Koala conservation and habitat requirements in a timber production forest in north-east New South Wales

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ABSTRACT

The habitat and conservation requirements of the koala were investigated in 1996 in a 6400 hectare timber production forest at Pine Creek in the Coffs Harbour region of north-east NSW. Minimum koala density varied from 50 hectares per koala in plantation forest to 9 hectares per koala in high site quality native forest and averaged 15 hectares per koala throughout. The total koala population was estimated by spotlight counts to be 350 to 450 individuals. Variation in scat density (determined by counts in fixed area plots) was best explained by food tree species richness, forest association, forest structure and logging history. Koalas preferred structurally complex, uneven-aged forests with some mature and oldgrowth elements, a large basal area, and mixed species associations dominated by tallowwood, grey gum and forest oak. Koalas were least abundant in plantations and structurally uniform, blackbutt dominated regrowth native forests with a low tree species diversity. Trees of 40-80 cm dbh and stands with more than three koala food tree species per survey plot (50 by 50 m) were preferred. Historical timber harvesting practices involving low intensity harvesting of large diameter stems were successful in maintaining koala populations. Modern, high intensity harvesting practices including extensive gap clearfelling and Australian group selection that remove a high proportion of stand basal area and leave only small diameter stems (<50 cm dbh) are incompatible with koala conservation. Failure of SFNSW to embrace alternatives to high intensity harvesting practice has resulted in the transfer of most koala habitat in Pine Creek State Forest to Bongil Bongil National Park.

Key words: koala, habitat, density, population, diet, logging, impact.

Introduction

Pine Creek State Forest was a timber production forest located approximately 18 km south of Coffs Harbour on the NSW north coast (Fig 1). In 1996 it supported approximately 4500 ha of native forest and 1900 ha of native species plantation divided into 50 management compartments. This area was managed for wood production from the late nineteenth century until 2003 when the bulk of prime koala *Phascolarctos cinereus* habitat was transferred to National Park. It has undergone three major periods of harvesting for sawlogs, before 1920, during the 1950s and 1960s, and in the late 1980s and 1990s (R. L. Newman and Partners Pty. Ltd. 1996). Minor harvesting of poles, sleepers and salvage (after wildfire) occurred in the intervening periods but was not thought to have had a major impact on forest structure (R L. Newman and Partners Pty. Ltd. 1996). After 1950 each major episode of sawlog harvesting was characterized by more intensive harvesting and removal of progressively smaller stems.

In 1995 I was advised by concerned residents that large gap clearfelling (Fig 2) was occurring in native forest and koala habitat in Pine Creek State Forest contrary to the specifications of the Coffs Harbour Urunga Management Area Environmental Impact Study (EIS) for which I had recently prepared a Fauna Impact Statement (SFNSW 1995, Smith *et al.* 1995). The Coffs Harbour Urunga Management Areas EIS (SFNSW 1995) limited extensive gap harvesting to small areas of even aged flooded gum and understocked moist forest on former private property (see Table 4 for the scientific names of the trees). It also excluded clearfelling from areas with koalas and koala feed trees under a protocol developed in consultation with the NSW National Parks and Wildlife Service that required surveys for evidence of koalas and other threatened species before logging. Pine Creek State Forest was known to be a regional stronghold for the koala (SFNSW 1995). Site inspections revealed the most destructive and intensive clearfelling that I have ever observed in a State Forest in northern NSW, including the removal of koala feed trees (grey gums with abundant scratches and scats) in contravention of NSW National Parks and Wildlife Service (NPWS) section 120 licence conditions that then regulated harvesting impacts on threatened fauna (Figure 2). Significant clearfelling had not previously occurred in north-east forests due to the absence of a woodchip market. Extensive gap clearfelling can be considered destructive because it reduces or eliminates habitat for mature, oldgrowth and hollow dependent fauna (Dunning and Smith 1996, Attiwill et al 1996, Smith et al. 1992, 1994, 1995). In this case the clearfelling was effectively land clearing.

