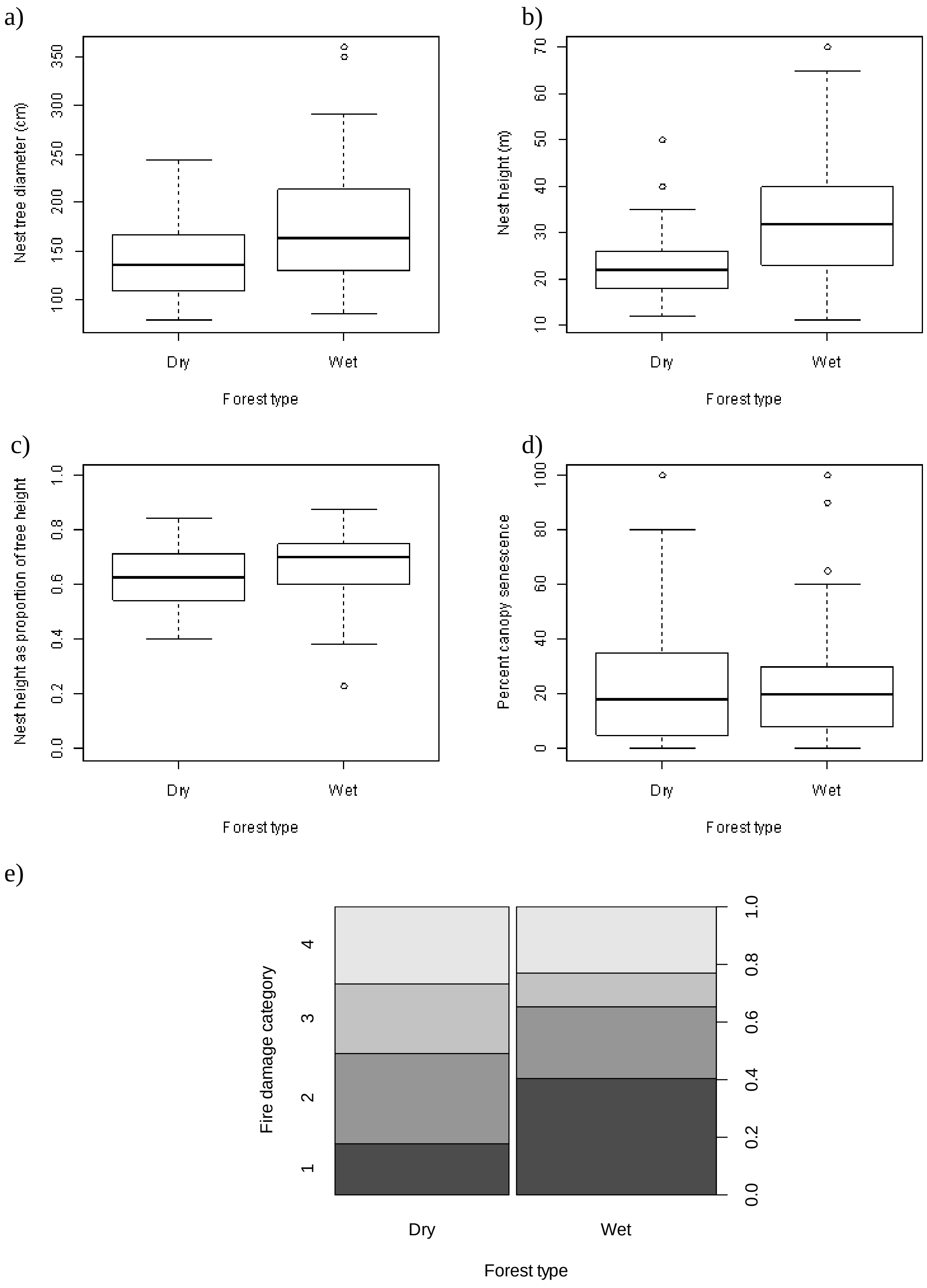


Figure 11. Boxplots for dry (n = 45) and wet (n = 52) forest types of (a) tree diameter, (b) height of the nest above the ground, (c) the height of the nest tree as a proportion of the tree height and (d) the percentage of the canopy that was dead or senescent. The box length is the interquartile range and the circles are outliers. (e) shows the relative fire damage to nest trees in wet and dry forest, where (1) has no damage, (2) has charcoal on the trunk, (3) has exposed wood due to burn damage and (4) the base of the trunk is burnt through and hollow.

Nests were located in a range of different tree species; 32 nests were located in *E. delegatensis,* 23 in *E. obliqua,* 17 in *E. globulus,* 14 in *E. regnans,* 8 in *E. viminalis*, and the remaining 9 nests in a range of other tree species, all native. Nest trees were on average 160 cm ± 56 SD in diameter at breast height, with trees in wet forest being generally larger than trees in dry forest (Figure 11a). Nests were on average 28 m ± 11 SD above the ground, being slightly higher in wet forest than dry forest (Figure 11b). However, nest trees were taller in wet forest, so the height of the nest relative to the height of the tree was only slightly higher in wet forests, with nests being located on average 65% of the height of the tree (Figure 11c). Nest trees were similar in senescence between forest types, with an average of 27% of the canopy being senescent (Figure 11d). There was a large amount of variability in the amount of burn damage to trees, with nest trees in wet forest having, on average, lower burn damage than nest trees in dry forest (Figure 11e). The majority of nests had less than 50% canopy cover above the nest (Figure 12a) and less than 10% canopy density below the nest (Figure 12b). The majority (92%) of nests examined were located in a fork in the trunk or in a fork in a primary branch (Figure 12c).

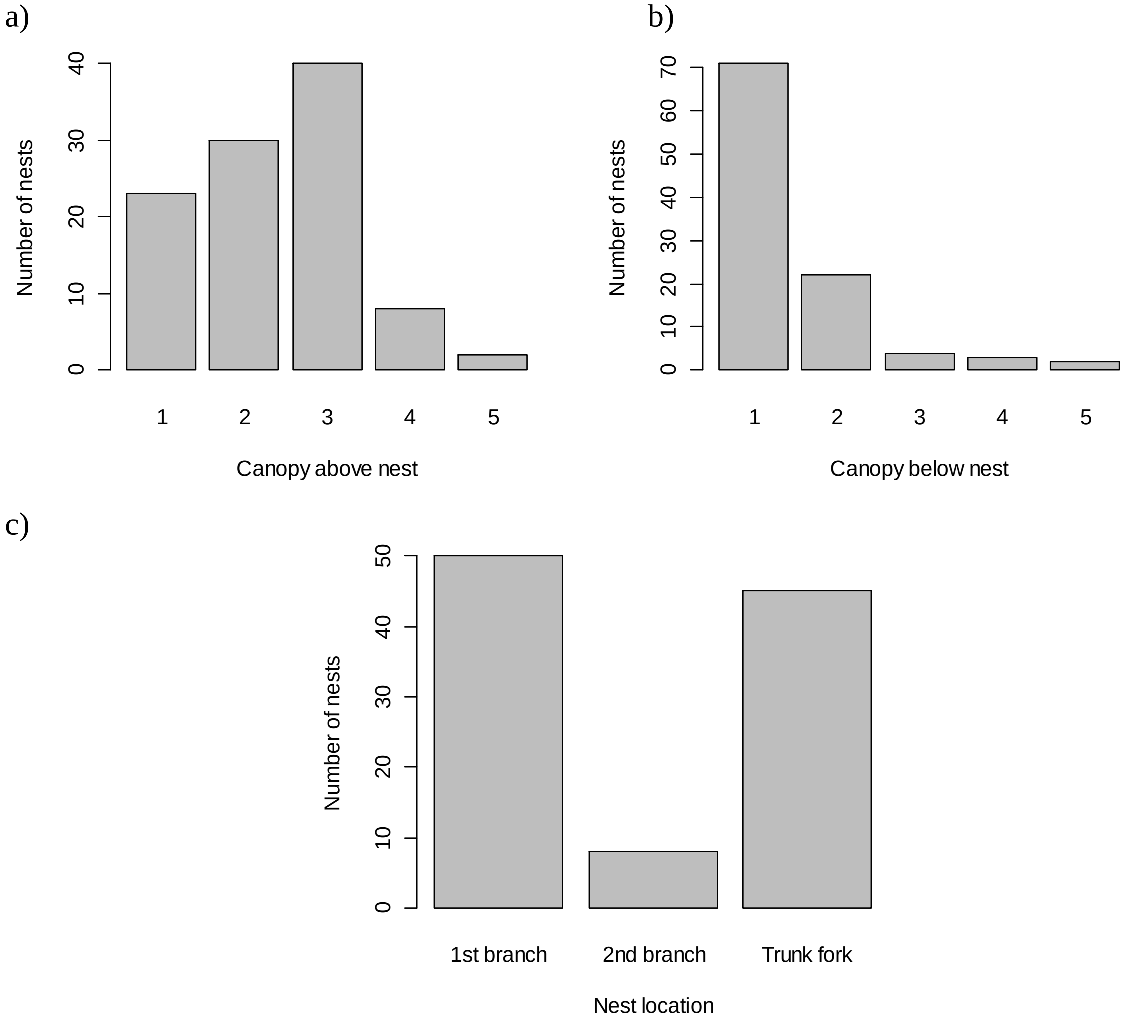


Figure 12. The number of eagle nests (n = 103) found in relation to (a) the canopy density above the nest, (b) canopy density below the nest and (c) the location of the nest, whether it be in the primary branch of the tree, secondary branch of the tree, or in a fork in the main trunk. The canopy density categories are (1) <10% cover, (2) 10–25%, (3) 25–50%, (4) 50–75% and (5) >75%.

3.3.3 Nest activity and nest site attributes

Of the 84 nests for which data were available on both breeding activity in at least one year and tree attributes, 46 were never observed with a nestling (i.e. ‘inactive’) and 38 were observed with a nestling at least once (i.e. were ‘active’). There was no significant difference between active and inactive nests in the slope of the site (P = 0.28), aspect of the site (P = 0.74), or forest type (P = 0.81) (Figure 13). There was no significant difference between active and inactive nests in nest height above the ground (P = 0.22), tree height (P = 0.21), height of the nest relative to the height of the tree (P = 0.30, Figure 14d), percentage of the crown that was senescing (P = 0.32, Figure 14e) or the density of the canopy above the nest (P = 0.70, Figure 14f). There was a non-significant trend that active nests were located in trees with a smaller diameter (KW chi-sq = 2.9, P = 0.09, Figure 14a). No formal analysis was conducted, but the activity status of nests seemed to vary between tree species, being lowest in *E. regnans* (Figure 15).

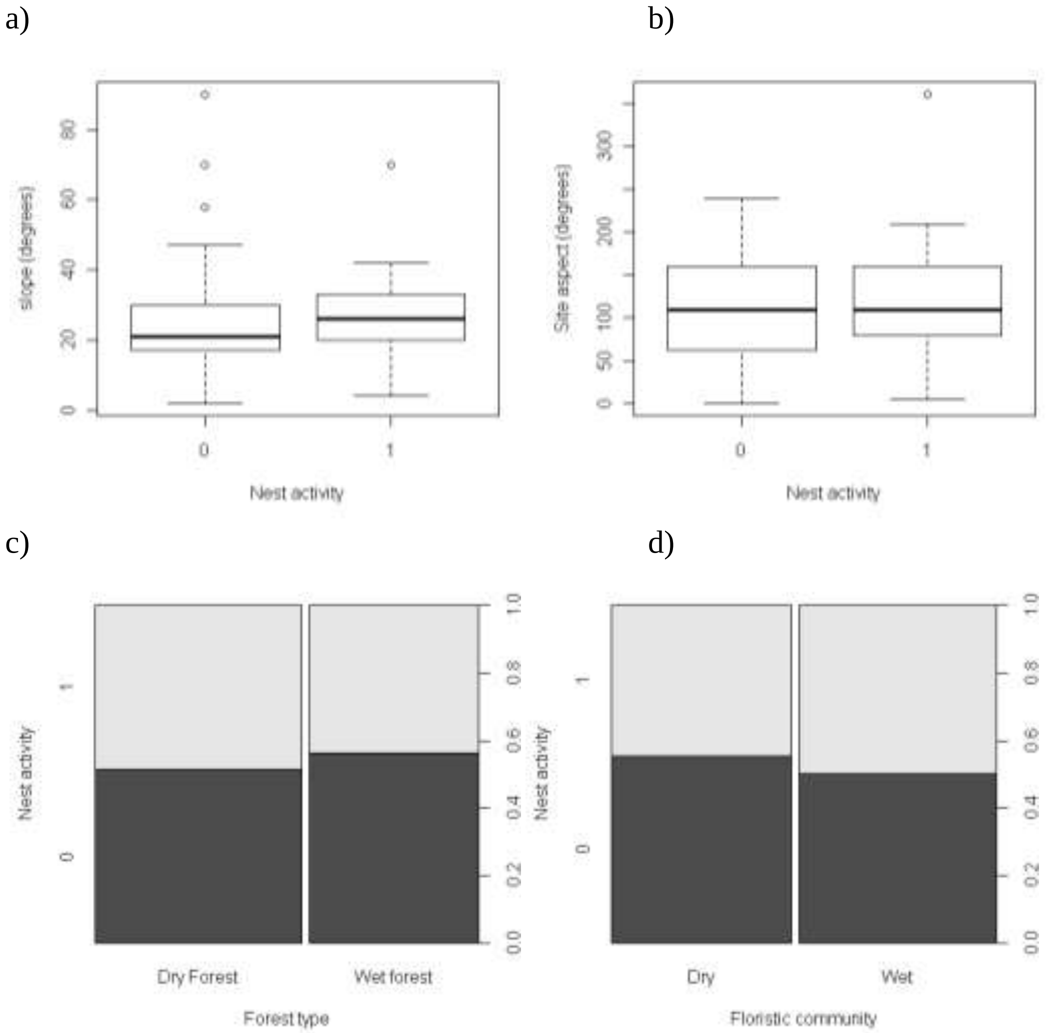


Figure 13. Active (nest activity = 1, n = 38) and inactive (n = 46) nests in relation to (a) slope of the site, (b) aspect of the site, (c) TasVeg forest type (note: non eucalypt forest types are excluded, n = 76) and (d) floristic community (n = 80). The width of the columns in figures c and d are proportional to the relative sample sizes.

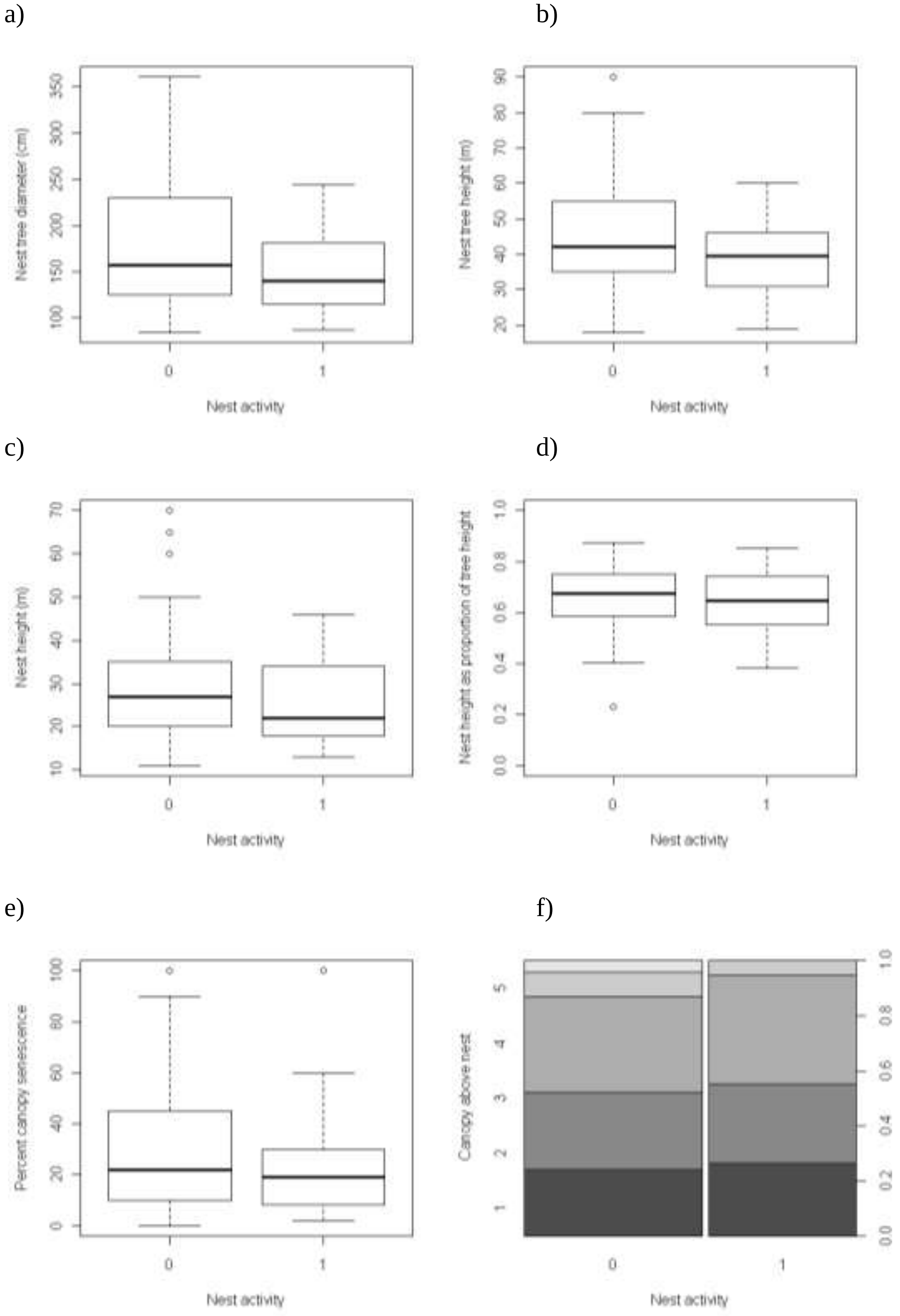


Figure 14. Active (Nest activity = 1, n = 38) and inactive (n = 46) nests in relation to (a) diameter of the nest tree, (b) height of the nest tree, (c) height of the nest above the ground, (d) height of the nest as a proportion of the tree height, (e) senescence of the nest tree canopy, and (f) density of the canopy above the nest. The canopy density categories are (1) <10% cover, (2) 10–25%, (3) 25–50%, (4) 50–75% and (5) >75%.

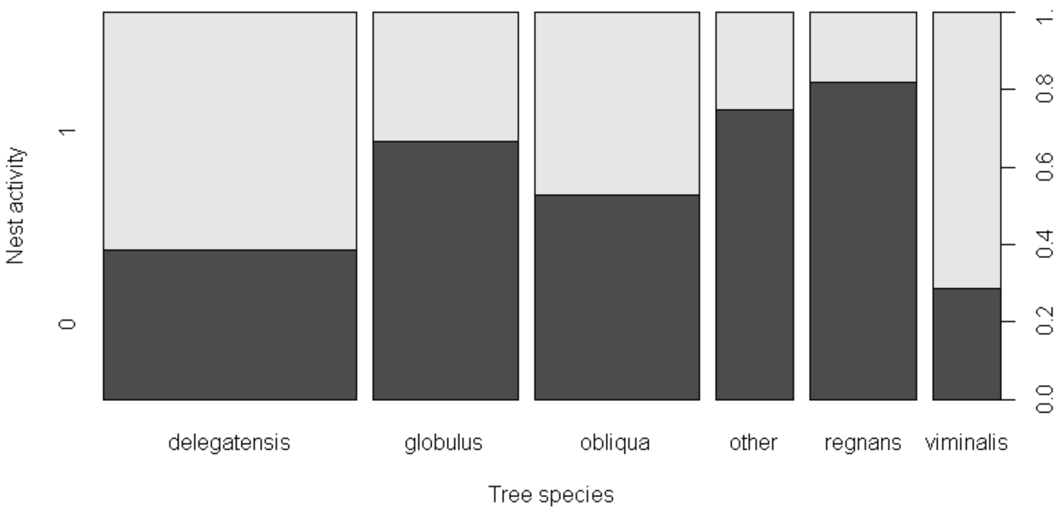


Figure 15. Active (grey, n = 38) and inactive (black, n = 46) nests in relation to the *Eucalyptus* species in which the nest was located. Trees in the 'other' category include *E. brookeriana, E. sieberi, E. nitida, E. pulchella, E. amygdalina* and a hybrid *E. globulus-viminalis.* The width of the bars is proportional to the relative sample size.

3.4 Discussion

3.4.1 Breeding chronology

The timing of the breeding season varies between years, but the duration of the breeding season appears to be relatively consistent. It is uncertain what factors drive the changes in the timing of the breeding season. It could be influenced by climatic variables and/or by prey availability (which may themselves be correlated).

It was shown in section 2 that breeding success varies between years. 2007 was the earliest year and the most successful year. However, there is not a clear pattern between the timing of the breeding season and the rates of breeding success.

3.4.2 Nest site attributes

The factors influencing the preference for particular nests may relate to current and historical factors and activities occurring within the breeding territory (see Section 2 current report), or may relate to the attributes of the nest tree itself. Nests surveyed in the current study were located in large trees, predominantly on moderate slopes with aspects sheltered from the prevailing westerly winds (i.e. on east-facing slopes), as has been found in other studies (e.g. Brown & Mooney 1997; Foster & Wallis 2010; Mooney & Holdsworth 1991; Mooney & Taylor 1996).

The trees in which eagle nests were located were large old trees, and often the largest trees in the immediate area (see Appendix D). Eucalypts generally only live to about 500 years old (Brookhouse & Brack 2006; Brookhouse 2006) and loss of nest trees and lack of recruitment is potentially an important issue for the persistence of this species (Bekessy et al. 2009, Appendix D current report). Appendix D provides details on the availability of potential recruitment trees around a sample of existing nests.

3.4.3 Management Implications

The results of this study show that the timing of management surveys (nest activity assessments) will not always coincide with the breeding season. This means that the accuracy of some nest activity assessments may be questionable. As a result the FPA have recommended the removal of the September nest checks, basing management decisions on the November nest check only in order to get more accurate results. FPA have also recommended that aerial surveys are used instead of ground-based surveys as they provide more accurate results (and are also cost-effective). Whichever survey method is used, the results of this study confirm that it is important to monitor the timing of eagle breeding so that the timing of both surveys and management can be adjusted according to the timing of breeding in a particular year. For example, the management period may need to be extended in some years if the onset of breeding was later than usual.