A survey for koalas and koala scats around the edges of logged areas and stumps within clearfelled areas concluded that " the evidence of high levels of koala activity is so abundant in the logged compartments that it could not have been missed by anyone genuinely

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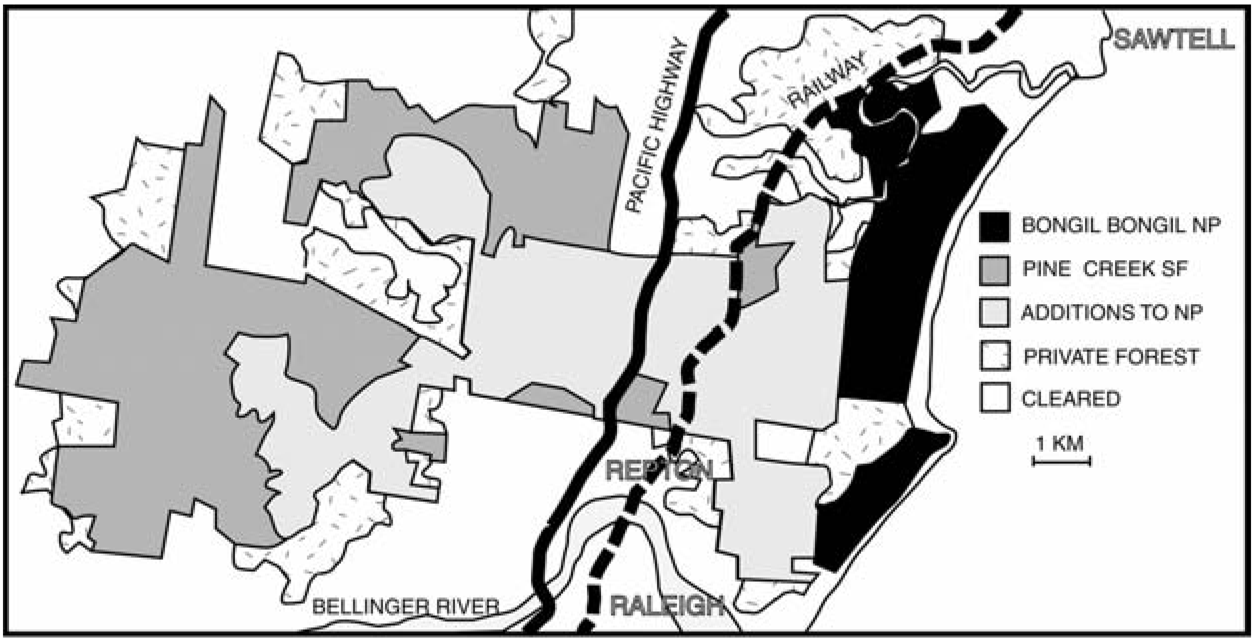


Figure 1. Pine Creek State forest and Bongil Bongil National Park showing additions to the Park from State Forest in 2003 (additions) and surrounding areas of private forest.

Figure 2. A local resident and NPWS investigator inspect gap clearfelling of koala habitat in Pine Creek State Forest in 1995 (photo A. Smith).

searching for evidence of koalas" (Moon 1995). Following inspections by officers of NPWS, harvesting operations were suspended in Pine Creek State Forest under the provisions of the *Endangered Fauna (Interim Protection) Act 1991* and clearfelling in Pine Creek was publicly condemned in local and state media. Approval to recommence harvesting Pine Creek State Forest was made conditional on the development of a joint SFNSW/NPWS plan of management for koala conservation and timber production. An inquiry into gap and cluster silviculure (gap clearfelling) was also announced by the Minister for Land and Water Conservation. In late 1995 I was appointed to a scientific panel (along with Dr. P. Attiwill and Dr. M. Burgman, University of Melbourne) to review the efficacy of gap and cluster silviculture (gap clearfelling), and in late 1996 I was commissioned to undertake a scientific study of koala habitat use, distribution, abundance and response to logging disturbance to provide background information for a Pine Creek koala plan of management. The specific aim of the latter project was to identify management strategies that would sustain both wood production and a viable koala population. Despite the prominence of the koala as a flagship species for biodiversity conservation in Australia, little was known about its habitat requirements in moist forest environments or its response to timber harvesting.

Methods

Study area

The Pine Creek Study Area (PCSA) included 6400 ha of native forest and native plantation in Pine Creek State Forest and an envelope of adjoining private and public forest to a distance of approximately 1 km. This area is bounded by cleared land to the north and south, the Pacific Ocean to the east, Bongil Bongil National Park to the north-east, and Tuckers Nob State Forest to the west. The PCSA forms a discrete koala habitat management unit in conjunction with Bongil Bongil National Park. These two areas are continuous and largely isolated from other koala habitat remnants in the region by clearing and development to the north, clearing along the Bellinger River to the south and by clearing and roads to the west with the exception of a narrow corridor of plantation and private forest connecting them to Tuckers Nob State Forest (Fig 1).

Survey methods and design

The distribution, abundance, habitat requirements and response of the koala to timber harvesting in Pine Creek State Forest were evaluated using a survey and habitat modelling approach (Ferrier and Smith 1990, Smith 1995, Smith *et al.* 1997). Koala scats (koala dung also called koala pellets), vegetation structure, vegetation floristics and signs of logging activity were measured at 116 stratified survey sites throughout the study area. Multivariate statistical analyses were used to formulate habitat models that predict koala scat abundance as a function of environmental and landuse variables at survey sites. An additional predictive model was developed using a subset of mapped environmental attributes stored in the State Forests of NSW Geographic Information Systems (GIS) database. This model was interpolated to map zones of high, medium and low relative koala abundance throughout the study area. Koala distribution maps were tested by comparing predicted koala abundance in each zone with actual abundance based on results of koala spotlight surveys and local community koala surveys. Koala density and population size in each zone was estimated by undertaking 161 km of koala spotlight surveys along roads throughout the PCSA.

Survey sites were stratified by forest type (plantation, blackbutt *Eucalyptus pilularis* forest, white mahogany *Eucalyptus acmeniodes*- grey gum *Eucalyptus propinqua*-grey ironbark *Eucalyptus siderophloia* forest, swamp forest, and tallowwood *Eucalyptus microcorys*-blue gum *Eucalyptus saligna*-flooded gum *Eucalyptus grandis* forest), time since logging (pre 1983, 1983-88,1989-present) and topographic position (ridge, slope and gully). Replicates in each stratum were geographically dispersed throughout the study area. The bulk of surveys were undertaken in Pine Creek State Forest rather than the surrounding envelope because some mapped logging history and environmental information was only available for the State Forest area.

Plot surveys

At each survey site a 50 m transect was marked out perpendicular to the nearest access road or track in an area of representative habitat. Sites were located up to 100 m from the track to avoid road edge effects. Percentage canopy, understorey and shrub cover, and floristic composition of the canopy and understorey were determined at each 1 metre interval along the transect line. Koala scats and trees were then counted by two observers systematically searching the ground in a 10 m wide strip either side of the transect line. The entire plot (20 m by 50 m) was searched but with more attention to the base of trees and areas under tree crowns. More than 90% of koala scats occurred within 1-2 m of the base of trees. During this search, all stumps and tree stems > 10 cm dbh (diameter at breast height) were recorded by species and size class (in 10 cm intervals up to 80 cm, and 20 cm intervals up to 120 cm). Stumps and stems greater than 60 cm dbh were counted to 25 m either side of the transect line. The resulting counts were converted to measures of tree and stump density (numbers per size class per hectare) for description of forest structure. Stumps were recorded as new (chainsaw cut with sharp spikes and splinters on the vertical split section and no decay), old (chainsaw cut with blunted or no spikes and splinters remaining on vertical split sections and little or no central decay) or very old (cross cut or with heavily decayed central cavities and sides).