4 Review of wedge-tailed eagle nesting habitat models

4.1 Introduction

Tasmanian wedge-tailed eagles are sensitive to disturbance, particularly during the breeding season (Mooney & Holdsworth 1991). Eagle nest management in Tasmania focuses on limiting the proximity and timing of disturbance around known nest sites, and research has shown that buffering nests from logging operations improves breeding success (Mooney & Holdsworth 1991). Knowledge of nests before the harvest operation begins has been shown to assist such conservation (Mooney 2000).

Modelling of wedge-tailed eagle nest site characteristics started even before the species was listed as threatened (Mooney 1988a) and has undergone steady development. Some key modelling was done by Brown and Mooney (1997) who examined the habitat attributes of 299 wedge-tailed eagle nests known at the time. This work included detailed modelling of 22 eagle nests in a 2400 km^2 area in eastern Tasmania covered by the Little Swanport 1:100,000 TASMAP mapsheet. The study examined the physical characteristics of areas around nests to help identify areas in which eagle nests were likely to be found. This modelling has been used to develop management guidelines which help practitioners identify areas likely to contain an eagle nest and that should be searched prior to any forest operation commencing. Technical guidelines for planners state that nest searches should be conducted in areas with a high probability of containing a nest, as determined by forest type, topography (slope, aspect and relief) and nearest neighbour distance (FPA 2006).

The modelling work conducted by Brown and Mooney (1997) made an extremely important contribution to eagle nest management in Tasmania. However, between 2007 and 2010 almost 9% of eagle nests found in forestry areas were located during the operation and not during the pre-harvest survey (Table 11). Locating nests during an operation has negative effects on both the breeding birds (which are more heavily disturbed) and the industry (which bears a larger cost if nests are located during logging rather than during pre-logging surveys). Nests located during harvest operations may have been missed during the pre-harvest surveys, or they may have been located outside of recommended search areas. Some informal analyses have suggested that a small proportion of new nests are located outside of areas currently modelled as prime eagle nest habitat (V. Tyquin pers. comm.). The location of nests in areas not modelled as prime eagle nest habitat may be a result of the predictive ability of the current model, and/or may be due to a change in the areas used by breeding eagles (possibly in response to a change in availability of quality habitat).

The diversity and resolution of spatial information has increased considerably since previous modelling. Furthermore, the tools available for modelling with presence-only data are now more sophisticated, and there has been a large increase in the number of nests known across the state. A review of existing eagle nest predictive models that takes advantage of the improvements in data availability and modelling tools will help refine the current nest searching techniques, providing benefits for both breeding eagles and the forest industry.

The objective of this current section of the report is to present the methods and results of the re-modelling of the environmental attributes associated with known wedge-tailed eagle nests and revision of the method for predicting potential wedge-tailed eagle nesting habitat.

Table 11. The number of nests found annually during recent forest operations, indicating the number that were found during industry pre-logging surveys and the number found during harvesting (DPIPWE and FPA, unpublished data).

Year	Nests found during pre-harvest surveys	Nests found during harvesting	% of new nests found during harvesting
2007	80	5	5.9%
2008	107	10	8.5%
2009	50	9	15.3%
2010	42	3	6.7%
Total	**279**	**27**	**8.8%**

4.2 Methods

We used all nests in the raptor nest database (NVA, DPIPWE, June 2011) for the current modelling, except nests where the locality data were considered too inaccurate (>20 m accuracy on GPS) and nests that were located in non-forest vegetation types. (It should be noted that many of the old nest records were reported to have a position accuracy of zero (i.e. were highly accurate), and were included in the sample. Most of these localities were probably obtained from a map rather than a GPS and it is likely that they actually had relatively low accuracy. However, these nests are also likely to represent areas that were selected for nesting when disturbance was less and may therefore represent high quality habitat. As a consequence, these nests were included in the modelling). The end result was a total of 926 nests used in the modelling. The raptor nests database includes all known nest records, both new and old, and some of the older nests may no longer exist (approximately one third of nest records were found prior to 1997, with some recorded as early as 1950). Many eagle nests in recent years have been located during pre-harvest surveys or during forestry operations (as this is where the search effort has been focused) so the known localities of eagle nests will be biased towards areas used for wood production. This model is being developed primarily for use in production forestry areas and so any bias in the data is expected to have minimal impact on model utility.

The program MaxEnt (version 3.3.3; Phillips et al. 2006) was used to model the distribution of wedge-tailed eagle nests using presence-only data and a range of habitat variables (Table 12). The habitat variables considered were determined from expert knowledge and previous modelling. Some of the nest records used in the modelling are old, so the vegetation data used in the model (Table 12) may not always reflect the condition of the vegetation when the nest was constructed.

MaxEnt uses the concept of maximum entropy, assuming the distribution of the given population will be uniform when all ecologically important parameters are taken into account (Phillips et al.

2006). MaxEnt creates a likelihood distribution for the species across the study area, starting from a uniform distribution and repeatedly improving the fit to the data. Each step of the MaxEnt algorithm increases the gain (goodness of fit) of the model by modifying the coefficient for one of the input features, and assigning the increase in gain to the environmental variable(s) that the feature depends on. The result is a map indicating the relative likelihood of nest occurrence across the study area. The program MaxEnt has received some criticism, largely because the results have been interpreted as a 'probability' of occurrence rather than an index of relative likelihood (Royle et al. 2012). Absolute probabilities of nest occurrence are not required for the current project and so MaxEnt is an appropriate tool to use for the current modelling.

We assumed that the nest records in the database were a random sample of eagle nests that occur in the landscape, and that there is a 50% chance of a nest being present in suitable areas (the assumption of 50% affects how closely the model output reflects a probability of occurrence, it does not affect the relative likelihood of different areas containing nests). The habitat attributes of the nest localities was compared to 10,000 randomly sampled localities across the state (there are approximately 119,500,000 possible random cells in Tasmania). MaxEnt estimates the ratio of the conditional density of the environmental variables at the nest sites compared to the random sites (i.e. the use of particular habitats compared to the relative availability of that habitat attribute as determined from the random sampling). The modelling process ensures that areas selected by the model to be predicted presence have the same average value, or within a certain margin of the average, for each covariate as was found for the nest records. The way the model 'fits' the environmental variables depends on the sample size available, but MaxEnt can fit extremely complex, non-linear relationships and simple pair-wise interactions.

We used 80% of the nests (the training data) to construct the model. The remaining 20% of the nests (the test data) were fitted to the model, and we used the AUC (area under curve) values of the test data to indicate the predictive ability of the model. AUC is the area under a receiver operating characteristic (ROC) curve. ROC curves are a plot of the proportion of positive results that are correctly predicted (sensitivity) against the proportion of negatives that are incorrectly predicted (1 − specificity), as the discrimination threshold is varied. The AUC value indicates the classifier performance of the model (Fawcett 2006) and an AUC of 1 indicates perfect predictive ability and an AUC of 0.5 indicates the model is no better than random.

MaxEnt fits a penalised maximum likelihood model that penalises overly complex models to reach a balance between model fit and complexity (Elith et al. 2011). We used the default regularisation parameter value of one. Although MaxEnt constrains model complexity, we wanted to exclude any variables that made a negligible contribution to model fit. To do this we fitted an initial model using all environmental variables (Table 12). In a step-wise manner we then excluded any variables where the 'jack-knifing' (i.e. excluding each variable in turn and creating a model with the remaining variables) indicated that exclusion of the variable did not reduce the AUC. If removal of the variable reduced the AUC of the test data by 1% or more then we retained the variable.

The model was also created using each variable in isolation. The gain (goodness of fit) of the global model (the model with all variables) is compared to the gain of the models that exclude

one of the variables and the gain of the models that only contain one of the variables. The results of the jack-knifing indicate which variable has the greatest explanatory power when used in isolation, and which has the most unique information that is not present in other variables and so removal of this variable has a big impact on model predictive ability. The jack-knifing gain was estimated using the change in gain of the test data, change in gain of the training data, and change in AUC of the test data.

We also examined the relative importance of the variables used in the models. MaxEnt randomly permutes the values of each variable among the data used in model construction, and measures the resulting change in AUC. The change in AUC values are normalised and presented as percentages to indicate the relative importance of each variable in determining model fit. To assess the predictive ability of the model we conducted 10-fold cross validation.

Prior information suggests that the habitat variables associated with eagle nests may be different in certain areas of the state (Mooney, pers. comm.). We therefore constructed three different models predicting wedge-tailed eagle nest habitat in (1) areas under 850 m altitude (excluding the north-west of the state), (2) areas higher than 700 m altitude, and (3) areas in the north-west of the state. There was an overlap between the low and high altitude models because a subjective examination found that nests in this altitude range varied in whether they were ‘typical’ of low altitude or high altitude nests. The north-west of the state was defined as including IBRA 5 region ‘King’ (excluding King Island) and the northern section of IBRA 5 ‘West’ for areas below 250 m altitude. We only modelled forested areas (as determined from the Forest Groups layer, excluding areas of plantation) and the environmental variables considered in the model are outlined in Table 12.

Table 12. Environmental variables considered in the nesting habitat model.

Variable	Description
MPI	Morphological Protection Index. A measure of the degree of dominance or enclosure of a location as described by Yokoyama et al. (2002). The technique uses a digital elevation model to calculate zenith and nadir angles (the largest angles that intersect with a respective high or low point in the terrain) in eight directions from the point of interest. The mean of these values is taken and values are low for convex forms (hills and flat areas) and high for concave forms (slopes and valleys). The model was run with a 2 km search radii on 25 m elevation data.
Wind100	An estimation of the wind exposure of a site using the wind effect tool in the SAGA program, calculated using 100 m cells (Ringeler 2008). The Wind100 value is derived from elevation data and the direction from which the wind originates (westerly). Higher values indicate greater wind exposure (generally high altitude areas) and lower values indicate greater wind protection (lower altitude areas).
Slope	The slope of the land for each 25 m grid square was determined from a 25 m digital elevation model (º).
Aspect	The direction in which each 25 m grid square of land faces, as measured when looking directly downhill. Classified as (1) N, (2) NE, (3) E, (4) SE, (5) S, (6) SW,

Variable	Description
	(7) W, (8) NW and (9) Flat.
Altitude	The height above sea level (m) for each 25 m grid square was determined from a 25 m digital elevation model.
Landform	A classification of the topography of an area, using the ‘synthetic land components of Tasmania’ mapping layer provided by Natural Resource Planning. The classifications were derived from 25 m digital elevation data, but processed to a minimum polygon size of 2 ha. Areas were classified as (1) ridges and upper slopes, (2) elevated plains, (3) gentle lower slopes, (4) lower plains, (5) steep lower slopes and incised streams, and (6) steep mid slopes.
Height	A classification of the height that the forest canopy is expected to reach when the stand reaches maturity, as determined from aerial photograph interpretation of land units at least 3 ha in size. Areas were classified as a continuous variable, but the data were in 5 m height classes from 5 m to 65 m. Where there was no stand height data we used the mature height data. Areas with no stand height or mature height data were not modelled (this was largely non-eucalypt forest, but included some regrowth eucalypt forest on private land).
Mature	The estimated density of mature eucalypt crowns in a forest stand, as determined from aerial photograph interpretation of land units at least 3 ha in size. Categories considered were: (1) 70–100% crown cover, (2) 40–70%, (3) 20–40%, (4) 5–20%, (5) <5%, (6) patchy mature crowns and (7) no mature crowns.
Regrowth	The estimated density of regrowth eucalypt crowns in a forest stand, as determined from aerial photograph interpretation of land units at least 3 ha in size. Categories considered were: (1) 90–100% crown cover, (2) 70–90%, (3) 50–70%, (4) 10–50%, (5) 1–10% (6) patchy regrowth crowns and (7) no regrowth crowns.
Growth Stage	A broad classification of the growth stage of the forest, determined from aerial photograph interpretation of land units at least 3 ha in size, being either (1) mature or (2) regrowth.

4.3 Results

4.3.1 Areas under 850 m altitude, excluding the north-west

The three main variables that best predicted the occurrence of eagle nests in low altitude areas were: MPI, aspect and the density of mature crowns (Table 13). Overall there was an increase in the likelihood of finding a nest on more protected slopes and in areas with an intermediate MPI value (i.e. mid-slope rather than hilltops, valleys or flat areas) (Figure 16a). Nests were most likely to be found on easterly aspects (Figure 16 b). Nests were unlikely to be found in areas with no mature eucalypts, and slightly more likely to be found in areas with relatively high densities of mature crowns (Figure 16d). Slope and landform of the site also made some contribution to model predictive ability, but these variables were correlated with some of the other variables (largely MPI) and so their removal made minimal impact on the AUC scores (Table 13). The variables that contributed the most to model predictive ability, and whose omission resulted in the biggest loss of model predictive ability was MPI (Figure 17). The predictive ability of the model was high, with an average AUC value (as obtained from 10-fold cross-validation of the model) of 0.83 (Figure 18). The map predicting the occurrence of wedge-tailed eagle nests for areas under 850 m altitude is provided in Figure 19.

Table 13. The models constructed for areas under 850m altitude, considering only forested areas (660 nests used for model building, 165 nests used for model testing). The models highlighted in grey are identified as the candidate optimal models.

Model	Variable (permutation) importance (%)										AUC test[a]
	MPI	Aspect	Height	Mature	Slope	Landform	Regen	Altitude	Wind100	Growthstage	
1	22.8	24.9	2.0	29.9	7.5	6.3	0.6	1.8	3.9	0.4	0.851
2	22.2	27.2	2.2	28.9	7.7	5.9	1.1	1.9	2.8		0.851
3	22.6	26.9	2.0	30.0	7.8	5.9		1.9	2.9		0.848
4	20.0	25.5	2.4	35.0	6.7	7.3			3.0		0.846
5	19.2	29.2		31.8	8.9	7.2			3.7		0.843
6	16.9	30.0		34.6	10.8	7.6					0.842
7	32.0	28.4		33.9		5.7					0.839
8	33.6	30.9		31.5	4.0						0.841
9	40.7	29.3		30.0							0.839

[a] The AUC test value is the area under the ROC curve when applied to the 20% of nests set aside for testing the model.

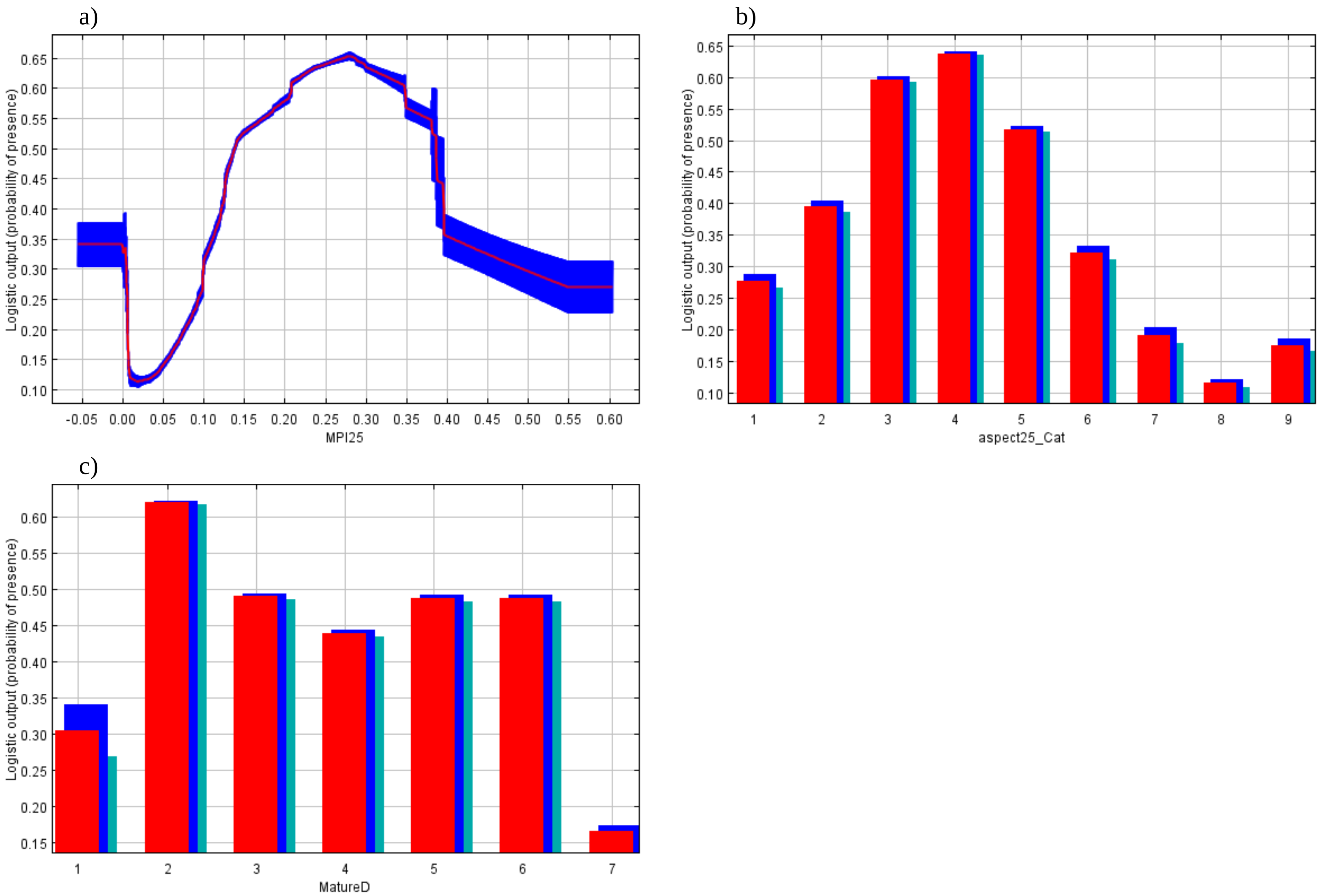


Figure 16. The predicted relationship between each of the variables used in the model for areas under 850 m altitude, when excluding the effect of the other variables. Mean values from 10-fold cross-validation are in red, and error margins (± 1 SD) are in blue and/or green. The variables considered were (a) MPI, (b) aspect, and (c) mature crown density. Refer to Table 12 for details on the categories used.

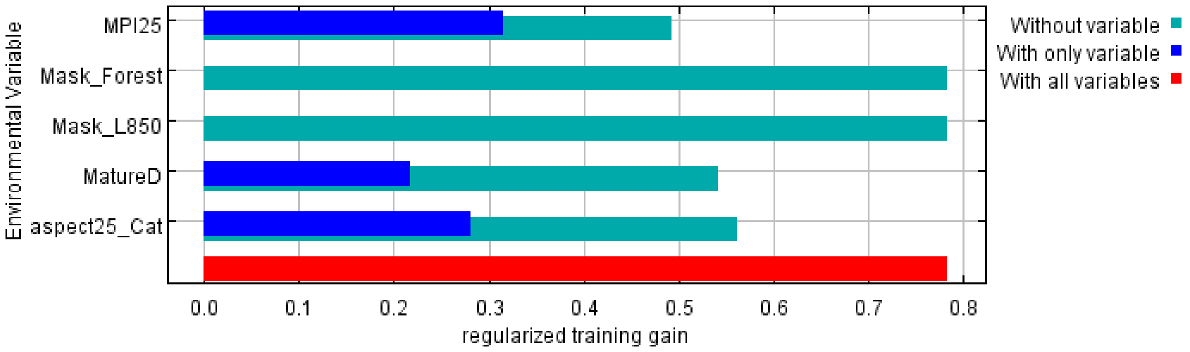


Figure 17. The results of jack-knifing the variables in the final model. The red bar indicates the model gain (goodness of fit) using all variables. The blue bars indicate the gain using only that variable in the model. The difference between the green and red bars indicates the loss of gain when a variable is excluded from the model. The two 'Mask' variables were included to specify the region to which the model applied (forest areas and areas <850 m altitude) but did not contribute to model prediction.

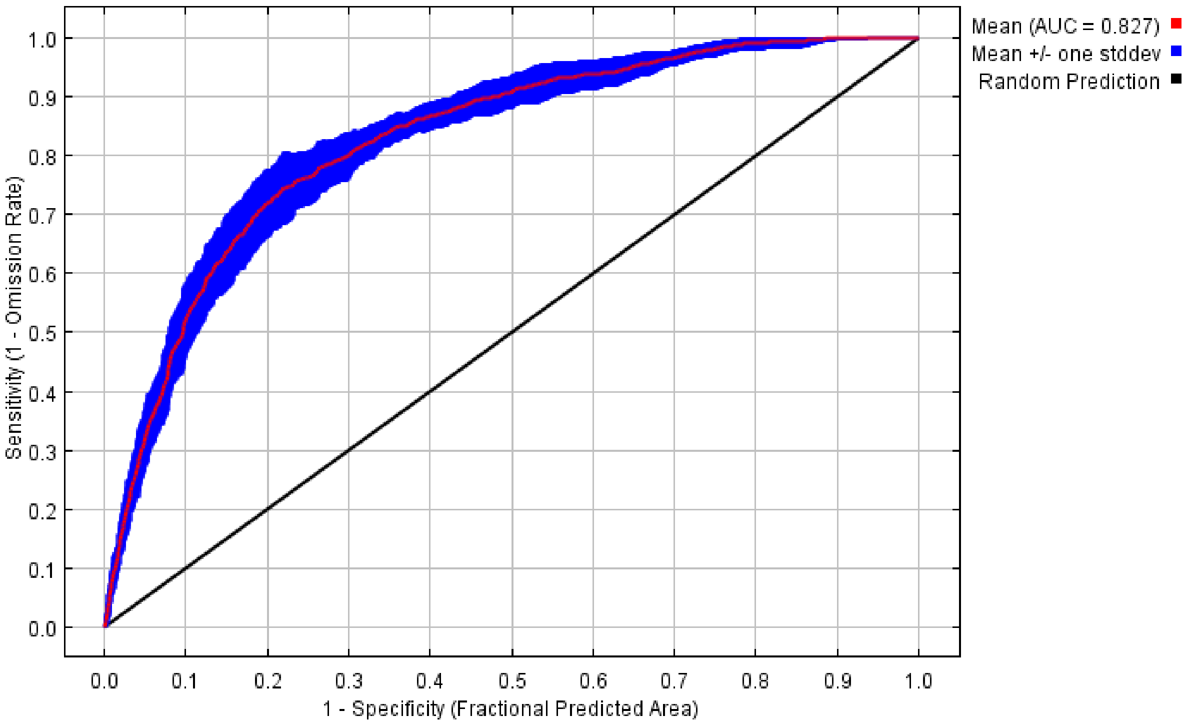


Figure 18. The ROC curve for areas under 850 m altitude for Model 9 which includes MPI, aspect, and density of mature crowns. The results are obtained from 10-fold cross-validation to obtain the mean and standard deviation of the AUC curve.