Koala scats at the base (or under the canopy) of any tree or shrub were collected and counted. Scats were assigned to the nearest tree species with a canopy extending directly overhead. A few scats collected in the open were not assigned to any particular tree species. In order to minimise any effects of rainfall on survey results, scat counts were undertaken on most sites (94) over a relatively short period (8 weeks) under relatively dry conditions before commencement of the rainy season (in November 1996). These scat counts are most likely to reflect patterns of habitat use by koalas over the preceding 8-12 months. The number of trees and shrubs with koala scats at their base or under their canopies were tallied for each plot to give an index of koala activity at the site. This index was found to exhibit the most favourable range of values and least noise in statistical associations with habitat variables.

Spotlight survey

A total of 161 km of roads in the study area was surveyed by an observer spotlighting from a 4 wheel drive vehicle travelling at approximately 5km/hour or less (first gear low range). Spotlighting was conducted on most of the roads in the study area. Spotlighting routes passed all but 6 scat survey plots which were located in relatively inaccessible areas. Initially, a spotlight transect of at least 500 m was undertaken by walking immediately adjacent to scat survey plots but this practice was abandoned because the number of sightings was too low for site based analysis. The right angle distance (from road edge to animal) was recorded to each arboreal mammal seen during road spotlighting. When a koala was observed, the size and species of tree in which it was located and its activity, sex, size and condition (coat condition and eye clarity) were recorded (when possible).

Environmental attributes at survey sites

Mapped Attributes

A range of mapped environmental and logging history attributes were extracted from maps and a GIS database provided by SFNSW for evaluation as potential predictors of koala scat abundance in Pine Creek State Forest. Mapped variables stored in the GIS were as follows: Geology (granodiorite, shale, alluvial);Topography (ridge, side slope, flood plain, drainage plain, coastal plain, streambed, tidal flat); Logging (year of last logging from 1983 to 1992); Soils (alluvium, colluvium, erosional, transgressional, marine); Forest Type (after Baur 1965); Compartment (compartment number from 1-50).

Some inconsistency was found in SFNSW mapping of plantation sites with some areas of apparent plantation mapped as natural forest. This introduced noise to analyses but did not affect the overall conclusions.

Logging History Attributes

Pine Creek State Forest was divided into 50 timber management units (compartments) each being approximately 130 hectares. A database maintained by State Forests (Urunga) provided a summary of all major recorded forestry activities which have been undertaken in each compartment including the following: felling of non-commercial and defective trees (cull felling or Timber Stand Improvement, TSI); sleeper (railway) harvesting; large pole harvesting; quota (sawlog) harvesting; salvage (post fire); logging; thinning (mainly plantation); clearfelling and replanting.

Most of these activities were confined to only a portion of each forest compartment. The exact location and portion of each compartment affected by most of these activities was not known, but maps showing the distribution and extent of major harvesting events were provided by SFNSW and R. L. Newman and Partners (1996).

For the purpose of analysing associations between koala scat abundance and compartment history, the number of events for each individual harvesting activity was summed (thinning, TSI, sleeper harvesting etc) in the compartment surrounding each survey site as an index of intensity of that activity. No allowance was made for sites that fell near the boundaries of other compartments with different histories. For example a compartment which was subject to quota logging in 1966, 1978 and 1994 would score a value of 3 for quota harvesting. The number of harvesting events was also summed (total events) to give a score for all logging events in each compartment. Additionally the year of most recent timber harvesting on the actual survey plot was recorded as an index of time since harvesting disturbance.

Forest Types

Forest types in the Pine Creek State Forest have been interpreted by aerial photography and mapped into associations described by Baur (1965). The dominant mapped forest types in Pine Creek State Forest are moist and dry blackbutt (types 36 and 37), tallowwood-Sydney blue gum (type 47), flooded gum (type 48), white mahogany-red mahogany-grey ironbark-grey gum (type 60), swamp mahogany (type 30) and native species (flooded gum, blackbutt) plantation.