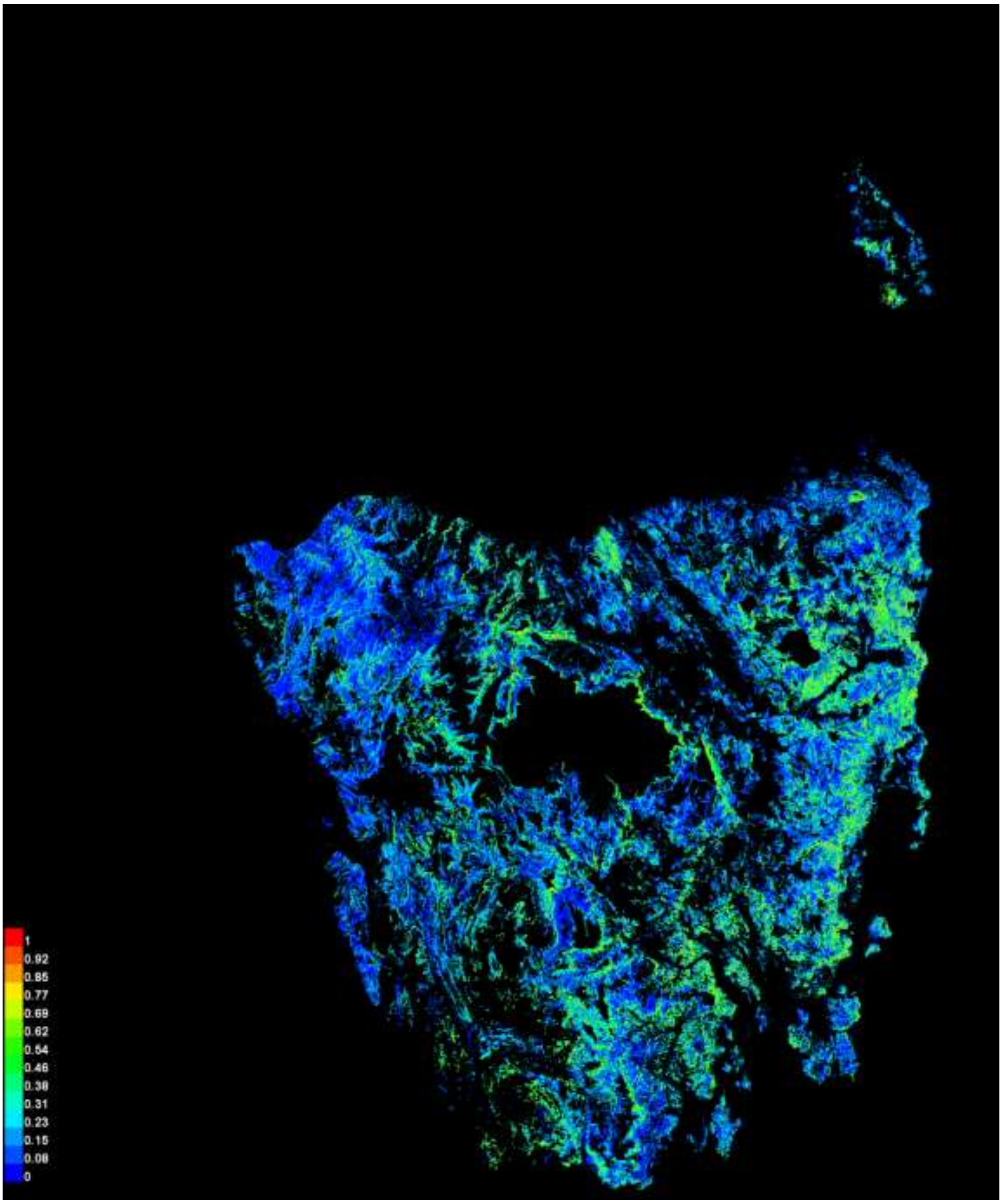


Figure 19. The predicted likelihood of the habitat being suitable for breeding eagles for areas under 850 m altitude, based on MPI, aspect, and density of mature crowns. The results are the mean values of a 10-fold cross-validation of the model.

4.3.2 Areas over 700 m altitude, excluding the north-west

At high altitude sites, the variables that best predicted the location of eagle nests were slope, aspect, wind protection and density of mature crowns (Table 14). Nests were more likely to occur in areas that were less exposed to the wind (generally low altitude areas), on easterly aspects, and on intermediate slopes (Figure 20). Nests were rare in areas with no mature trees (Figure 20). The variable that contributed the most to model predictive ability, when considered in isolation, was mature crown density. The variable whose omission resulted in the biggest loss of model predictive ability was aspect (Figure 21). The permutations indicated that slope contributed the most to model construction (Table 14). The predictive ability of the model was high, with an average AUC value (as obtained from 10-fold cross-validation of the model) of 0.82 (Figure 22). The map predicting the occurrence of wedge-tailed eagle nests for areas over 700 m altitude is provided in Figure 23.

Table 14. The models constructed for areas over 700 m asl, considering only forested areas (98 nests used for model building, 24 nests used for model testing). The model highlighted in grey is identified as the candidate optimal model.

Model	Variable (permutation) importance (%)										AUC test[a]
	MPI	Aspect	Height	Mature	Slope	Landform	Regen	Altitude	Wind100	Growthstage	
1	1.4	18.5	5.5	17.6	26.9	0.5	0.2	11.8	17.7	0.0	0.808
2	1.8	20.5	6.3	19.6	18.0	0.6		13.8	19.3	0.0	0.809
3	1.6	18.8	7.4	16.3	28.9	0.0		12.0	15.0		0.810
4	1.7	15.4	5.6	21.2	26.8			12.1	17.2		0.808
5		21.2	6.6	18.9	25.4			12.7	15.2		0.808
6		17.2		29.1	22.7			12.7	18.3		0.806
7		23.1		21.5	37.1				18.4		0.808

[a] The AUC test value is the area under the receiver operating characteristic curve when applied to the 20% of nests set aside for testing the model.

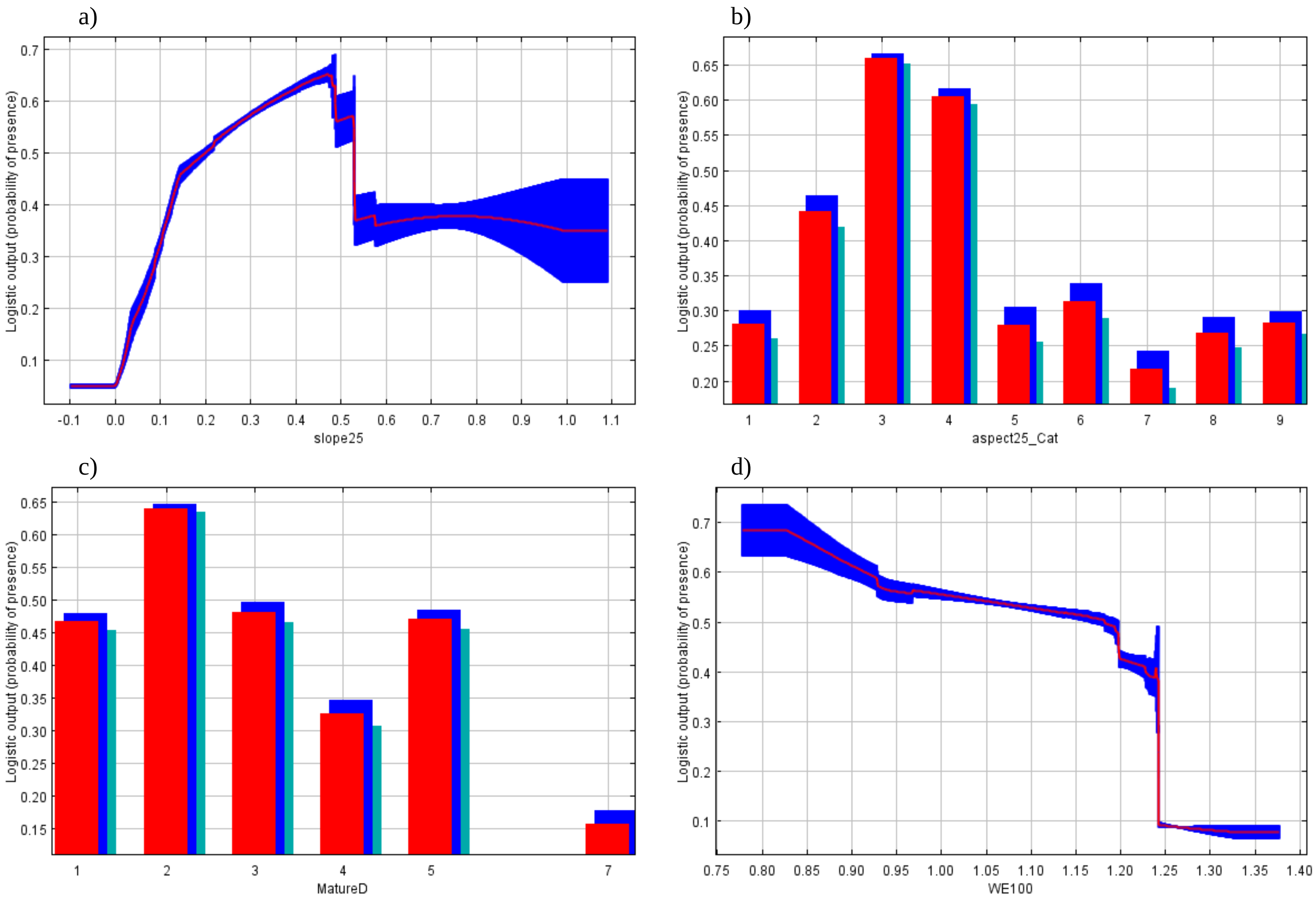


Figure 20. The predicted relationship between each of the variables used in the model for areas over 700 m altitude, when excluding the effect of the other variables. Mean values from 10-fold cross-validation are in red, and error margins (± 1 SD) are in blue and/or green. The variables considered were (a) slope, (b) aspect, (c) mature crown density and (d) wind exposure. Refer to Table 12 for details on the categories used.

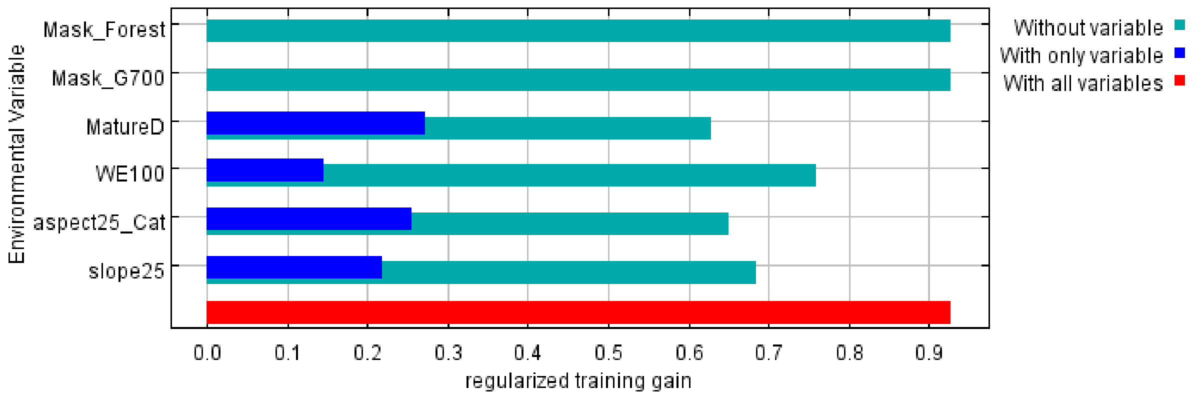


Figure 21. The results of jack-knifing the variable in the final model. The red bar indicates the model gain (goodness of fit) using all variables. The blue bars indicate the gain using only that variable in the model. The difference between the green and red bars indicates the loss of gain when a variable is excluded from the model. The two 'Mask' variables were included to specify the region to which the model applied (forest areas and areas >700 m altitude) but did not contribute to model prediction.

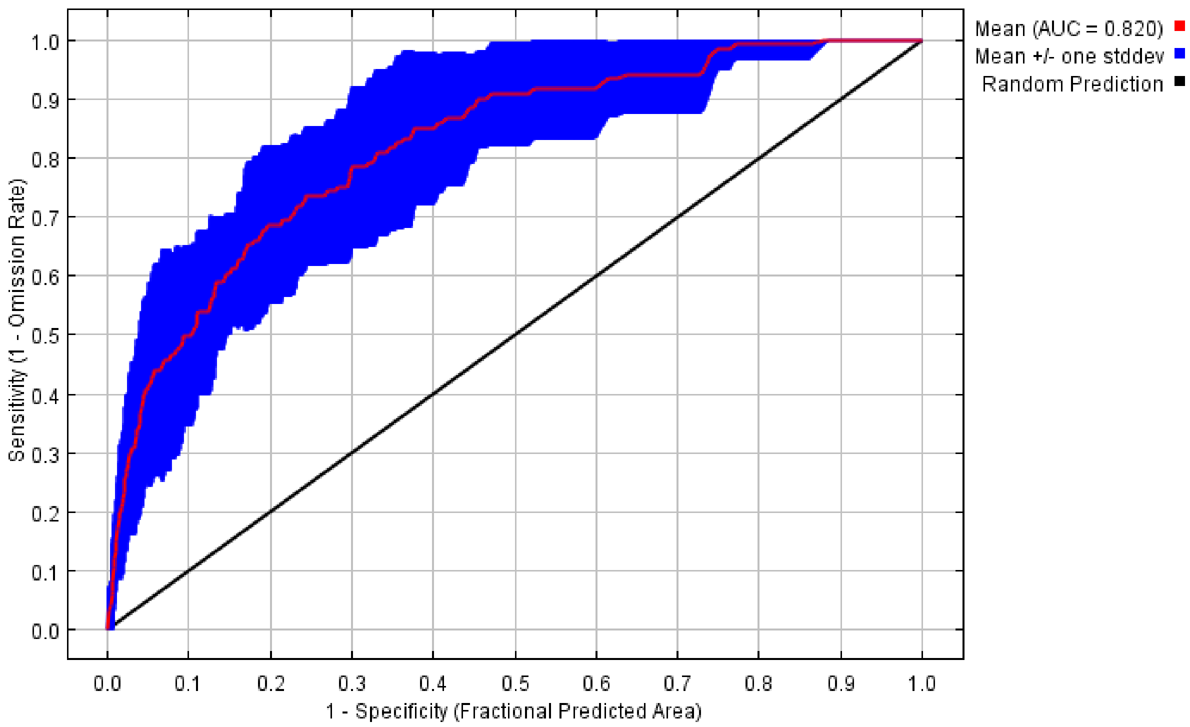


Figure 22. The ROC curve for areas over 700 m altitude for Model 7, which includes slope, aspect, Wind100 and density of mature crowns. The results are obtained from 10-fold cross-validation to obtain the mean and standard deviation of the AUC curve.

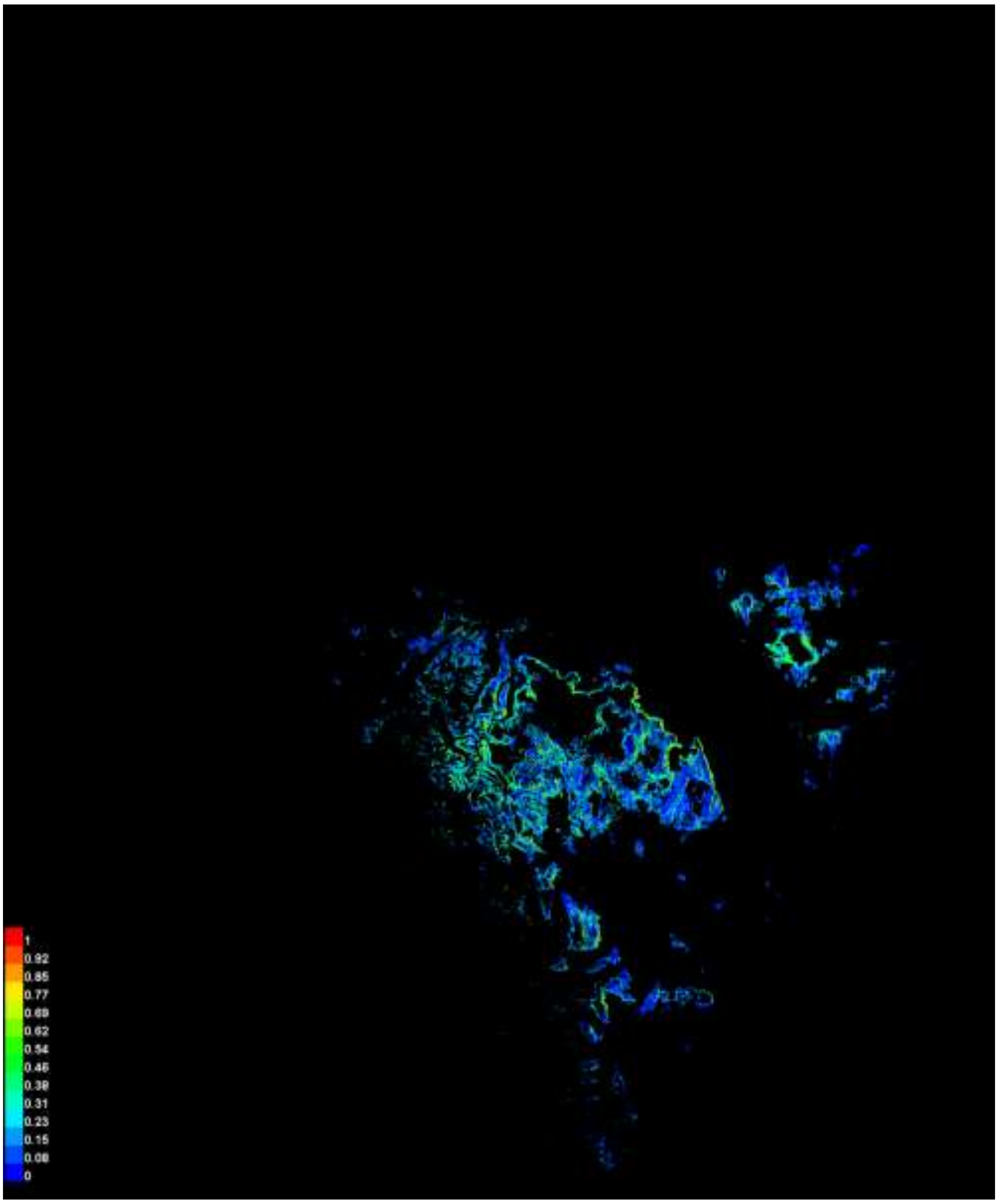


Figure 23. The predicted likelihood of the habitat being suitable for breeding eagles for areas over 700 m altitude, which includes slope, aspect, Wind100 and density of mature crowns. The results are the mean values of a 10-fold cross-validation of the model.

4.3.3 The north-west

The number of nests used in the construction of the north-west model was much lower than the other two regions (although the area examined was also smaller). The variable 'aspect' contributed to model fit for the data, but reduced predictive ability for the test data set and so was excluded. The final model was largely determined by altitude, with some refinement by mature crown density and wind exposure and a little by landform. While landform appeared to contribute little to the model (Table 15), cross-validation showed that exclusion reduced model fit (Figure 25). The final model indicates that nests were more likely to be found at lower altitudes, in relatively protected areas (intermediate Wind100 values) with higher densities of mature crowns (Figure 24). Nest success was highest on steep lower slopes and incised streams, and lowest on gentle lower slopes and steep mid slopes (Figure 24d). The variable that contributed the most to model predictive ability when considered in isolation, and whose omission resulted in the biggest loss of model predictive ability, was altitude (Figure 25). The predictive ability of the model was intermediate, with an average AUC value (as obtained from 10-fold cross-validation of the model) of 0.76 (Figure 26). The map predicting the occurrence of wedge-tailed eagle nests for the north-west region of the state is provided in Figure 27.

Table 15. The models constructed for the north-west, considering only forested areas (52 nests used for model building, 13 nests used for model testing). The model highlighted in grey is identified as the optimal model.

Model	Variable (permutation) importance (%)										AUC test[a]
	MPI	Aspect	Height	Mature	Slope	Landform	Regen	Altitude	Wind100	Growthstage	
1	0.0	29.1	1.0	8.9	0.2	3.8	7.2	37.7	12.1	0.0	0.681
2	1.8	25.2	0.2	17.8	0.9	1.3	2.3	40.9	9.6		0.682
3	2.1		0.5	20.9	1.9	0.6	4.2	56.1	13.7		0.720
4	3.1		0.6	21.0		2.2	4.1	55.0	13.9		0.715
5	2.8		0.8	25.8		1.9		55.8	13.0		0.749
6	2.5			16.6		6.0		62.8	12.2		0.746
7				30.1		4.7		52.5	12.6		0.744
8				25.6				60.5	13.9		0.724

[a] The AUC test value is the area under the ROC curve when applied to the 20% of nests set aside for testing the model.

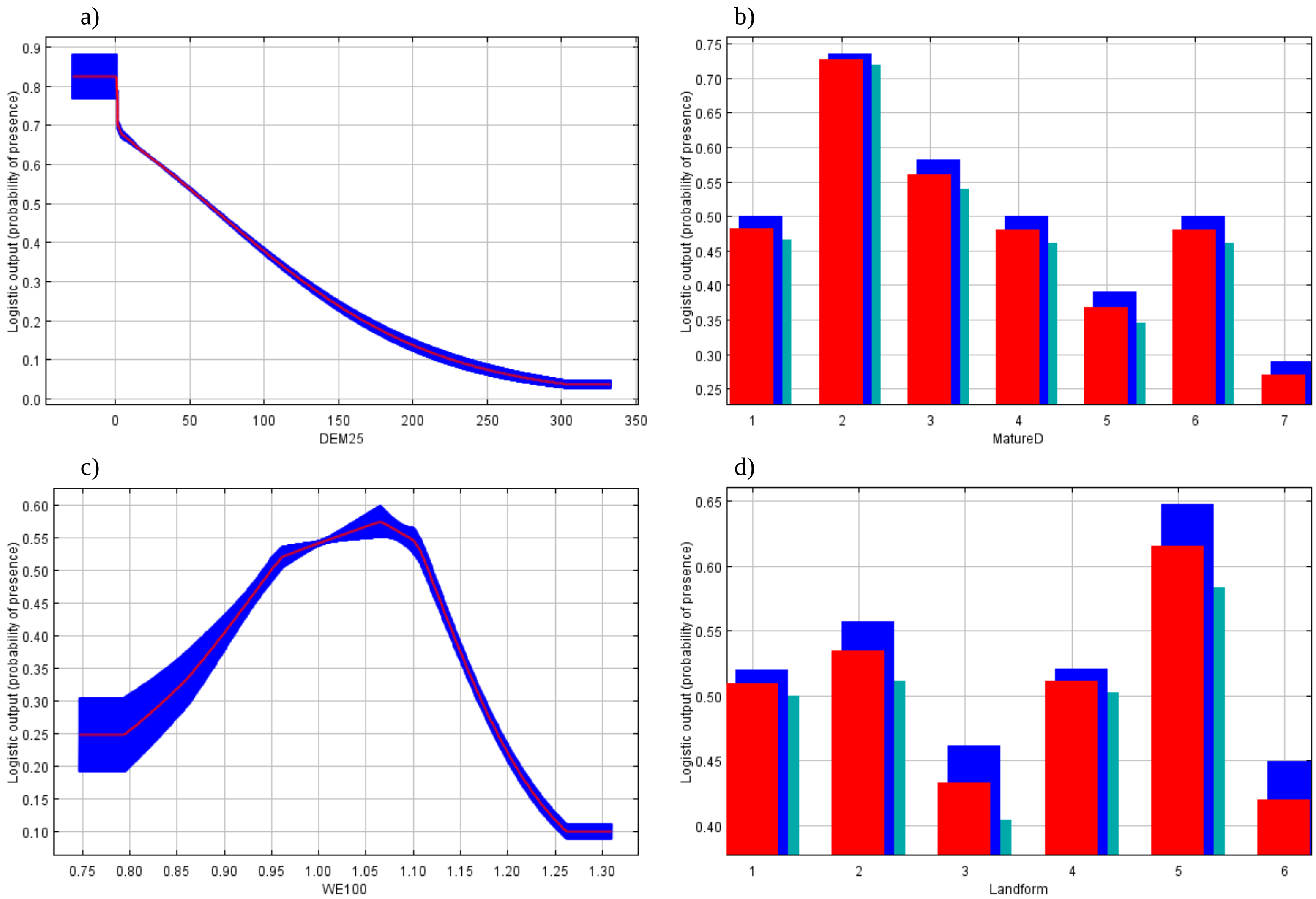


Figure 24. The predicted relationship between each of the variables used in the model for areas in the north-west, when excluding the effect of the other variables. Mean values from 10-fold cross-validation are in red, and error margins (± 1 SD) are in blue and/or green. The variables considered were (a) altitude, (b) mature crown density, (c) wind exposure and (d) landform. Refer to Table 12 for details on the categories used.

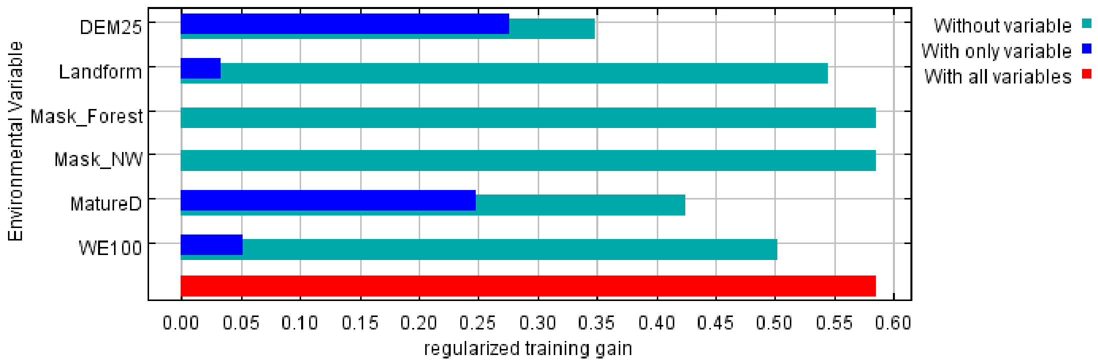


Figure 25. The results of jack-knifing the variables in the final model. The red bar indicates the model gain (goodness of fit) using all variables. The blue bars indicate the gain using only that variable in the model. The difference between the green and red bars indicates the loss of gain when a variable is excluded from the model. The two 'Mask' variables were included to specify the region to which the model applied (forest areas and NW) but did not contribute to model prediction.

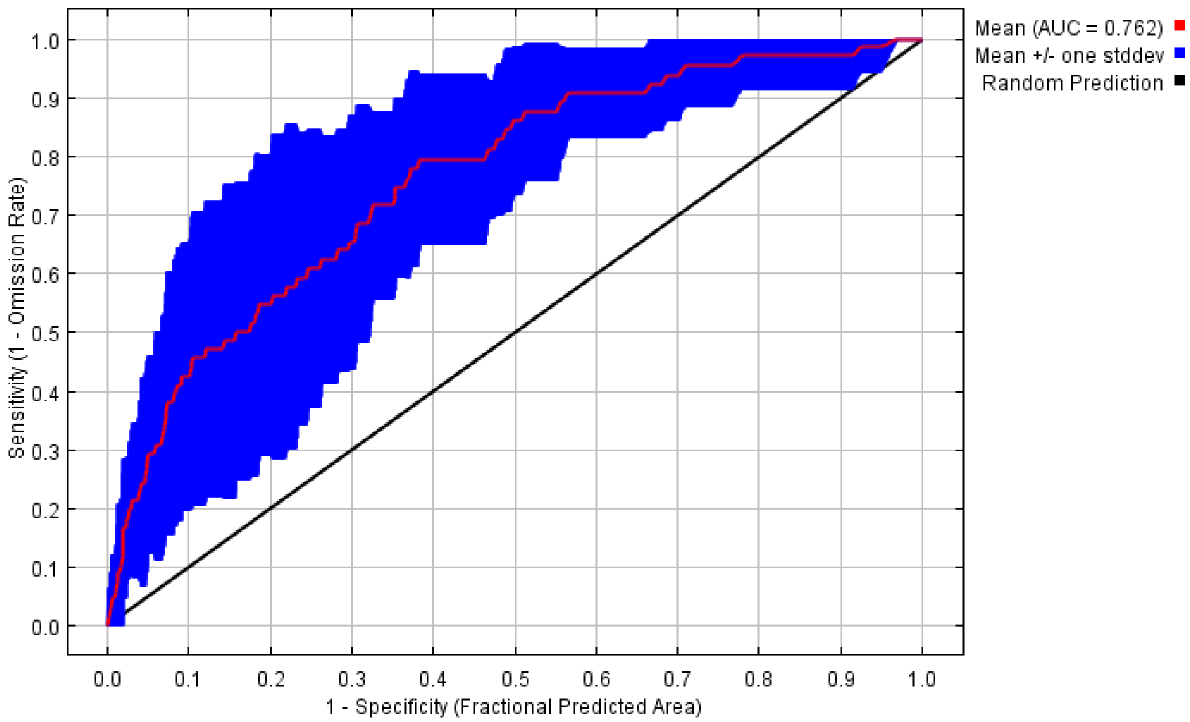


Figure 26. The ROC curve the north-west Model 7, which includes altitude, landform, mature crown density and wind exposure. The results are obtained from 10-fold cross-validation to obtain the mean and standard deviation of the AUC curve.

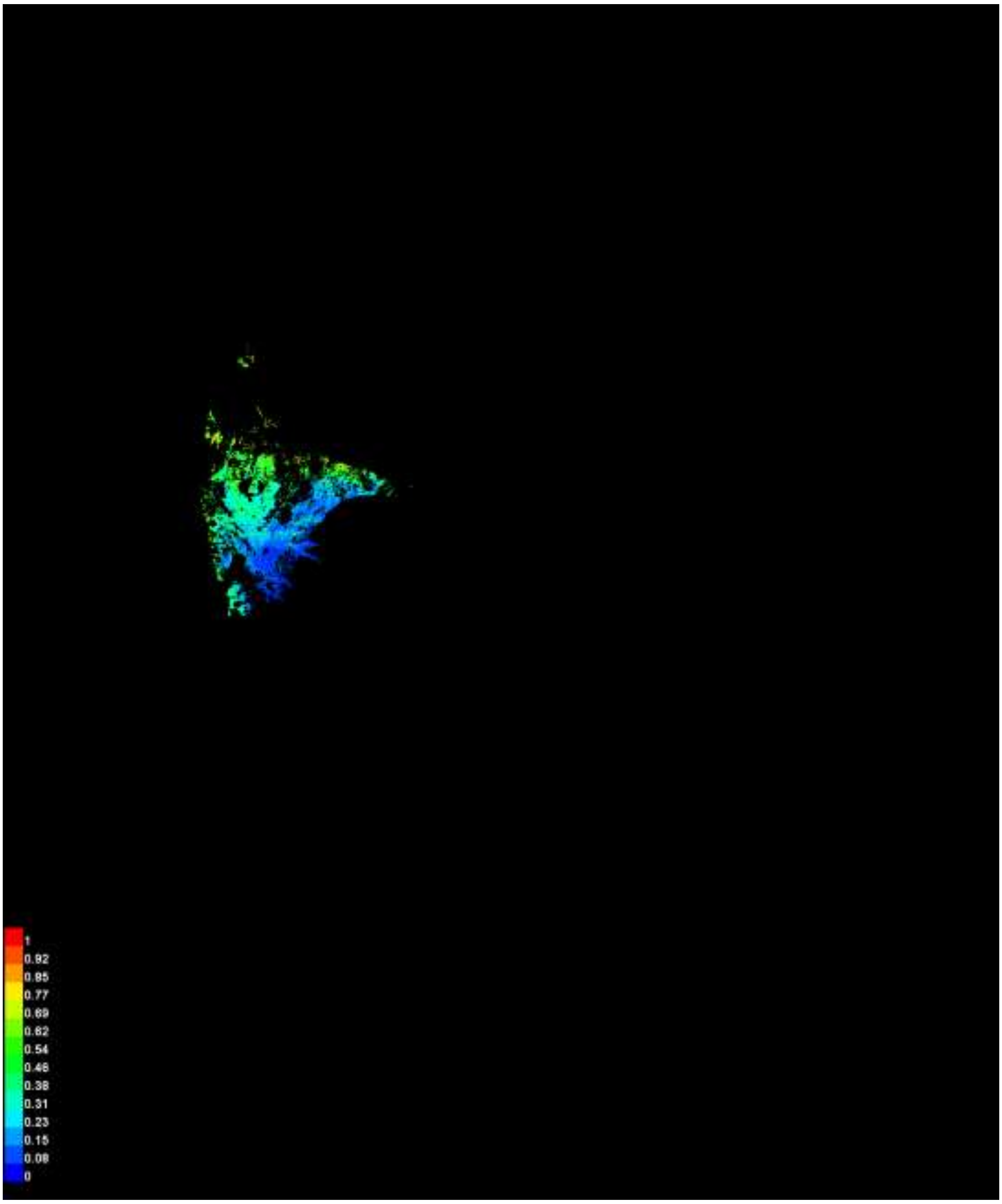


Figure 27. The predicted likelihood of the habitat being suitable for breeding eagles in the north-west, based on altitude, mature crown density, wind exposure and landform. The results are obtained from mean values of a 10-fold cross-validation of the model.

4.4 Comparing three state-wide models predicting eagle nest habitat

There are two other spatial models that currently predict the availability of wedge-tailed eagle nesting habitat. The first is a model by Forestry Tasmania (i.e. the FT model), which uses PI-type information to capture the key recommendations made by Brown and Mooney (1997). The second is a model that has been produced by Bill Brown (DPIPWE) and is the final stages of development. The Brown model has used empirical data and expert opinion to select relevant available spatial data to model suitable habitat. The Brown model has two parts, one approach for the majority of the state, and a slightly different approach for the north-west.

To compare the predictive ability of the three models, we determined the percentage of known nests that were identified from the different models, as well as the area of land covered by each of the models. To do this we downloaded all wedge-tailed eagle nests from the raptor nest database in the NVA (i.e. we excluded eagle nests that were not specified as being wedge-tailed eagle nests). We excluded nests where the accuracy of the locality data was low (greater than 20 m)**,** leaving a sample of 789 nests.

We excluded nests and areas of the habitat models that were not in areas mapped as forest on the TasVeg2 layer (i.e. dry eucalypt forest and woodland, wet eucalypt forest and woodland, rainforest and related scrub, non eucalypt forest and woodland). We then clipped the nests and models to the three different geographic locations used for the MaxEnt modelling; areas under 850 m altitude, areas over 700 m altitude, and areas in the north-west of the state. We then determined which nests were included in the area covered by each of the models, and for the MaxEnt model we determined the likelihood class for each of the nests. We determined the percentage of nests that were included in areas covered by the different models, and we determined the percentage of the forested area that was covered by each of the models (Table 16).

The results showed that for a particular level of accuracy (i.e. to capture the locality of a set percentage of nests), the FT model covered the greatest area, the Brown model covered the next greatest area and the MaxEnt model covered the smallest area. This means the MaxEnt model targets eagle habitat most accurately, followed by the Brown model, followed by the FT model. Therefore if the MaxEnt model is used a greater percentage of nests are expected to be located for a set search area.

Table 16. The percentage of wedge-tailed eagle nests and the percentage of forest area captured by the three alternative models (MaxEnt, Brown and FT), for the three study areas (L850 = low altitude areas, G700 = high altitude areas, NW = north-west of the state). Nests included were those that had accurate locality information (<20 m) and were located in areas mapped by TasVeg as being forest. Areas in grey shading are the MaxEnt likelihood of nest occurrence classes where the percentage of nests captured most closely compares to the percentage of nests captured by the Brown and FT models.

Model	L850		G700		NW	
	Forest nests	Area[a]	Forest nests	Area[a]	Forest nests	Area[a]
TOTAL	680 nests	3,156,724 ha	94 nests	646,691.8 ha	56 nests	170,834 ha
MaxEnt model						
90%+	0.0%	0.0%	0.0%	0.0%	1.8%	0.01%
80%+	4.1%	0.2%	14.9%	0.4%	7.1%	0.6%
70%+	25.9%	1.9%	28.7%	1.7%	25.0%	2.8%
60%+	48.2%	5.0%	40.4%	3.7%	42.9%	6.7%
50%+	62.2%	8.9%	48.9%	6.8%	53.6%	12.7%
40%+	71.2%	13.4%	67.0%	11.2%	67.9%	20.5%
30%+	79.6%	20.5%	71.3%	17.2%	78.6%	32.8%
20%+	88.8%	31.8%	87.2%	25.7%	83.9%	49.9%
10%+	95.7%	49.3%	95.7%	37.9%	89.3%	68.7%
0%+	100%	81.4%	100%	68.8%	92.9%	86.0%
Brown	62.5%	18.9%	63.8%	18.0%	*	*
FT model	64.7%	25.2%	69.1%	62.0%	50.0%	19.4%

[a] Note: the sum of the forest areas is more than the area of forest reported in the FPA State of the Forest Report 2012 due to differences in how forest area was defined, and due to the overlap in area considered between the L850 and G700 models.

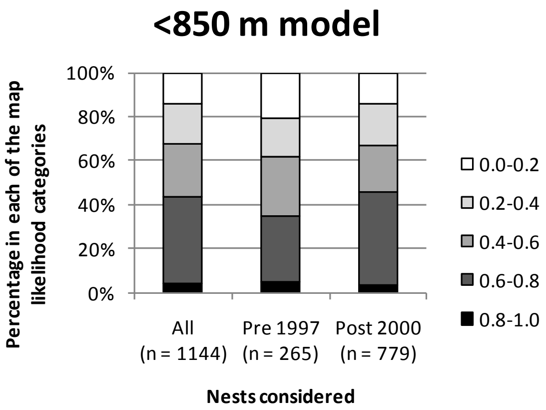
* Data were unavailable at the time of writing this report

4.5 Changes in nest site selection over time and reservation levels of eagle habitat

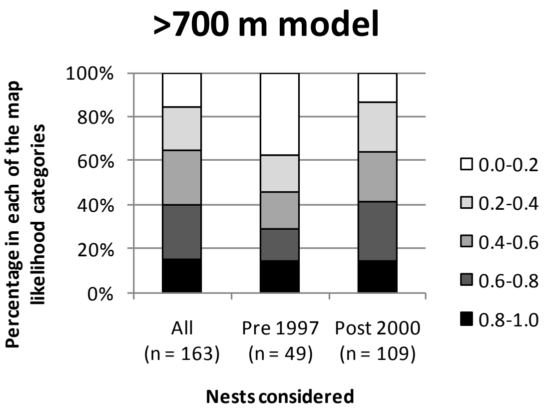
To coarsely assess whether there is any evidence of a change in the areas selected for nest construction over time we determined the number of nests in each of the likelihood classes for nests first recorded prior to 1997, and nests first recorded after 2000. We did this by extracting all eagle nest records from the NVA, and determining the first observation record for each nest. We included white-bellied sea eagle nests as well as wedge-tailed eagle nests because some nests are used by both species. Nests are generally numbered sequentially according to when they are found, so nests with smaller identification numbers were usually located before nests with larger identification numbers. However, when observations lacked an observation date, an arbitrary date of 1/1/1985 has been entered. Therefore we excluded all nests with this observation date that had an observation ID greater than 500. We also

excluded nests with a small observation number that had a late observation date, and nests with a very large observation number that had a young observation date as this data may have been erroneous. The areas in which nests are being constructed appear to be relatively consistent across the time periods considered, with perhaps a slight higher proportion of nests in the lower model categories for older nests (Figure 28).

a)



b)



c)

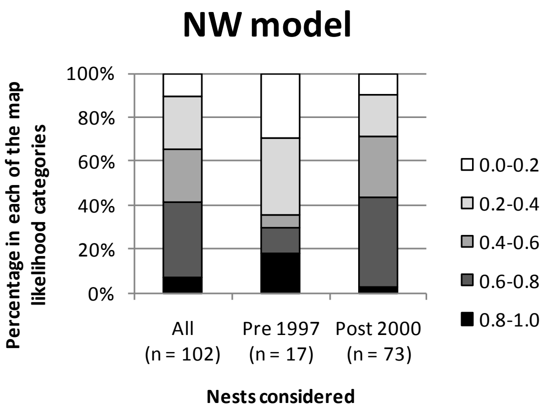


Figure 28. The percentage of (a) all nests, (b) nests first recorded during or before 1997 and (c) nests first recorded during or after 2000 that were located in each of the map likelihood categories (darker colours indicate higher likelihood of nest occurrence). (Note: this data includes sea eagle nests as well because some nests have been used by both species, and does not exclude nests with inaccurate locality data).

To further examine if there is a change in areas being used by eagles as a result of disturbance, we compared the likelihood category for all nests found after 2000, with all nests located in large reserves (>100 ha). For nests located within the boundaries of both the low and high altitude models, we used the higher likelihood classification. We found no evidence that new nests and nests in large reserves differ in how well they are reflected by the models.

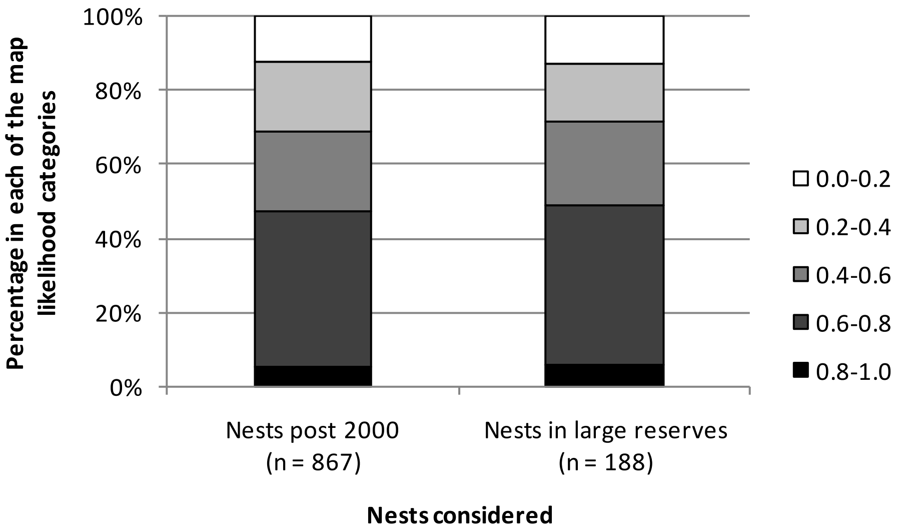


Figure 29. The percentage of nests first recorded during or after 2000 and nests in reserves greater than 100 ha in each of the map likelihood categories (darker colours indicate higher likelihood of nest occurrence). Only nests in areas covered by the model were considered. For nests that were covered by both the <850 and >700 models, we used the highest likelihood value.

To assess the reservation levels of high quality eagle habitat we determined the area of each likelihood class that is encompassed by the CAR Reserve layer relative to the total area covered by this likelihood class for each of the three models. For the majority of the state 35–46% of the each likelihood category was in reserve, with slightly lower levels of reservation in the north-west (Table 17). There is some variability between likelihood categories in the level of reservation, but no obvious bias towards reserving areas more or less suitable for eagles.

Table 17. For each of the nest occurrence likelihood classes the percentage of the area that is captured in formal or informal reserves.

Range of nest occurrence likelihoods	Percentage of modelled area in formal or informal reserve		
	<850 m	>700 m	NW
0.0–0.2	35.9	35.9	28.7
0.2–0.4	41.4	45.5	20.2
0.4–0.6	37.0	46.4	17.9
0.6–0.8	40.7	42.9	18.4
0.8–1.0	38.8	37.2	22.1
Total	37.5	39.3	23.4

4.6 Discussion

Our results confirmed the conclusions reached in previous studies (Brown & Mooney 1997; Mooney 1988a; Mooney & Holdsworth 1991) - that eagles construct nests in areas that contain mature eucalypts and are sheltered from wind. Previous modelling found that the height of the forest was important, but stand height was not identified as an important predictor in the current modelling. The differences among the three models we produced (<850m, >700m and NW) are assumed to occur because different variables best reflect wind protection in the different regions of Tasmania due to variation in landform, vegetation type and altitude.