Statistical associations

A variety of statistical procedures (chi-square, t-test, regression, correlation, classification, decision trees, principal components analysis, and analysis of variance) were applied to the data using Systat, Statview and KnowledgeSeeker statistical software to identify significant associations between koala scat abundance and all environmental and landuse variables. The resulting associations were interpreted by reference to the species' known ecological and behavioural requirements to provide an explanation for the patterns observed and to predict the potential effects of landuse activity on koala populations in the study area. Scatterplots were used to examine associations with continuous variables and linear trends were analysed by linear regression and non-parametric Spearman Rank Correlation. Decision tree analysis was used to analyse non-linear trends by splitting continuous variables into two or more categories each with a minimum of 9 or more sites. Confounding between continuous predictor variables was examined by correlation and principal components analysis. Associations with categorical variables (e.g. soil types) were examined by analysis of variance and associations with all variables (linear, non-linear and categorical) were examined simultaneously by decision tree analysis.

Community distribution records

A register of koala records in the study area was maintained by the Urunga Forestry District. An unpublished map showing the location of koala records in the study area was prepared by local resident John Murray. Together these databases incorporated records of koalas, koala calls and koala scats compiled from a wide range of sources including the following: observations by employees of State Forests of NSW; observations by employees of the NSW National Parks and Wildlife Service; WIRES records of sick and dead koalas (maintained and compiled by C. Moon); local community survey records (compiled by J. Murray), and NSW NPWS Wildlife Atlas records. These sources were examined and all records, which satisfied the following criteria, were extracted: they were based on a koala sighting (e.g. records of scats, scratches, calls were excluded); they were accurately reported (within a distance of 100 m); they were reported within the past 10 years. Together these records formed a database of 109 "Community Group" records. This database was used to test koala habitat models and verify the distribution map.

Information on the feeding preferences of captive koalas maintained by local koala carers in the region was compiled by local resident John Pile.

Decisions Tree Modelling

Decision tree analysis was used to develop habitat models that predict koala scat abundance on survey sites as a function of all measured and mapped attributes, including linear, non-linear and categorical variables. Decision tree analysis commenced by identifying the environmental or landuse variable which best split survey sites into two or more groups with significantly different average numbers of scats. Each group was then further tested to find the variable which best subdivided it into two or more subgroups with significantly different average numbers of scats, and this process was continued until no more statistically significant splits were possible. At each step in the process it was sometimes possible to select from two or more alternative variables, each of which caused a statistically significant split, thus resulting in a range of alternative models. When there was a choice the most ecologically appropriate variable was selected at each split. The full range of alternative models were examined to check for any important ecological patterns or associations not evident in the primary model or previous univariate analyses. Decision tree analysis was useful for unravelling the effects of confounding between some continuous variables. For example, it was possible to eliminate the effects of confounding with plantations by examining associations with environmental variables independently within plantation and non-plantation sites.

Koala Diet

The diet of koalas in the PCSA was investigated in a separate study (C. M. Phillips and A. Smith unpublished data) by detailed analysis of 96 scats collected at koala sites surveyed during this study. Tree species and plant remains in scats were identified by comparison of epidermal patterns on leaf fragments with reference material collected from the study area. A total of 17 tree species were identified in koala scats. The frequency of occurrence of each tree species in the scats was compared with expected frequency of occurrence based on the proportion (percentage) of each tree species in survey plots from which scats were collected as an index of dietary preference.

Results

Forest structure

Forest Structure in the Study Area

Survey sites were classified into six structurally distinct groups (listed below) after log2 transformation of the number of stems per hectare in seven diameter classes using Wards clustering algorithm with a Euclidean distance estimator (Table 1). A log2 transformation is commonly applied to stand structural data to prevent over-weighting of the number of stems in smaller diameter classes. Under a log2 transformation the number of stems per hectare generally exhibits a linear decline from the smaller to larger size classes in natural (unlogged) uneven-aged forest with continuous recruitment.

The six groups (classes) were hand ranked in order of increasing predominance of stems in the larger size classes (>50 cm dbh) to reflect a gradient of increasing structural complexity and un-evenness (Class) from uniform regrowth forests to uneven-aged forests with mature and oldgrowth elements.

Group 1: A structurally uniform regrowth forest characterized by the virtual absence of stems over 50 cm dbh. The majority (70%) of survey sites in this class were located in plantations. These sites contained no koala scats.