We found that nests in low altitude regions were most likely to occur on easterly slopes that were protected from the wind. Nests were more likely to be found mid-slope rather than on hilltops or in gullies. In high altitude areas (e.g. the central plateau highlands) nests were more likely to occur on mid-slopes of intermediate steepness that were easterly facing. They were also located in areas with greater protection from the wind, generally corresponding to lower altitude areas. In the north-west nests were located in low altitude areas and were more likely to be found in gullies and steep lower-slopes.

In all areas, except the north-west, nests were more likely to be located on east facing slopes. East facing slopes are likely to be more protected from the prevailing westerly winds that occur in Tasmania. The north-west has minimal topographic relief, with most of the region being fairly low-lying, so easterly slopes may not provide the same level of protection in the north-west as it does in other regions of the state.

Nests were unlikely to be found in areas with no mature eucalypts, with some indication that they are more likely to be found in areas with a higher density of mature eucalypts. Eagle nests are large structures and require large branches to support them, so nests are generally found in large, mature trees. The fact that some nests occur in areas mapped as having no mature trees could be due to inaccuracies in the mapping layers, inaccuracies in the nest localities, or because the nest records are old and existed when the forest structure was different to that of today.

We examined the location of old (pre 1997) and new (post 2000) nests in relation to the predicted map classes to see if there was any evidence of a shift in the areas used for nesting by eagles. This analysis is not to be considered as conclusive, because both the old and new nests were used in the construction of the map. However, we found no evidence of a general trend for new nests to be located in lower quality habitat. Some new nests may be constructed in unusually low quality habitat (J. Wiersma, pers. obs.), but the data does not support a general trend across the population for eagles to be selecting lower quality habitat.

The results showed that in most areas of the state there is no bias for or against reserves being located in areas most likely to contain eagle nests.

4.6.1 Management implications

While eagle nests can be found in areas predicted to have a low likelihood of nest occurrence, the majority of nests are located in areas predicted to have a relatively high likelihood of nest occurrence. The majority of the state is predicted to have low likelihood of nest occurrence. Therefore these models can provide a high resolution tool to assist forest planners in deciding where to concentrate eagle searches. For areas of the state where there is overlap between the low and high altitude models, we recommend that both models are examined and used to identify search areas.

While this mapping layer is a potentially useful tool, it does have some limitations. Firstly, there is a bias in the nest locality data that were used to construct the models, in that nests are most frequently found during production forestry activities. While this may create some bias in the predictive maps, this bias cannot be addressed until greater searching is done in reserves. The map is expected to be primarily used as part of industry activities and so the conservation implication of any bias is expected to be minimal.

The second limitation is that older nests are likely to have lower accuracy, but changes in habitat selection may have occurred over time due to disturbance in the landscape. To cater for potential changes in habitat selection we used older nests despite a lack of knowledge about the accuracy of the locality records. The use of these nests may have had some impact on the model results, but the potential contribution of these nests was considered more important than the risk of not including them.

The MaxEnt model is more efficient in identifying potential eagle nesting habitat than existing models, in that the ‘search’ area is approximately halved to locate a similar proportion of known nests. The MaxEnt model provides greater detail than existing models, by presenting areas in terms of their likelihood of containing a nest rather than being areas of potential habitat versus not potential habitat. While the MaxEnt model does not provide a definitive answer for the areas that should or should not be searched for new nests, the data provided in Table 16 can be used to establish which areas should be surveyed to achieve a specified level of ‘risk’ of missing nests. Therefore the MaxEnt model is expected to be a useful planning tool that will help improve management of eagle nests in production forestry areas.

5 Summary and conclusions

This study was initiated in 2007. The first year of data was used to conduct a preliminary exploration of the relationship between the production of a nestling at a nest site, and the characteristics of the nest, nest tree and surrounding area. The study also evaluated how the characteristics of the nest can be used to indirectly determine whether the nest produced a nestling in the most recent breeding season (Wiersma & Koch 2012). This analysis of nest site characteristics enabled revision of the Nest Activity Sheet used by forest planners to improve the accuracy of nest assessments done by trained eagle officers.

In the second year of study it became obvious that there could be considerable variation in the timing of the breeding season, with the 2008–09 season starting approximately six weeks later than the 2007–08 season. This result prompted a review of the management period, with the recommendation made to extend the period when management actions are required to allow for this annual variation in breeding events (FPA & DPIPWE 2011).

The current report showed that the rates of nest success can vary considerably between years, and that non-use of a nest in a particular year does not mean a nest won't be used at some stage in the future. Most nests tended to be used in successive years, with generally only one or no unproductive years between breeding events. However there are nests that were not successful in the first four years of survey from which a chick was produced on the fifth year, and nests that were used for one or two years and then not for the rest of the study. Eagles may not breed every year, and most nests will not produce a nestling in any one year. The most productive nests appear to be ones that are at higher altitude, on moderate slopes and in heterogeneous landscapes (i.e. areas that contain young and old forest and agricultural land).

The results of this study suggest that current management appears to effectively minimise the impact of forestry operations on breeding Tasmanian wedge-tailed eagles. The size of prescribed nest reserves appears to be adequate if the reserves are designed appropriately (i.e. to minimise exposure to prevailing wind) and other required conservation measures applied. The occurrence of forestry operations within 1 km of the nest in the 12 months **prior** to the breeding season was related in the models to a reduced likelihood that a nestling will be produced. However, forest operations were more prevalent around inactive nests than active nests and so the result may not be due to a causal relationship. In fact, when individual nests were examined they were equally likely to be used in successive years whether a forest operation occurred within 1 km of the nest or not. Therefore while it is recommended that further study be done (particularly of the effect of aerial operations near nests during the breeding season) our data found no evidence that forestry activities conducted under current management recommendations are affecting the breeding success of eagles. There are, however, limitations to this study. For example, this is an observational study not an experimental study, so it is difficult to make strong conclusions on causal relationships. In addition, this study monitored the success of a selection of nests, not the breeding success of breeding pairs. Further study is required; particularly research to determine whether forest operations in the landscape around inactive nests prevent breeding birds from using these nests in the future.

We found no evidence that nests likely to be active can be identified according to the attributes of the nest tree or the characteristics of the area immediately around a nest. However, all nests were located in large mature trees in areas that are sheltered from the wind. The new MaxEnt eagle habitat models developed in this project can be used to improve the location of existing nests before forestry operations occur (or other land-use activities that may disturb breeding pairs).

5.1 Recommended future work

This study has made a considerable contribution to our understanding of eagle breeding biology and the effectiveness of current management for maintaining breeding success of wedge-tailed eagles. It is important that this work is continued in order to further increase our understanding of the long-term changes in nest use and re-use, particularly in relation to disturbance. However, other studies are also recommended in order to fully understand the effectiveness of current management.

- *Monitoring the eagle population (i.e. trend monitoring) -an essential component of an effectiveness monitoring program.* Trend monitoring allows the cumulative impacts of different land uses and climatic conditions on species to be examined. Trend monitoring has limited capacity to identify the causes of any changes to the population, but can be complemented by studies such as this one to assess if/which factors are impacting populations.

- *A study of variation in the timing of eagle breeding season in relation to climatic conditions.* The results of this work could potentially be used to predict if a breeding season is expected to be early or late, so that the management period could be adjusted accordingly.

- *A study examining nest success in relation to patch size.* Data collected in the current study supported the use of a 10 ha reserve around eagle nests. However patch size was only considered in three broad groups. A study examining nest success in relation to patch size that focused on smaller patches (5-20 ha) could examine in more detail whether 10 ha, or a slightly smaller or larger patch, is the optimal reserve size.

- *A behavioural study that looks at how particular types of disturbance affect individual breeding birds*. The power of the current study to evaluate the effectiveness of current eagle nest management depends on the number of instances when particular forest operations occur near active nests during the study. For example, the current data set had very few known instances of aerial operations occurring within 1km of the nest during the breeding season. Therefore the power of this study to evaluate the impact of this type of operation is extremely limited. A behavioural study that looks at how particular types of disturbance affect individual breeding birds will provide greater understanding of the effectiveness of current management.

- *A behavioural study to help identify the primary nests within a breeding territory*. Behavioural studies could also be used to assess the areas that wedge-tailed eagles use

when not at the nest site. For example, such a study could explore the importance of mature forest and agricultural land for foraging. This type of study also has the potential to help identify the primary nests within a breeding territory, and provide insight on how landscapes could be managed to maximise eagle conservation. Nests differ in how frequently they're used by breeding birds. Being able to differentiate between frequently-used and lesser-used nests could be used to prioritise management.

- *Development of a planning tool to identify the 500m/1km line-of-sight area around known nests.* This planning tool would help forest planners identify exclusion zones and would facilitate implementation monitoring of the eagle provisions. While a line-of-sight model has been produced for some areas (B. Brown pers. comm.), it has yet to be made available to all forest planners for all nests.

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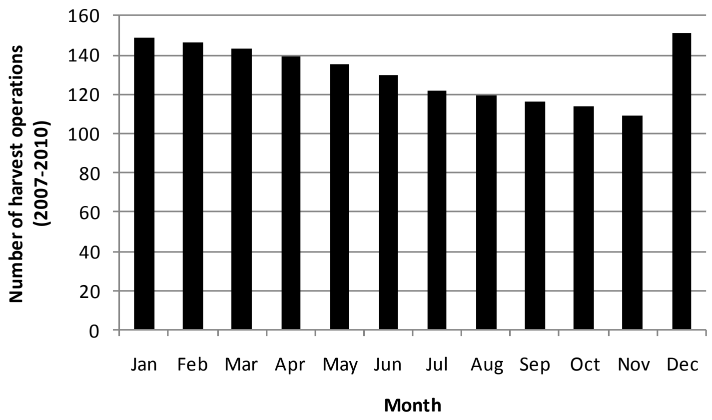
7 Appendix A: Project milestones, key activities, and dates for priority action achievements

Activity	Milestone	Achievement indicator	Progress
Selection of additional ‘control’ and ‘managed’ nest sites in areas in each bioregion of the State.	Addition of new ‘managed and ‘semi-natural nest sites to the project nest site database.	Sites selected and locality confirmed by August 2009.	Completed
Continue collection of tree and site level variables (including disturbance and protection measures) for each nest site using methods established in 2007–08.	Completion of environmental variable data collection.	Environmental variable data collected and entered by May 2009.	Completed
Data analysis.	Completion of data analysis. The relationship between nest site characteristics (including degree of disturbance and protection measures) and nest use and productivity will be explored using Generalised Linear Modelling in which link functions appropriate to the outcomes will be used, such as a logit link for fledging success. The model will be conducted using Bayesian methods to properly account for uncertainty in variables and potentially in the model. It is expected that the model results will also form a component of a larger Bayesian population viability model.	Data analysed and summary graphs/tables.	Completed
Complete the monitoring of the implementation of eagle nest management prescriptions for 2007–08 FPPs.	Analyse the data collected and summarise for report.	Relevant report chapter completed in March 2010.	To be completed in 2012–13
Collate results/information and produce a final report including detailed results of the three year project work and recommendations for future monitoring. Report will include any recommendations for changes to the conservation management actions for the maintenance of nesting habitat for the wedge-tailed eagle.	Complete 3 year Final Report.	Final report and recommendations used to inform the revision of management actions.	Completed
Planning for 2010–11 annual nest survey.	2010–11 survey data.	Data provided by aerial survey	Completed
Determine the timing of breeding events.	Define breeding stages and time spent by eagles at each stage to provide timeline of events from known age nestlings.	Development of graphs from known age nestlings	Completed
Explore the relationship between nest success and forest patch size.	Estimate patch size and conduct analyses.	Results from statistical analyses	Completed
Review wedge-tailed eagle habitat model from data collected from field work.	Collect tree level data.	Production of new WTE habitat model	Completed

8 Appendix B. Graphs of raw data of forest operations

To try and determine the types of forest operations that may impact eagle breeding, we qualitatively examined the forest operations data in more detail. We differentiated forest operations data into harvest operations (‘harv’), burning (operation type = ‘burn’ or ‘frb’) or aerial disturbance (operation type = ‘ferts’, ‘herbi’, ‘pestc’ or ‘sow’). Some of the categories included as aerial disturbance may have been conducted from the ground rather than from the air, but data were not available to differentiate between these. Furthermore, if a harvest operation is suspended for a period (e.g. during the breeding season) this is not indicated in the data set and so the duration of some forest operations indicated in this data set are likely to be longer than actually occurred. This detail of data was only available for operations conducted by Forestry Tasmania, and so we excluded nest-years that were within 1km of a forest operation conducted by a different company. We examined the success and non-success of nests in relation to the type, timing and duration of disturbance. The majority of operations were harvesting, but aerial and burning occurred and were more prevalent around April-May than other times of the year (Figure 30). The data suggests that disturbance during the breeding season may influence nest success in later years (Figure 35), and the longer the duration of the disturbance the less likely a nestling will be produced on a nest (Figure 39). The data do not show an obviously strong impact of harvesting (Figure 32, Figure 36), but potentially an impact from burning and aerial work (Figure 33, Figure 34, Figure 37, Figure 38). No formal analysis has been conducted looking at the type, timing or duration of disturbance.

a)



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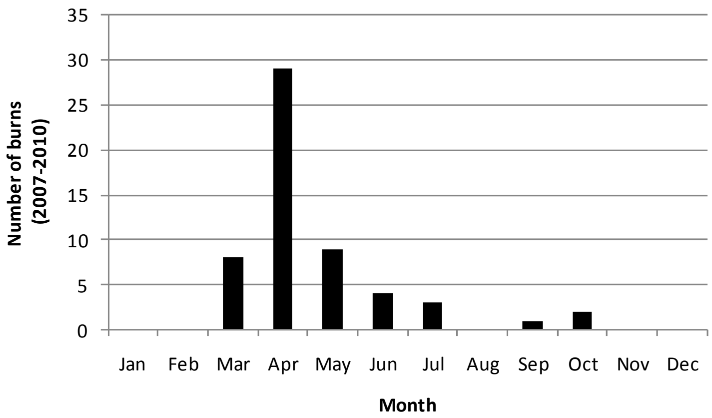


c)

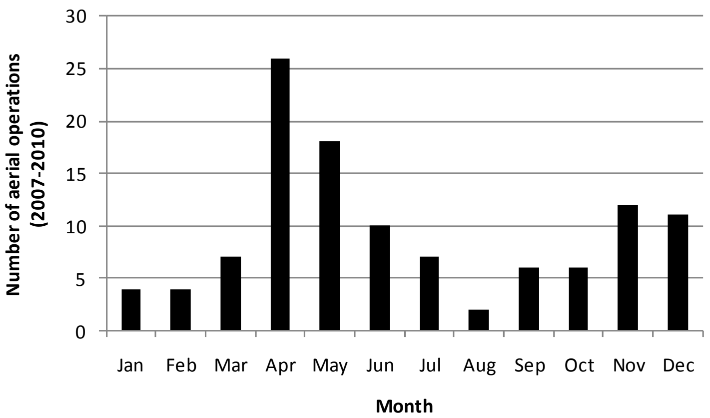


Figure 30. Raw data for the total number of (a) harvest operations, (b) burns and (c) aerial operations that occurred on a particular month for the years 2007 – 2010. These figures show only Forestry Tasmania data (note, for December the data spans from 2006 to 2009 rather than from 2007–2010).

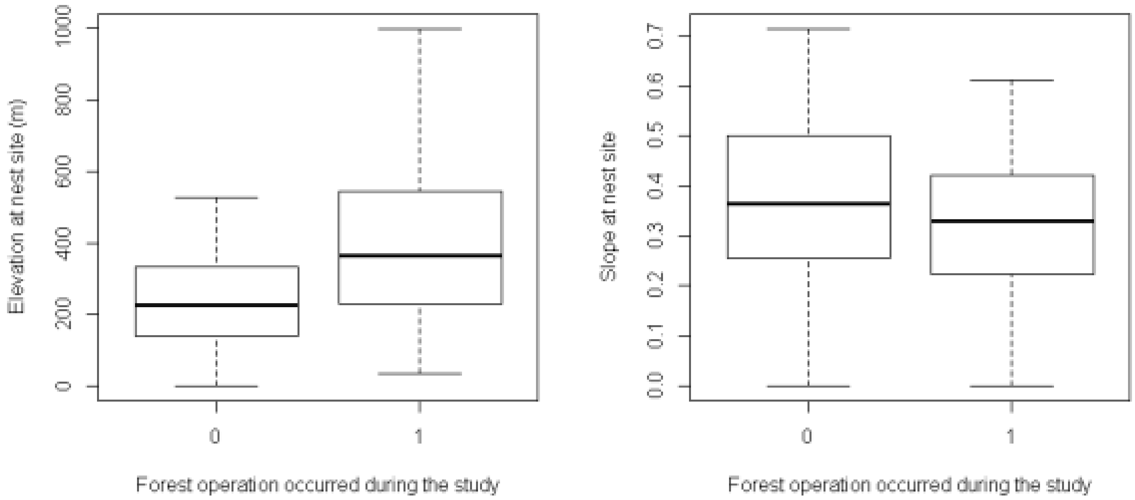


Figure 31. Raw data considering whether the (a) altitude or (b) slope of the site on which the study nest trees were located is related to whether a forest operation occurred within 1km of the nest during the course of the study. N = 145 nests. '1' indicates presence and '0' indicates absence.

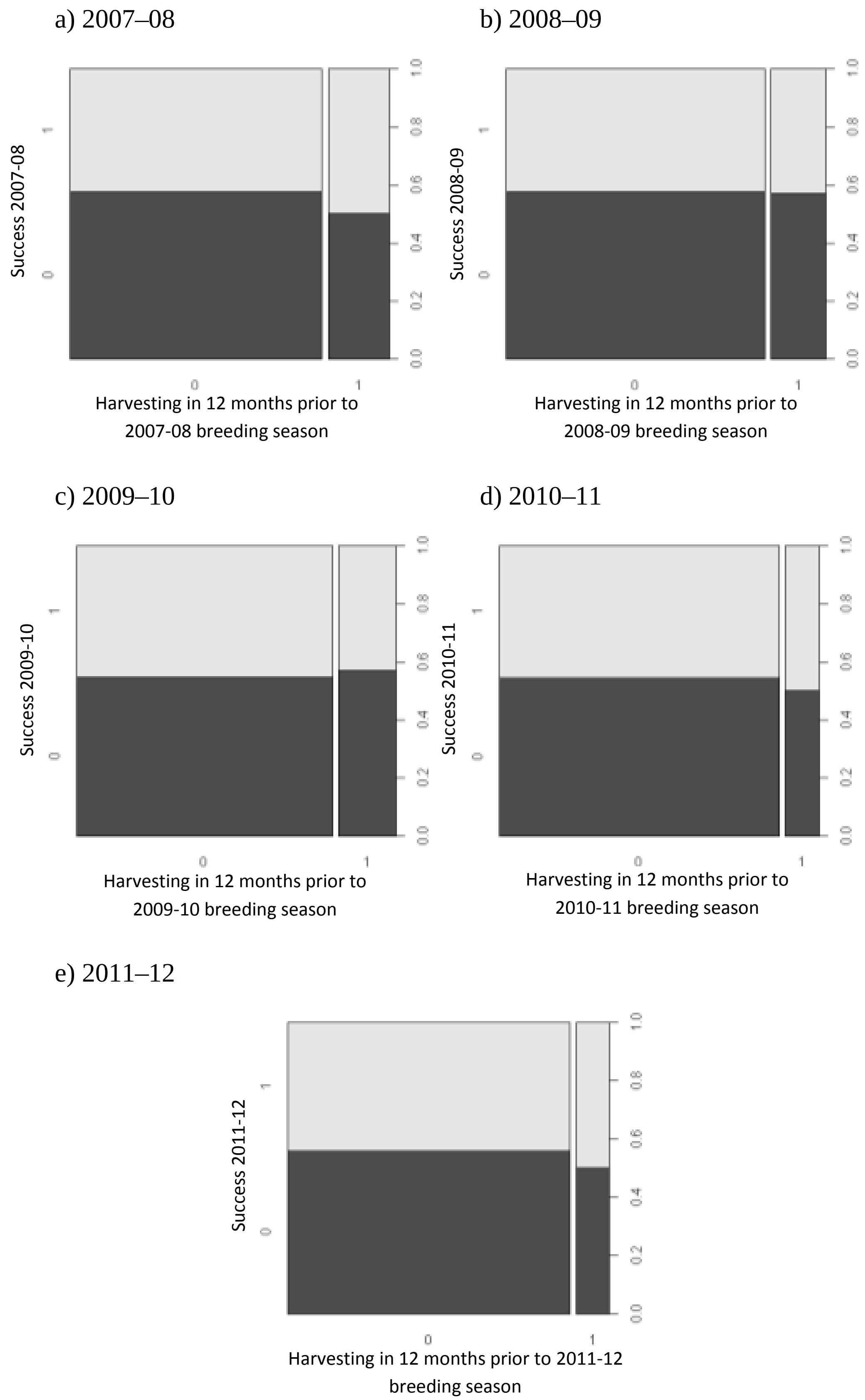


Figure 32. Raw data comparing seasonal nest success with the occurrence of a forest operation in the 12 months prior to the breeding season. This data uses only Forestry Tasmania data, and excludes nests where an operation by another company was known to occur during this time. Sample sizes are 41 (2007), 34 (2008), 84 (2009), 82 (2010) and 101 (2011). '1' indicates presence and '0' indicates absence. The width of the bars indicates the relative sample sizes.

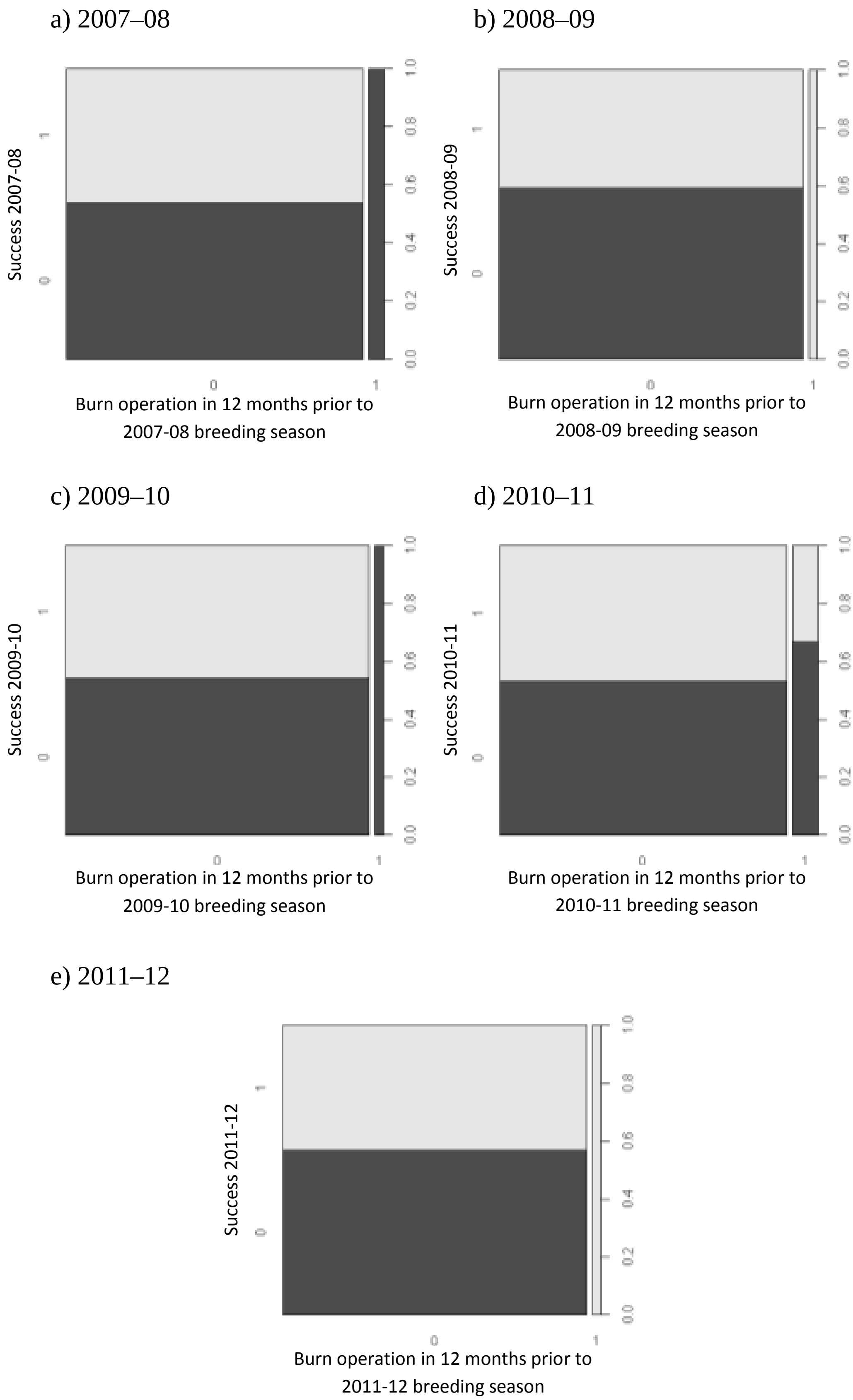


Figure 33. Raw data comparing seasonal nest success with the occurrence of a burn operation in the 12 months prior to the breeding season. This data uses only Forestry Tasmania data, and excludes nests where an operation by another company was known to occur during this time. Sample sizes are 41 (2007), 34 (2008), 84 (2009), 82 (2010) and 101 (2011). '1' indicates presence and '0' indicates absence. The width of the bars indicates the relative sample sizes.

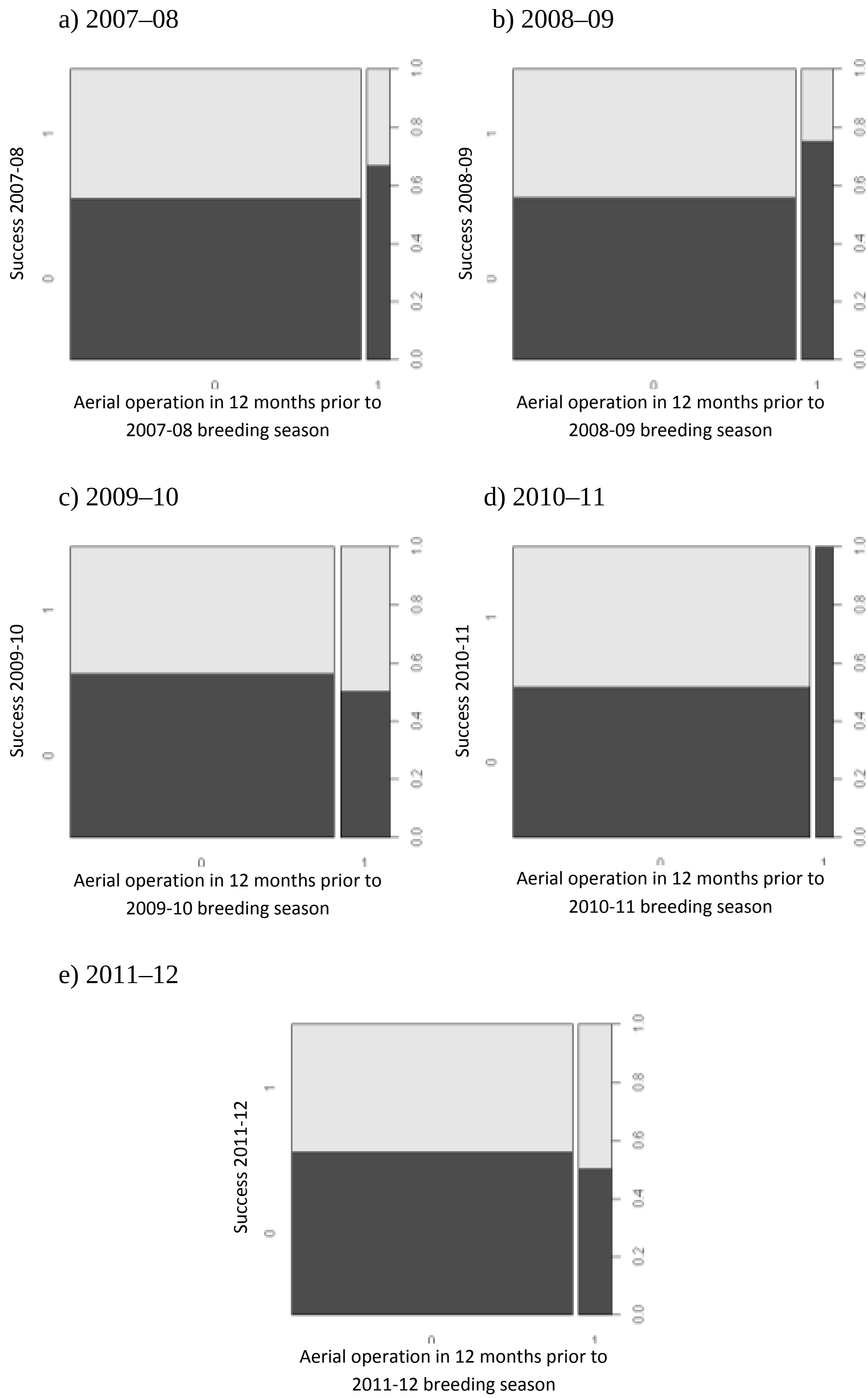
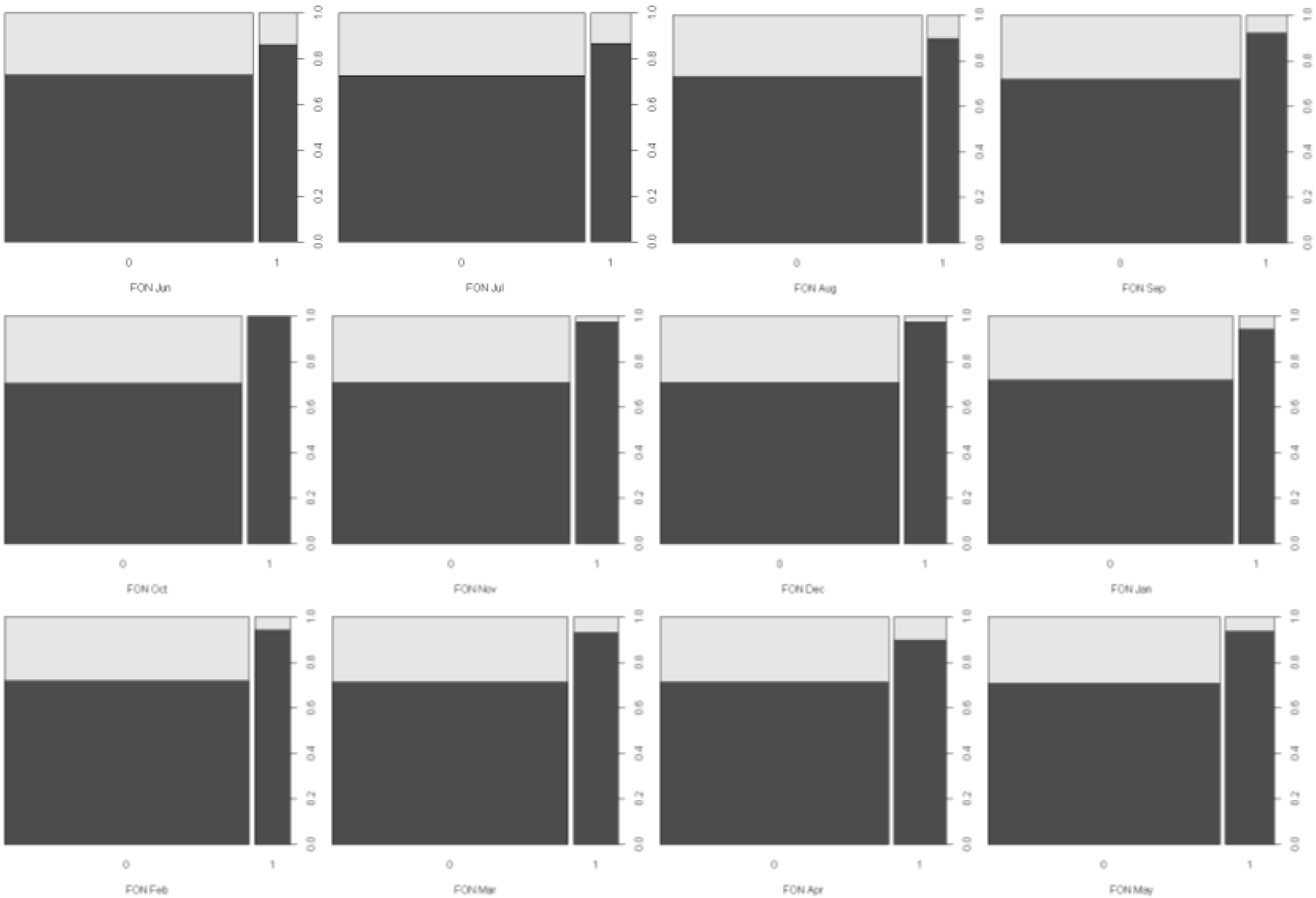


Figure 34. Raw data comparing seasonal nest success with the occurrence of a aerial operation in the 12 months prior to the breeding season. This data uses only Forestry Tasmania data, and excludes nests where an operation by another company was known to occur during this time. Sample sizes are 41 (2007), 34 (2008), 84 (2009), 82 (2010) and 101 (2011). '1' indicates presence and '0' indicates absence. The width of the bars indicates the relative sample sizes.


FON Jun
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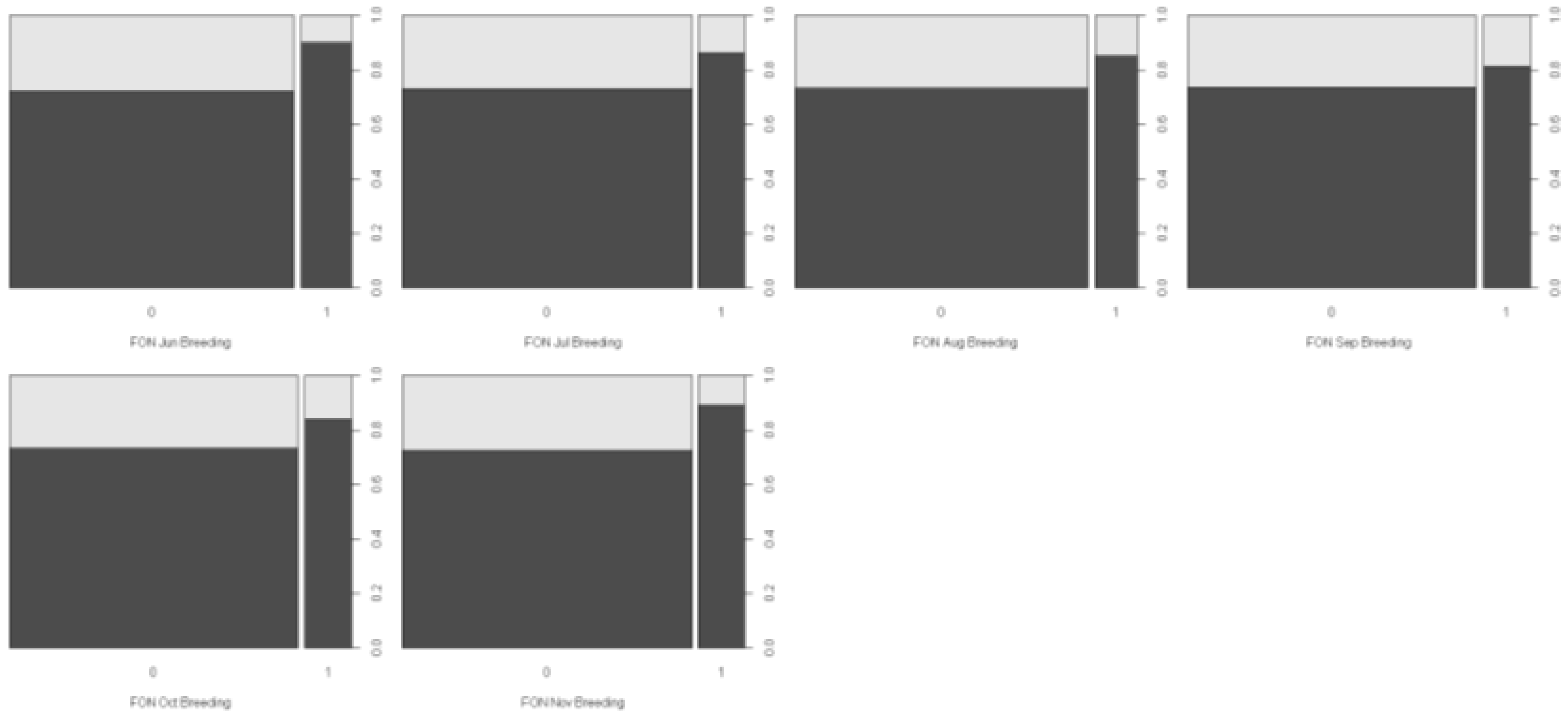
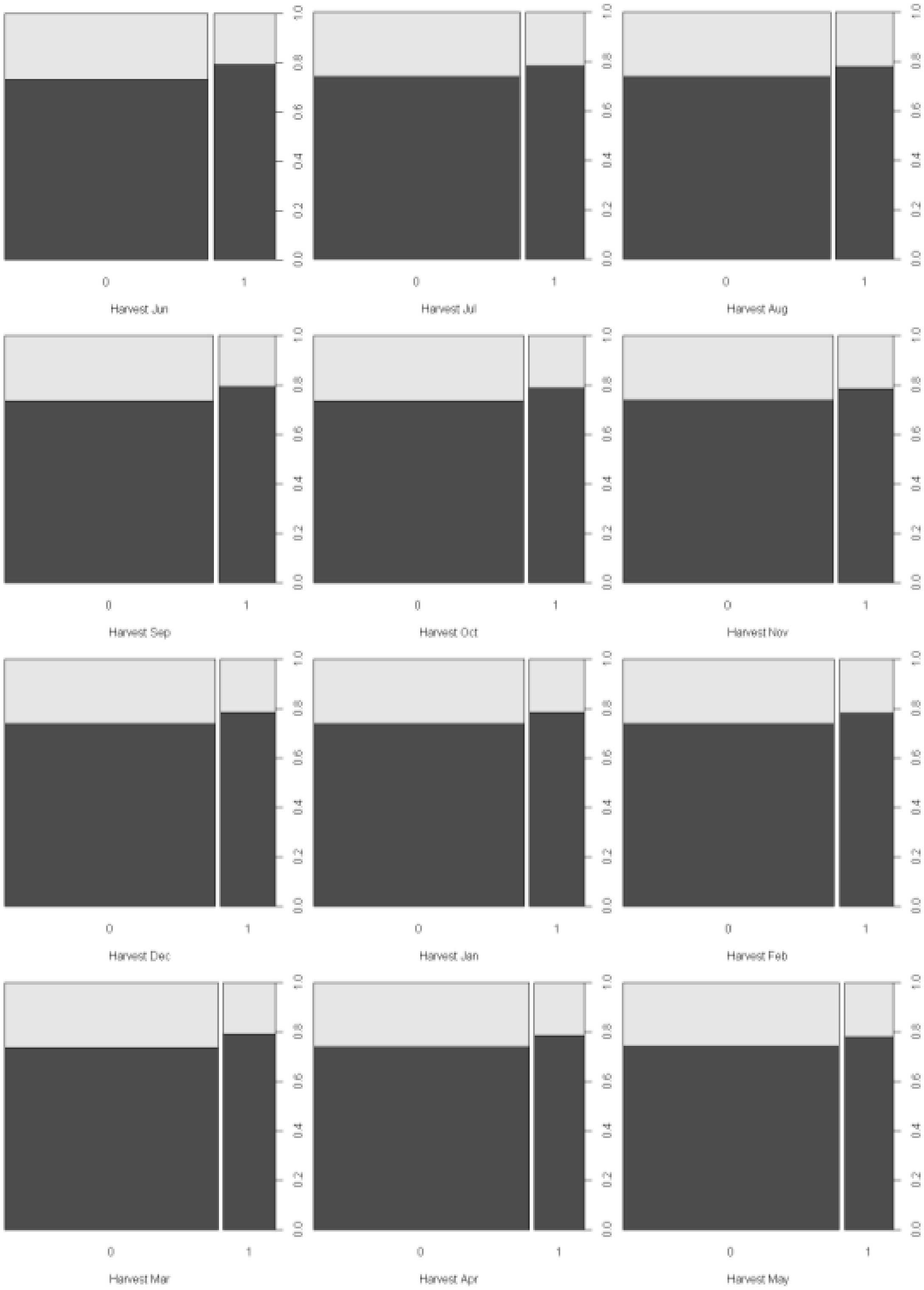


Figure 35. Raw data comparing seasonal nest success with the occurrence of a forest operation (FON) for each of the 12 months prior to the breeding season, and the six months during the breeding season. This data uses only Forestry Tasmania data, and excludes nest-years where an operation by another company was known to occur during this time. Sample size is 730 nest-years. '1' indicates presence and '0' indicates absence. The width of the bars indicates the relative sample sizes.


Harvest Jun
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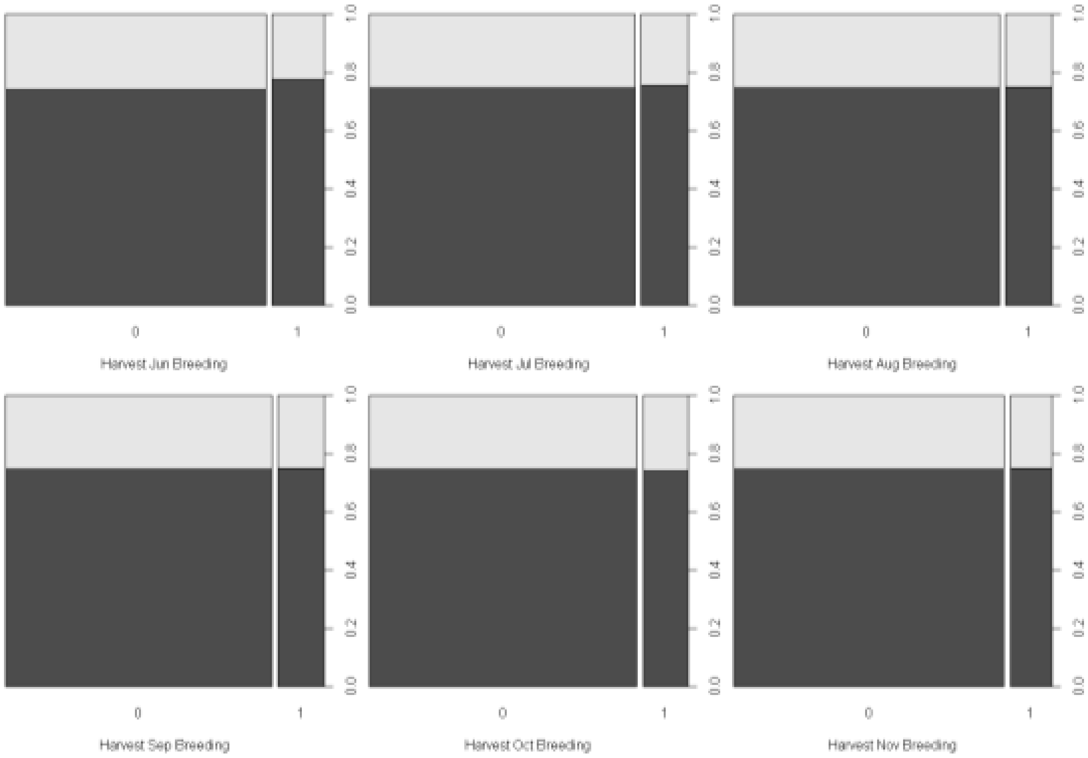


Figure 36. Raw data comparing seasonal nest success with the occurrence of a harvest operation for each of the 12 months prior to the breeding season, and the six months during the breeding season. This data uses only Forestry Tasmania data, and excludes nest-years where an operation by another company was known to occur during this time. Sample size is 730 nest-years. '1' indicates presence and '0' indicates absence. The width of the bars indicates the relative sample sizes.