Group 2: A young regrowth or plantation forest characterized by a predominance of stems below 40cm dbh but with some retained stems in larger size classes. Overall stocking was lower in this group than others. This pattern may occur within a plantation forest where larger trees have remained within the stand at the time of establishment or within native forest where harvesting has reduced the number of stems larger than 40 cm dbh. This class included an average of 0.63 trees/site with koala scats.

Group 3: An advanced regrowth or pole forest characterized by the absence of stems over 60 cm dbh. Similar to Group 1 but with a moderate number of stems in the 50-60cm dbh class. This pattern may result from a combination of TSI (removal of culls and defective unmillable oldgrowth) and intensive harvesting of stems over approximately 50 cm dbh. This class included an average of 0.33 trees/site with koala scats.

Group 4: An uneven-aged forest with a reduced abundance of mature and oldgrowth stems. This pattern is consistent with diameter limited harvesting (cutting trees above a minimum diameter, usually about 50 cm) of some large diameter stems and some TSI. Sites in this class supported an average of 0.8 trees with koala scats.

Group 5: An uneven-aged forest with abundant mature stems but no oldgrowth elements. This pattern may result from a combination of TSI and diameter limited harvesting more than 15 to 20 years previously. Sites in this class supported an average of 1.65 trees with koala scats.

Group 6: An uneven-aged forest approaching the natural condition expected in eucalyptus forests with continuous

Table 1. Means of the logged (base 2) number of stems per hectare in six structural forest groups and the mean number of trees per plot with koala scats in each group.

DBH CLASS	10-20	20-30	30-40	40-50	50-60	60-80	>80	SCATS
GROUP 1	8.2	7.4	6.5	4.8	0	0	0.3	0
GROUP 2	8	6.7	3.8	0.7	1.8	0.8	0.5	0.63
GROUP 3	7.7	7	6.4	5.6	3.7	0	0	0.33
GROUP 4	7.8	6.7	6.1	4.9	0	2.9	1.5	0.80
GROUP 5	7.6	6.7	6.2	5.2	4.3	3.2	0	1.65
GROUP 6	7.5	6.5	5.6	4.8	4.2	2.8	2.7	1.50

Table 2. Statistically significant (p<0.05) correlations between the number of trees with koala scats in survey plots and measured continuous and categorical variables in all survey sites determined by Spearman rank correlation and decision tree analysis (DTA). r is an index of the amount of variation in koala scat abundance explained by the variable which varies from 0 to 1, p is an index of the statistical probability that the association occurs by chance. DTA p values are presented for analysis of quantitative data (the mean number of trees with koala scats per plot) and frequency data (the frequency of plots with koala scats, tested by Chi-square).

Variable	Spearman r	Correlation p	DTA means	DTA frequency
Forest Structure				
Class	0.26	0.02	0.039	.030
No. stems 60-80 cm dbh	0.34	0.01	0.005	.034
No. stems 70-80 cm dbh	0.27	0.01		.042
No. stems 60-70 cm dbh	0.30	0.01	0.034	.050
No. stems 50-60 cm dbh	0.25	0.02		
No stems 40-50 cm dbh	0.20	0.05		.014
Forest Floristics				
No. Allocasuarina torulosa	0.27	0.02	0.031	.031
No. Lophostemon confertus	0.22	0.05	0.006	
No. Eucalyptus microcorys	0.23	0.05	0.031	.002
No. Syncarpia glomulifera	0.26	0.02	0.031	
No. Eucalyptus propinqua				.017
No. of preferred food tree spp	0.29	0.01	0.004	.002
Floristic group			0.021	
Landuse				
No. TSI events in compartment	0.29	0.01	0.016	.012
No. all logging/planting events in compartment	0.26	0.01	0.000	.049
No. cross cut stumps				.002
Distance to plantation	0.22	0.05		
Plantation vs Non plantation				.003

recruitment. This is the only group with a moderate or higher number of stems in the over 80 cm diameter class of sufficient size to provide some oldgrowth structural features. This pattern is consistent with a history little or no harvesting or TSI. Sites in this group supported an average of 1.50 trees with koala scats.