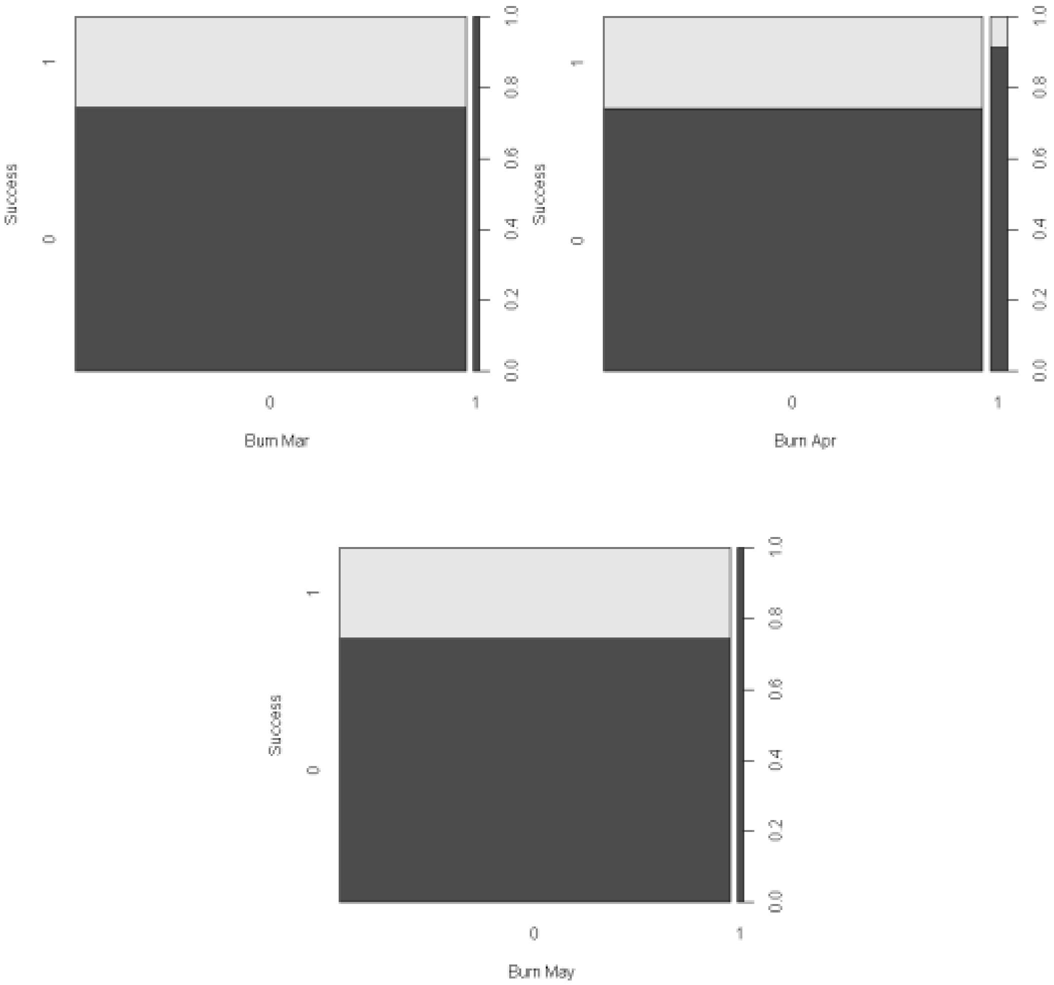
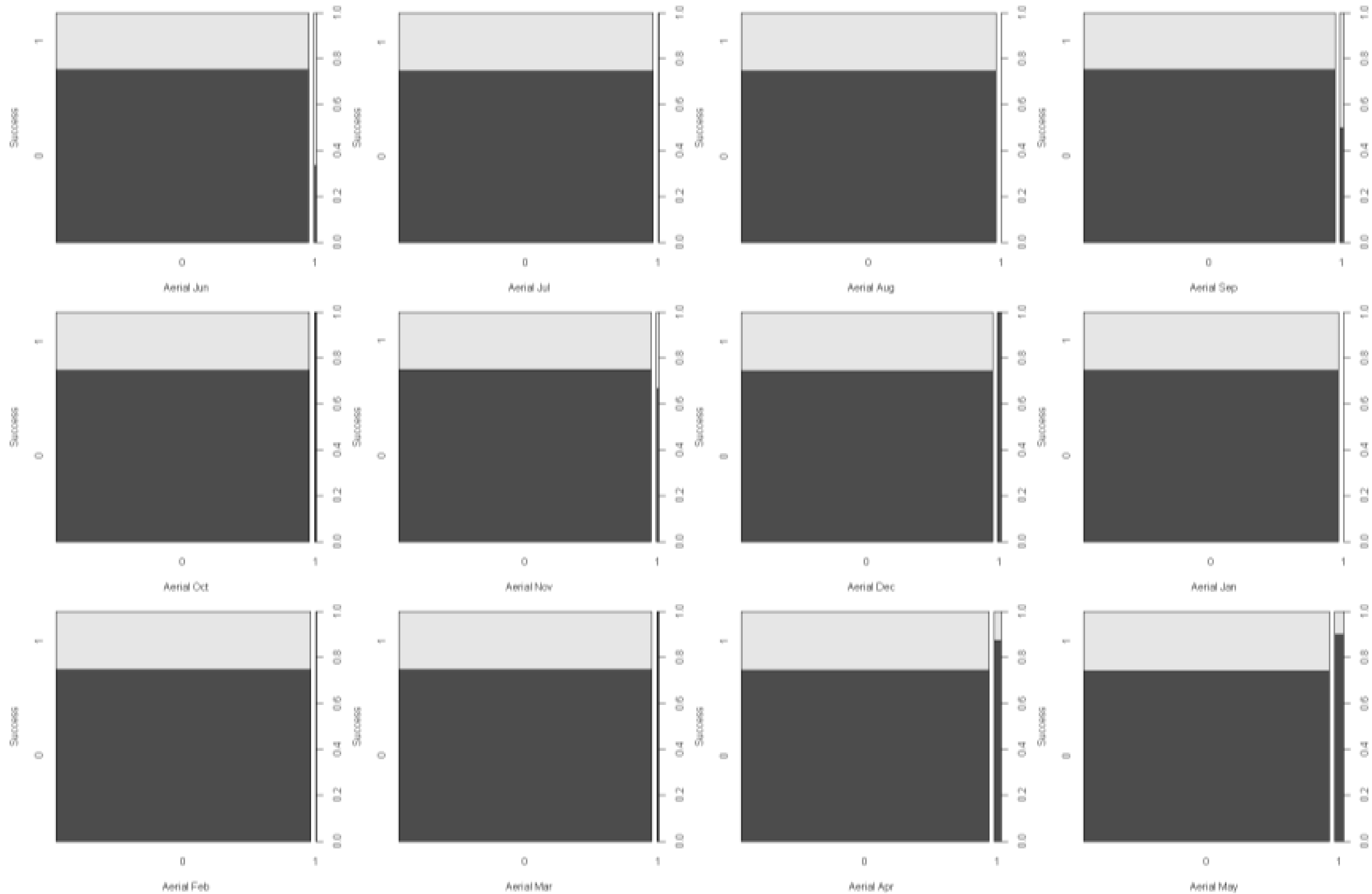


Figure 37. Raw data comparing seasonal nest success with the occurrence of a burn operation for the three months of the burning season prior to the breeding season. This data uses only Forestry Tasmania data, and excludes nest-years where an operation by another company was known to occur during this time. Sample size is 730 nest-years. '1' indicates presence and '0' indicates absence. The width of the bars indicates the relative sample sizes.


Success
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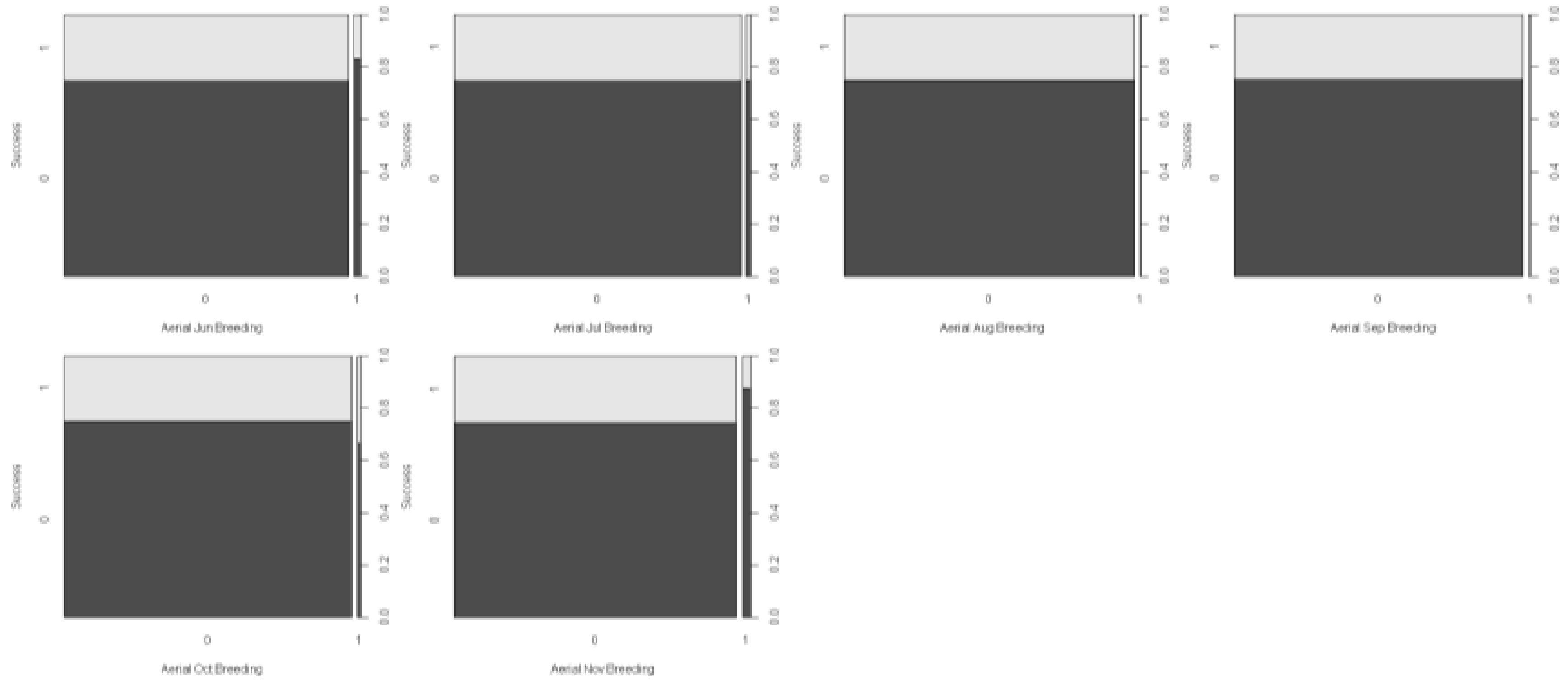
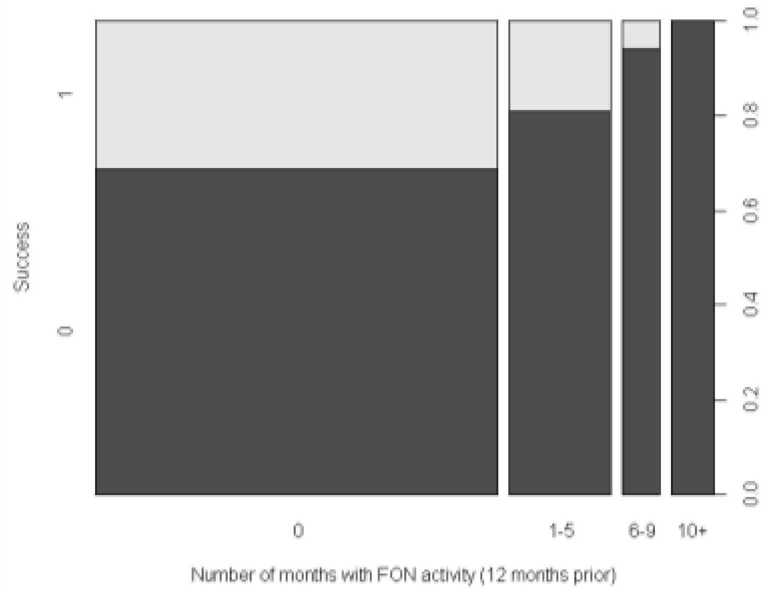


Figure 38. Raw data comparing seasonal nest success with the occurrence of an aerial operation for each of the 12 months prior to the breeding season, and the six months during the breeding season. This data uses only Forestry Tasmania data, and excludes nest-years where an operation by another company was known to occur during this time. Sample size is 730 nest-years. ‘1’ indicates presence and ‘0’ indicates absence. The width of the bars indicates the relative sample sizes.

a)



b)

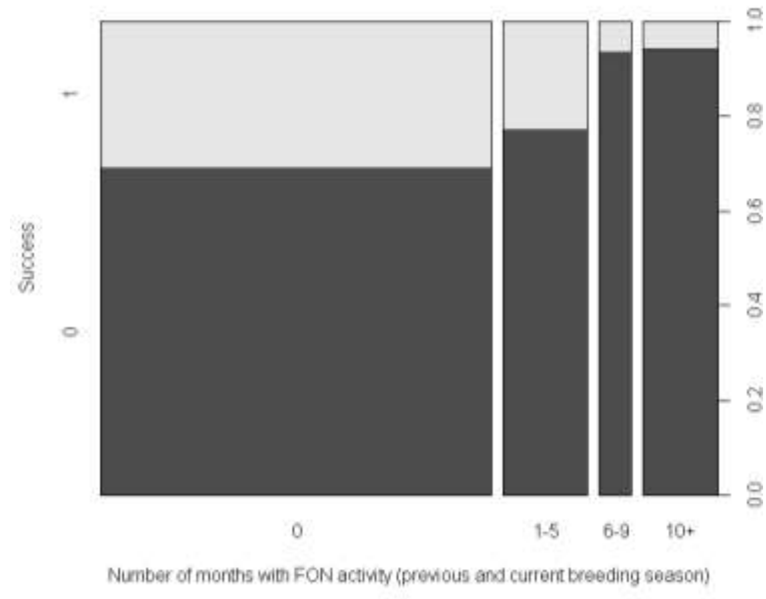


Figure 39. Raw data comparing seasonal nest success with the duration (number of months) of forest operation for (a) the 12 months prior to the breeding season, and (b) the 12 months prior to the breeding season and the six months during the breeding season. This data uses only Forestry Tasmania data, and excludes nest-years where an operation by another company was known to occur during this time. Sample size is 730 nest-years. '1' indicates presence and '0' indicates absence. The width of the bars indicates the relative sample sizes.

9 Appendix C - Summary of nest success rates for the Tasmanian wedge-tailed eagle from various authors

Source of data	Year of study	Description of nest location	Number of nests assessed	Nest success rate %
Mooney and Holdsworth (1991)	1989	Disturbed[1]	19	43
		Little disturbed[2]	11	84
Mooney and Taylor (1996)	1996	-	11	60
State of the Forests Report (Forest Practices Authority 2007)	2000	-	206	27.7
	2001	-	127	22.0
	2002	-	72	20.8
	2003	-	67	4.5
	2004	-	92	19.5
	2005	-	209	10.1
Brown, unpublished data and Mooney (2005)	2000	Disturbed	129	23.3
		Little Disturbed	43	39.5
	2001	Disturbed	93	14
		Little Disturbed	27	51.9
This study	2007-08		47	40
	2008-09		47	9
	2009-10		105	28
	2010-11		104	19
	2011-12		116	17

[1] clearfell/clearing, partial harvest, roading/quarrying, intensive farming, intensive recreation, directed disturbance,

[2] non-intensive farming and non-intensive recreation.

10 Appendix D: Eagle nest tree recruitment

In March, April and May of 2011, the Forest Practices Authority hosted a Dutch intern student from the University of Applied Science Van Hall Larenstein, Cyriel van de Winckel. Cyriel spent a substantial amount of time in the field and on the computer, conducting a small research project that contributed to the larger FPA project monitoring the effectiveness of the wedge-tailed eagle management provisions. Cyriel has given permission that a condensed and edited summary of his project be published as an appendix in the current report.

10.1 Background

Recent modelling of the relative importance of different sources of mortality and nesting loss for wedge-tailed eagles concluded that loss of current and potential future nesting sites is a major threat for this species (Bekessy et al. 2009). Wedge-tailed eagle nests in Tasmania are lost periodically due to windthrow, collapse, fire or tree felling. Therefore it is important that eagle management considers the availability of potential nesting sites.

Current eagle management in production forest areas is focused primarily at placing a 10 ha reserve around known eagle nests. The 10 ha size is thought to partially buffer the disturbance-sensitive wedge-tailed eagles against human activities occurring outside the reserve, with nests to be located at least 100 m from the edge of the reserve (FPA Threatened Fauna Adviser). The objective of the current project was to consider the long-term habitat potential for eagles in eagle reserves, by assessing the availability of recruitment trees.

10.2 Methods

10.2.1 Study Sites

The current study was conducted in 35 eagle nest reserves (informal forestry reserves) across Tasmania (Figure 40). Although informal attempts were made to examine nest reserves located in a range of forest types, geographical regions and land tenures, no formal stratification of sampling was done. Instead, sites were examined opportunistically according to the activities of other eagle nest surveys being conducted by FPA staff.

The size of the forest patch within which each nest reserve was located was assessed as per the current report. That is, reserves were located on Google Earth images and the outline of visible, connecting (<50 m), undisturbed forest areas was traced. Due to differences between the time images were taken (variable) and the time of survey, current patch size may not exactly match the estimated size of the patches. The vegetation community at each nest tree was assessed both remotely (using TasVeg mapping layer) and on-site using the FPA Forest Botany Manual (Forest Practices Authority 2005). Site aspect and slope were remotely assessed at the location of each nest tree using the Digital Elevation Model.

Figure 40. Map of Tasmania showing the location of nest reserves examined for the current study.

10.2.2 Recruitment Trees

The definition for a recruitment trees was based on the known attributes of existing nest trees and nest sites (Brown & Mooney 1997; Wiersma 2010; Wiersma et al. 2009). To be considered a recruitment tree, the tree had to have the following characteristics:

- DBH ≥ 75 cm
- ≤ 50% of the canopy is comprised of dead branches
- A major three (or more) way fork in the primary or secondary branches, that was located in the mid third of the tree canopy (or at the same height as the current nest height), on the downhill side of the trunk.
- Be located on a slope ≤70 º
- Be located in a sheltered position from prevailing winds (i.e. generally not in a north-west aspect)

At each nest reserve, each recruitment tree within 80 m (horizontal) of the nest tree was assessed. The distance of 80 m was used because current management states that eagle nests must be at least 100 m from the reserve boundary and in a 10 ha reserve (if assumed to be circular and centred on the nest tree) this equates to trees within 80 m of the nest. The following data were collected for each recruitment tree:

- Dbh (cm): Tree diameter measured at breast height using a diameter tape.
- Slope (º): The slope on which the tree is located, measured using a clinometer.
- Aspect (º): The aspect (º) of the site facing directly downslope from the tree, measured using a compass.
- Tree height (m): Measured using a range finder.
- Location: GDA coordinates as measured using a GPS.
- Basal area: three assessments were conducted around the nest tree using a factor 4 basal wedge, in haphazardly selected locations.
- Forest type: as classified by the Forest Botany Manual.

Due to the small sample size of this study, no formal analysis is conducted and only summary statistics are provided. Prevailing winds are generally westerly in Tasmania and wedge-tailed eagles are known to select sheltered sites (e.g. Mooney and Holdsworth 1991). We therefore examined graphically how the number of recruitment trees in a reserve varied with site aspect. Forest density can also vary with vegetation type, so we also examined how the number of recruitment trees varied with vegetation type, both assessed from TasVeg mapping layers and from on-site field assessments using the Forest Botany Manual.

10.3 Results

In the 35 nest reserves assessed, 68 trees were found that met the definition of a recruitment tree. 17.6% of the reserves had no recruitment trees (Figure 41). The recruitment trees had an average diameter of 122 cm ±45 SD and a height of 37 m ± 7 SD. They were found on an average slope of 19º ± 12 SD, and an aspect of 131º ± 66 SD.

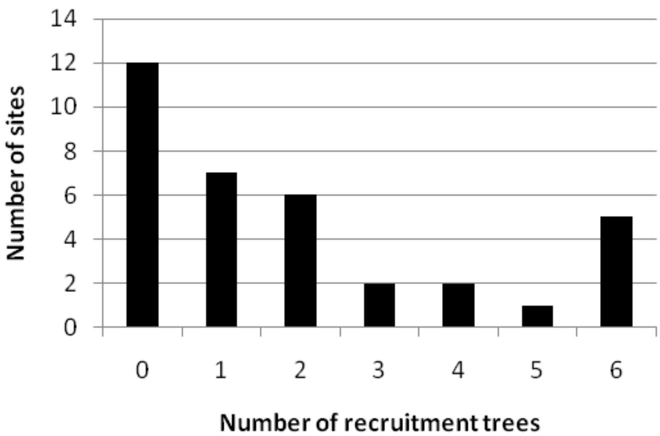


Figure 41. The number of recruitment trees in the 35 sites examined.

We found no suggestion that sites with different aspects (ie. shelter) differed dramatically in the number of recruitment trees they contained (Figure 42).

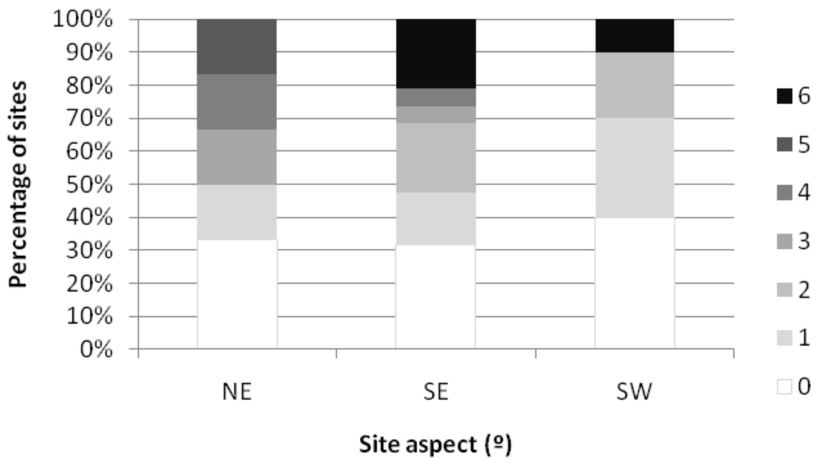


Figure 42. The percentage of nest sites that contain different number of recruitment trees, for nest reserves with a north-easterly aspect (6 sites), a south-easterly aspect (19 sites) and a south-westerly aspect (10 sites).

The nest reserves examined were located primarily in wet (n = 14) and dry (n = 14) forest types, as determined from the TasVeg mapping layer. A small number of the reserves examined were mapped as rainforest (n = 2), non-eucalypt forest or woodland (n = 3), or urban, agricultural or exotic vegetation (n = 2) (Figure 43). Of the 14 nest sites mapped as a TasVeg wet forest community, two (14%) were found to be dry forest communities during field visits. More than four recruitment trees were found in 36% of wet forest reserves examined and 7% of dry forest reserves (Figure 43). Of the 14 nest sites mapped as a TasVeg dry forest community, 9 (64%) were classified as a wet forest type using the Forest Botany Manual during field visits.

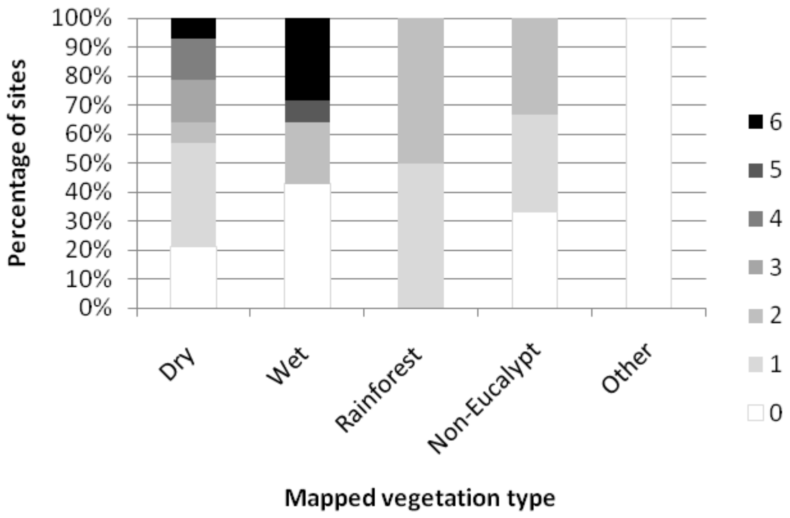


Figure 43. The percentage of nest sites that contain different number of recruitment trees, for nest reserves that differ in the vegetation type as determined from the TasVeg mapping layer. Vegetation communities are: dry forest (14 sites), wet forest (14 sites), rainforest (2 sites), non-eucalypt forest and woodland (3 sites) and other areas including agricultural, urban and exotic vegetation (2 sites).

10.4 Discussion

The results presented suggest that availability of recruitment trees may be low in many nest reserves, with 54% of the 35 reserves examined have one or no recruitment trees. Eagles are selective in the trees they construct nests in, so the quality of the recruitment trees is uncertain. There was no strong evidence suggesting that the number of recruitment trees varies with site aspect, which is related to wind exposure in many areas. Similarly, no evidence was found to suggest that the number of recruitment trees varies with size of the forest patch, with larger patches expected to provide greater buffering and reduced windthrow. There was some evidence to suggest that forest type may influence availability of recruitment trees, with wet forest having more sites with large numbers of recruitment trees than dry forest sites. This is possibly a result of the generally faster growth rates and greater density of trees in wet forest areas, or because wetter vegetation types examined in the current study were often located in sheltered gullies that may be more protected from wind and fire. Field observations suggested that the size of the gulley in which the nest tree was located was often a greater limiting factor for the number of recruitment trees than the size of the patch.

While the location of the nest reserves examined suggest no preference for wet forest types, on-site surveys found that vegetation around the nest tree was frequently classified as wet forest, while mapping layers indicated the area was predominantly dry forest. In dry forest types, gulley areas frequently have wetter vegetation types. Eagle nests are frequently located in gulley areas (J. Wiersma pers. comm.), but this may be because gullys can provide more shelter from wind, or have larger trees due to lower fire risk than the surrounding area, rather than be due to vegetation type per se.

A simulation study looking at the recruitment of large old trees (hollow-bearing trees) found that at least two recruitment trees need to be retained within a harvested area for every hollow-bearing tree (Gibbons et al. 2010). However this study mainly considered mortality that resulted from harvesting events. Mortality of retained patches in Tasmania can be subject to considerable windthrow, with mortality being highest at the edge of retained areas (Duhig et al. 2000). However, it is possible that more than one recruitment tree is required in a nest reserve to increase the likelihood that suitable habitat will be available for nesting eagles into the future.

10.4.1 Conclusion

Sample sizes were small for the current study and so firm conclusions on the recruitment potential cannot be made. However, the results gathered to date suggest that many nest reserves have little or no recruitment potential over the short to intermediate term. Lack of recruitment was seen as a key factor affecting population viability (Bekessy et al. 2009). Nest sites will not necessarily be limiting in the future as not all nests are used in any given year. However the current study suggests that the availability of recruitment nest trees requires further investigation to ensure that adequate and suitable nesting habitat for wedge-tailed eagles is maintained into the future.

11 Appendix E: Reconstruction of the wedge-tailed eagle nesting habitat model Stage 1

11.1 Summary

The initial attempt to reconstruct the wedge-tailed eagle nesting habitat model involved employing a consultant (S. Thurstans) to use all nests now in the raptor database and repeat the modelling technique used by Brown and Mooney (1997). All of the variables assessed were identified as being distributed significantly different at eagle nest locations than in the environment, most likely due to the large number of nests (804) used in the modelling process. The large number of variables identified as significant left the selection of the most appropriate variables and thresholds to use in model construction to be judged subjectively. The model produced included the variables of mature and regrowth crown density, forest height and topography, and captured 72% of the 804 nests used in the modelling process. However, this model covered 40% of the forested area in Tasmania. The low specificity of the model and the subjectivity required for model construction meant that an alternative approach was adopted, as outlined in Section 4 of the current report.

11.2 Introduction

Eagle management in production forestry areas is focused primarily on controlling disturbance around established nests, so locating nests is a critical part of Tasmania's eagle management strategy. The existing guidelines on locating eagle nests are outlined in FPA Technical Note 1 and are based on research conducted by Brown and Mooney (1997). The three most important predictors of eagle nest habitat identified in this study are forest height, the slope and aspect of the site.

While Tasmanian raptor biologists agree that the existing model identifies prime eagle nest habitat, an increasing number of nests are being located outside of prime areas. While the reason for this is uncertain, it is important that eagle nests are found and managed even if they are located outside prime habitat. The aim of the current study was to reconstruct the eagle nest habitat model to see whether it could be further refined from previous work and capture any changes in nest locations that may be occurring.

11.3 Methods

11.3.1 Nest site database

All nests listed in the Tasmanian raptor database (2009) were examined, and inaccurate or incomplete records (records without GPS coordinates and those with coordinates that had an accuracy of more than 20 m) were omitted from further examination. This resulted in a total of 1005 nests available for modelling. A random sample of 20% of these nest sites was excluded from the modelling process in order to provide a data set to test the resulting model. (Note: time constraints and model output meant that this testing was not done). A total of 804 nests were used for testing habitat selection and constructing a habitat model.

11.3.2 Habitat variables

The study area was defined as forests in mainland Tasmania, which included areas classified in the Forest Groups data (2009) as 'low native eucalypt forest', 'other native forest' or 'rainforest and tall native eucalypt forest'. Ecologists identified nine habitat variables that are available on mapping layers and potentially influence eagle nest locations (Table 18). GIS techniques were used to assess the proportion of the study area covered by the different categories (i.e. relative availability) for each categorical habitat variable. To assess relative availability of continuous variables, all continuous variables were transformed into categorical variables. This was done by dividing the range of values (max-min value) into 20 bins of parameters separated by equal intervals. (For example there are 360º for the habitat variable 'aspect', so the bin interval is 18º, meaning the categories were 0-18º, 19-36º, 37-54º etc). For some of the variables, some of the twenty bins were consolidated to ascertain an expected frequency of at least five, necessary for chi-square tests.

Table 18. Habitat variables that potentially influence eagle nest locations and were examined during construction of the eagle nest habitat model.

Variable	Description
Slope	The slope of the land on which the nest is located, as determined from a 25m digital elevation model (º).
Aspect	The direction in which the land faces when looking directly downhill, as determined from a 25m digital elevation model and measured in degrees.
Topography	A classification of the topography of an area, using a mapping layer provided by R. Knight. Areas were classified as ridge, upper slope, mid-slope, lower slope and gulley.
Forest height	A classification of the height that the forest canopy is expected to reach when the stand reaches maturity. Areas were classified as (a) >76m, (b) 55-76 m, (c) 41-55m, (d) 34-41m, (e) 27-34m, (f) 15-27m, (g) <15m.
Mature crown density	The estimated density of mature crowns in a forest stand, as determined from aerial photograph interpretation. Categories considered were: (a) 70-100% crown cover, (b) 40-70%, (c) 20-40%, (d) 5-20%, (f) <5%.
Regrowth crown density	The estimated density of regrowth crowns in a forest stand, as determined from aerial photograph interpretation. Categories considered were: (a) 90-100% crown cover, (b) 70-90%, (c) 50-70%, (d) 10-50%, (f) 1-10%.
Growth stage	A classification of the dominant canopy component as determined from aerial photograph interpretation. Categories considered were (a) mature, (b) regrowth or (c) young regeneration.
Wind effect	Wind effect is an estimate of wind exposure at a site, as estimated from landscape topography. It was calculated using the Wind Effect module in the program SAGA (System for Automated Geoscientific Analyses, Cimmery 2010).
Morphic protection index	A measure of the degree of dominance or enclosure of a location as described by Yokoyama et al. (2002). The technique uses a digital elevation model to calculate zenith and nadir angles (the largest angles that intersect with a respective high or low point in the terrain) in eight directions from the point of interest. The mean of these values is taken and positive values are high for convex forms, while negative values are high for concave forms.

11.3.3 Model construction

The model construction technique used was based on work by Brown and Mooney (1997) and Thurstans (2009).

The first stage was to test whether eagle nests were more likely to be associated with particular habitat attributes, by successively comparing the observed and expected number of nests for each habitat variable. The expected frequencies (the number of nests expected in each habitat category if nest occurrence was random) were determined by multiplying the proportion of the study area assigned a particular habitat category by the number of nests sampled. For example, if 5% of the study area was assigned the topography category ‘ridge’ and a total of 804 nests were examined, then we would expect to find 40 nests on ridges if eagles showed no preference for topography ($0.05 \times 804 = 40.2$). The habitat variable categories were subjectively consolidated so that each category had an expected frequency of at least five nests. Chi-square tests were used to compare the observed and expected frequencies of nests for each habitat variable.

For each of the habitat variables with a significant difference between observed and expected number of nests, the raw data were examined to subjectively assess the strength and nature of the relationship. A subset of variables (and categories of variables) was then subjectively selected for model construction, with vector variables being preferentially selected over raster variables (slope, aspect, wind and morphic protection index) due to ease of data manipulation with available software resources. Model construction involved removing all localities within the study area that did not have the attributes identified as important for eagles.

11.3.4 Limitations

There are a number of limitations to using this method to construct a habitat model, the main limitations being:

- The chi-square analysis does not indicate appropriate threshold levels (i.e. which categories are significantly different to expected).
- This approach does not take interactions between variables into account, but is an amalgamation of single-variable assessments.
- There was a high level of subjectivity in this process, including variables considered for model construction and the categories of the variables considered.
- The number of nests used in the final model was much less than the original number of nests, because nests were excluded as each variable was added.

11.4 Results

The observed number of nests in a habitat category differed significantly ($P < 0.001$) from expected for all the habitat variables examined. The high levels of significance are almost certainly due to the large sample size. These results gave little guidance as to which variables were most useful for model construction. Examining the raw data gave some insight into the

habitat variables that appear to be selected by eagles (Figure 44, Figure 45). Nests were more likely to be found in areas of high mature crown density, taller forests, on steep slopes (Figure 44), on protected slopes and facing in an easterly direction (Figure 45).

The variables identified for the habitat model were mature crown density, regrowth crown density, forest height and topography (Figure 44). Areas covered by these four variables capture 72% of nests and cover 39% of the study area.

Table 19. A summary of the final habitat model, indicating the habitat variables included, the categories of the habitat variable included, the number of nests found in those habitat categories, the progressive number and percentage of nests captured by the model as successive variables were added.

Variables	Parameters	No. of nests captured by variable	Progressive No. nests captured	% of 804 nests
Mature density	A, B, C, D	650[a]	650[a]	81%
Regrowth density	C, D			
Forest height	20 - 65 m	710	633	79%
Topography	gentle slopes steep slopes steep mid-slopes	732	580	72%

[a] The number of nests captured by mature and regrowth densities were added together, as they were mutually exclusive subsets of the study area.

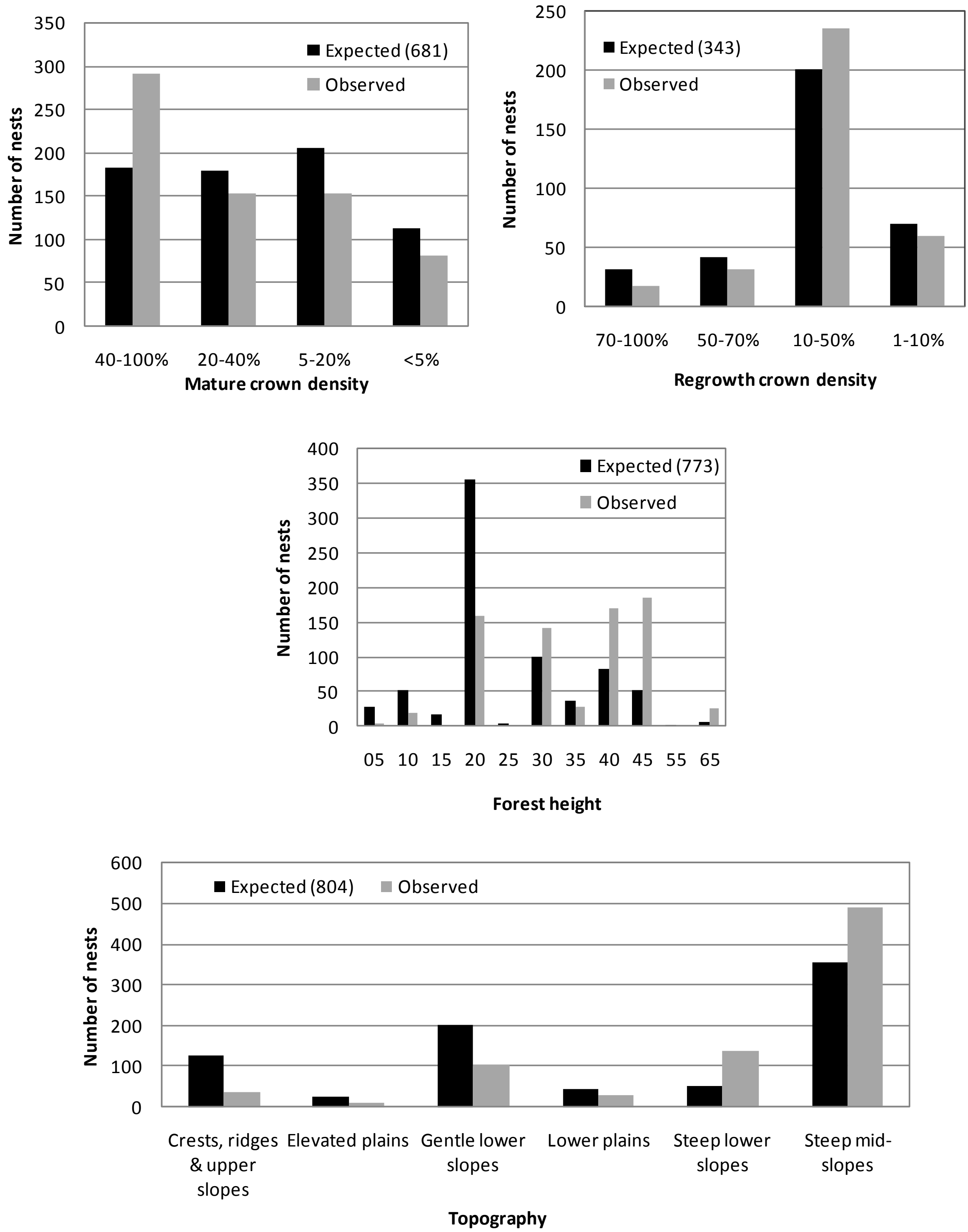


Figure 44. The expected and observed number of nests for each category of the four habitat variables included in the habitat model. Due to differences in the coverage of datasets, not all variables were available for every nest location, reducing the sample size. The numbers of nests expected for each category were then generated for the relevant sample size and are indicated in brackets.

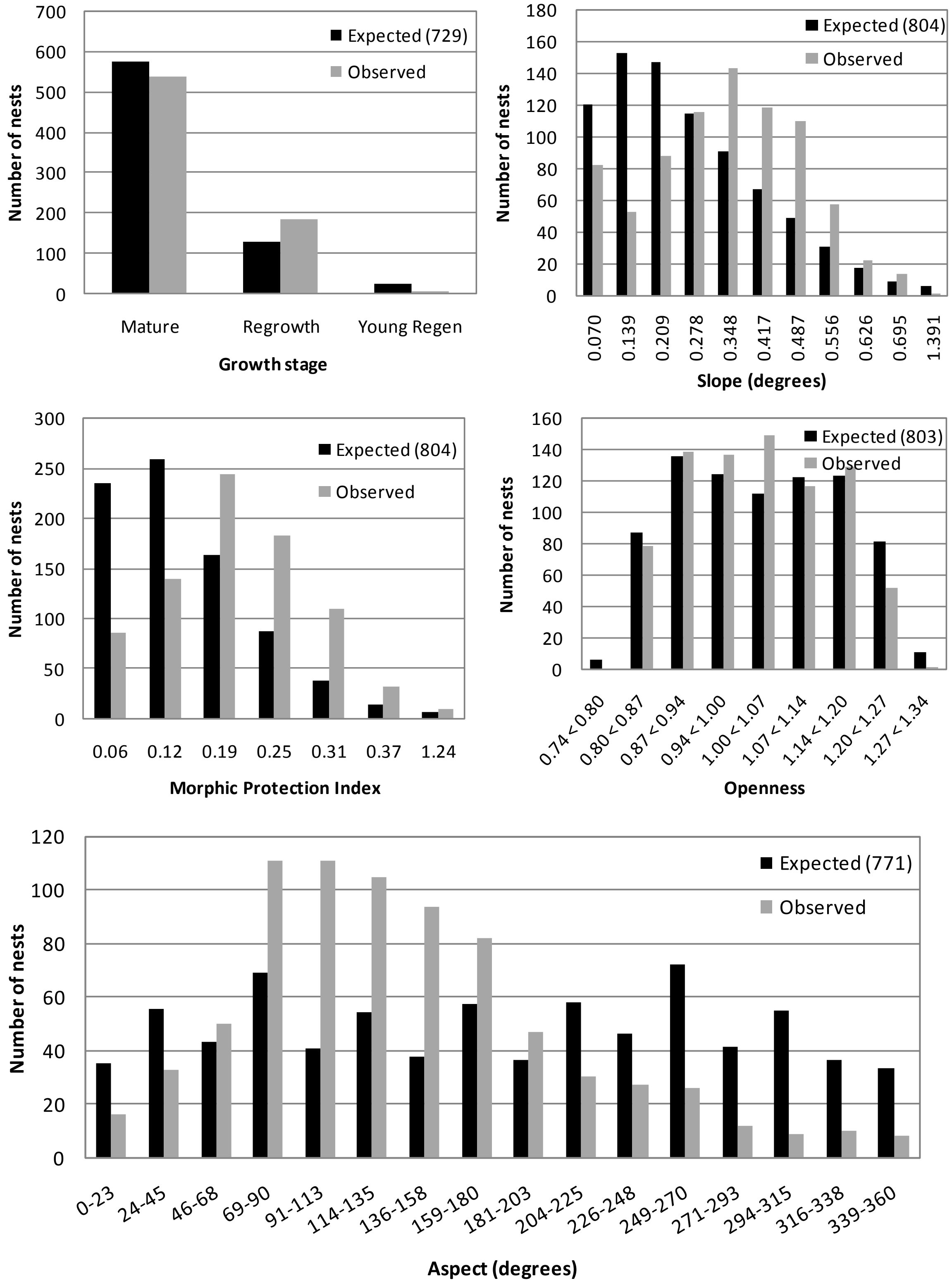


Figure 45. The expected and observed number of nests for each category of the five habitat variables not included in habitat model. The number of nests that had values for the variable in question is indicated in brackets after 'expected', as this was the value that was used to calculate the expected number of nests in each category.

11.5 Discussion and conclusion

The results of the current work confirm that the variables identified by Brown and Mooney (1997, i.e. forest height, slope and aspect) are important predictors of eagle nesting habitat. However, many nests are located outside of areas indicated by their model (Table 18). The new model used mature crown density, regrowth crown density, forest height and topography to model eagle nest habitat. This new model captured a larger percentage of nests than the old model (72% versus 40%), but was very broad and also captured a large amount of the study area (39%). In comparison, the Brown and Mooney (1997) model covered only 21% of their study area in south-eastern Tasmania, and covers 36.5% of the forested area in Tasmania.

There was a large amount of subjectivity involved in creating the new model, as the approach taken to assess habitat selection provided only minimal guidance on which categories of which variables to include. One of the reasons why the approach was less successful for the current modelling than in previous work (Brown and Mooney 1997, Thurstans 2009) was almost certainly due to the much larger sample size of the current study. With over 800 nests in the current analysis, there was a lot of power for the chi-square tests to detect a difference between observed and expected nest frequencies. The chi-square test does not identify how large an effect this is, and so the result may be significant but have only a relatively small influence in practice. We therefore suggest that the current approach is not the most appropriate technique to adopt for the current large dataset. Consequently an alternative approach was taken to reconstruct the eagle nest habitat model, as outlined in Section 4 of this report.

Table 20. An assessment of the relative accuracy of the original habitat model (as described in Brown and Mooney, 1997) applied to the 804 nests known in 2011.

Variables	Parameters	No. of nests captured by variable	Progressive No. nests captured	% of 804 nests
Forest height	(E2 - E4) 15 - 55m	416	416	52%
Slope	4°< slope < 30°	666	356	44%
Aspect	22° < aspect < 248°	692	320	40%

11.6 References

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