Koala Associations with Forest Structure

Koala scats were detected on 49% of survey sites and were widely distributed throughout the study area in all forest strata. A Kruskal-Wallis analysis of variance across all forest structural groups (Class) revealed a significant difference across all groups in the mean number of trees with koala scats (Table 2, $p < 0.05$). Scat abundance differed most significantly (t test $p = 0.003$) between the structurally uniform regrowth groups (1-3) with a mean of 0.3 trees with scats/site and uneven-aged structurally diverse groups (4-6) with a mean of 1.3 trees with scats/site. Much of this effect was due to significant differences in the mean number of trees with koala scats between Class 1 and Classes 5 and 6 ($P<0.05$, Dunnett t test). Class 1 sites were primarily located in plantation while Class 5 and 6 sites were primarily located in non-plantation forest. This raised the possibility that the association between the number of trees with koala scats and Class was confounded with the effects of plantation establishment. However, further analysis indicated that the association cannot be attributed solely to differences in koala abundance between plantation and non-plantation forest. The mean number of trees with scats was significantly correlated with Class (Spearman Rank Correlation, $P<0.02$) indicating a general trend of increasing mean number of trees with scats with increasing predominance of stems in larger size classes (>50 cm dbh). There is also a significant difference in the mean number of trees with koala scats between Class 3 and Class 5 sites that were primarily located within non-plantation forest. Decision tree analysis also revealed that Class was a significant predictor of the mean number of trees with koala scats within non-plantation forests. The mean number of trees with koala scats within non-plantation sites differed most significantly between Classes 1,2,3 &4 combined and Classes 5&6 combined ($P<0.03$).

Koala Associations with Tree Size

The number of trees with koala scats in sample plots was also correlated with the number of stems/hectare in each individual size classes. The number of trees with scats was significantly correlated with the number of stems in the medium to large size classes (50-60 cm, 60-70 cm and 70-80 cm, Table 2).

There were no significant correlations with the number of stems in tree size classes less than 40 cm dbh or greater than 80 cm dbh.

Frequency of Scats by Tree Size

The observed number of trees with scats in each size class across all sites was compared with the expected number (based on total counts of all stems in each size class in all surveys sites) to determine whether scats were

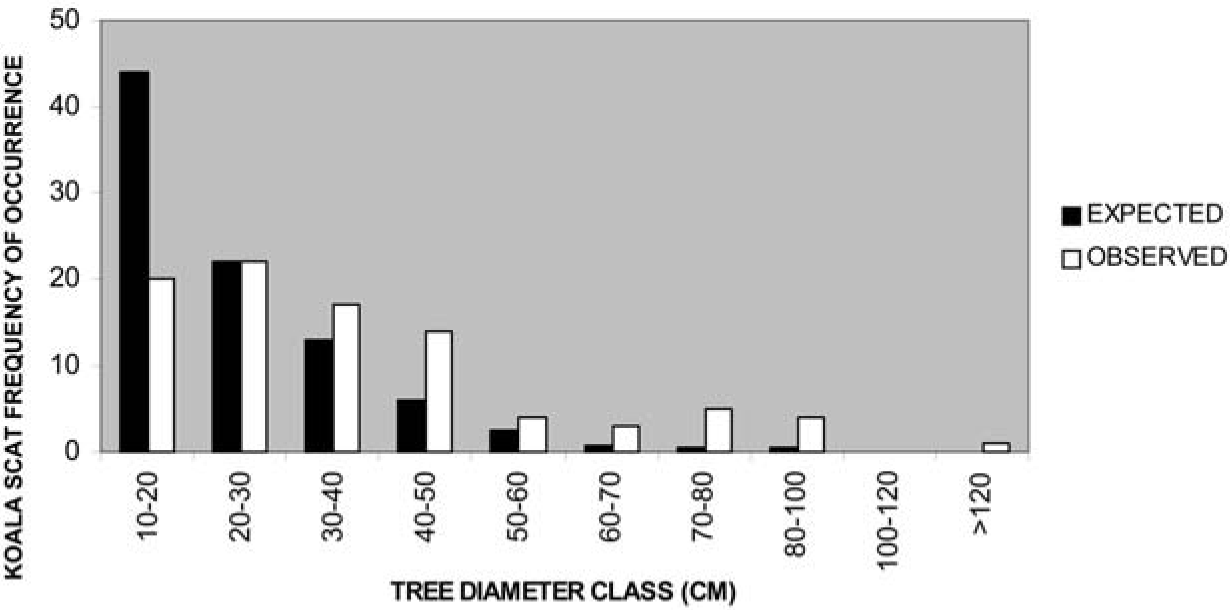


Figure 3. Observed frequency of occurrence of koala scats under trees of different sizes compared with expected frequency assuming that trees are selected in direct proportion to numbers present in the forest

associated with particular tree size classes. Results of this analysis revealed a significant discrepancy between tree size distribution in survey plots and the size distribution of trees with scats (Fig 3). Scats occurred more than expected at the base of trees over 30 cm dbh. Significant discrepancies (Chi-square test $P< 0.05$) were apparent in the 40-50 cm and 10-20 cm dbh classes with the larger stems favoured and the smaller stems avoided. Stems of 60-70, 70-80 and 80-100 were also associated with scats more than expected but these differences could not be statistically validated because of small samples sizes.

Tree Preferences of Captive Koalas

The tree species preferences of captive koalas reported by four carers in Coffs Harbour region are listed in Table 3. Tree species were ranked on a score of 0-4 according to information provided by four individual carers. The most preferred species was tallowwood (4), followed by swamp mahogany *Eucalyptus robusta* (2.7), forest red gum *Eucalyptus tereticornis* (2.5), grey gum (2.3) flooded gum, blue gum and white mahogany (2), swamp paperbark *Melaleuca quinquenervia* (1), forest oak *Allocasuarina torulosa* (0.7), and blackbutt (0.5). All of these species were classified as preferred tree species for the purpose of calculating average food tree species richness in survey plots.

Tree preferences of wild koalas

The pooled frequency of occurrence of koala scats beneath particular tree species on survey plots was compared with the frequency of all tree species on survey plots (94 sites). When observed and expected frequencies were compared by Chi-square analysis, koala scats were found to occur significantly more often than expected beneath tallowwood (Chi-square = 60) and grey gum (Chi-square = 27) and less often than expected below flooded gum (Chi-square = 11) (Fig 4). Other differences in observed and expected frequencies in figure 4 are either not significantly different or sample sizes were too small for statistical analysis.

A similar analysis was carried out to compare the frequency of observation of koalas in tree species reported during spotlight surveys with the expected frequency assuming that relative tree species abundance along spotlight routes was equivalent to that recorded on survey plots. This analysis revealed that koalas were sighted significantly more often than expected (Chi-square = 27) in tallowwood trees (Fig 5). Other differences in observed and expected frequencies in figure 5 are either not significantly different or sample sizes were too small for statistical analysis.

Associations between the number of trees with scats on survey plots and the abundance of individual tree (>10 cm dbh) and shrub species were also analysed. Significant Spearman rank correlations were found with a number of tree species including forest oaks, tallowwoods, brushbox *Lophostemon confertus*, and turpentines *Syncarpia glomulifera*.

Decision tree analysis confirmed the results of Spearman rank correlation and identified an additional significant association with the number of grey gums. The results of the decision tree analysis suggested that the form of the relationship between mean koala scat abundance or frequency of occurrence and the abundance of some food tree species was non-linear with a rapid initial increase followed by a levelling off. For example, koala scats occurred on only 14% of sites with no tallowwoods per plot, 53% of sites with between one and six tallowwoods per plot and 60% of plots with more than six tallowwoods per plot (Chi-square =13, $P<0.002$). Thus while the most rapid change in koala response to tallowwood occurs between 0 and 1 trees per plot (equivalent to 10 trees per hectare <60 cm dbh or 4 trees per hectare >60 cm dbh) maximum frequency of occurrence occurs on plots with more than 60 tallowwood trees per hectare < 60 cm dbh or 24 tallowwood trees per hectare >60 cm dbh.

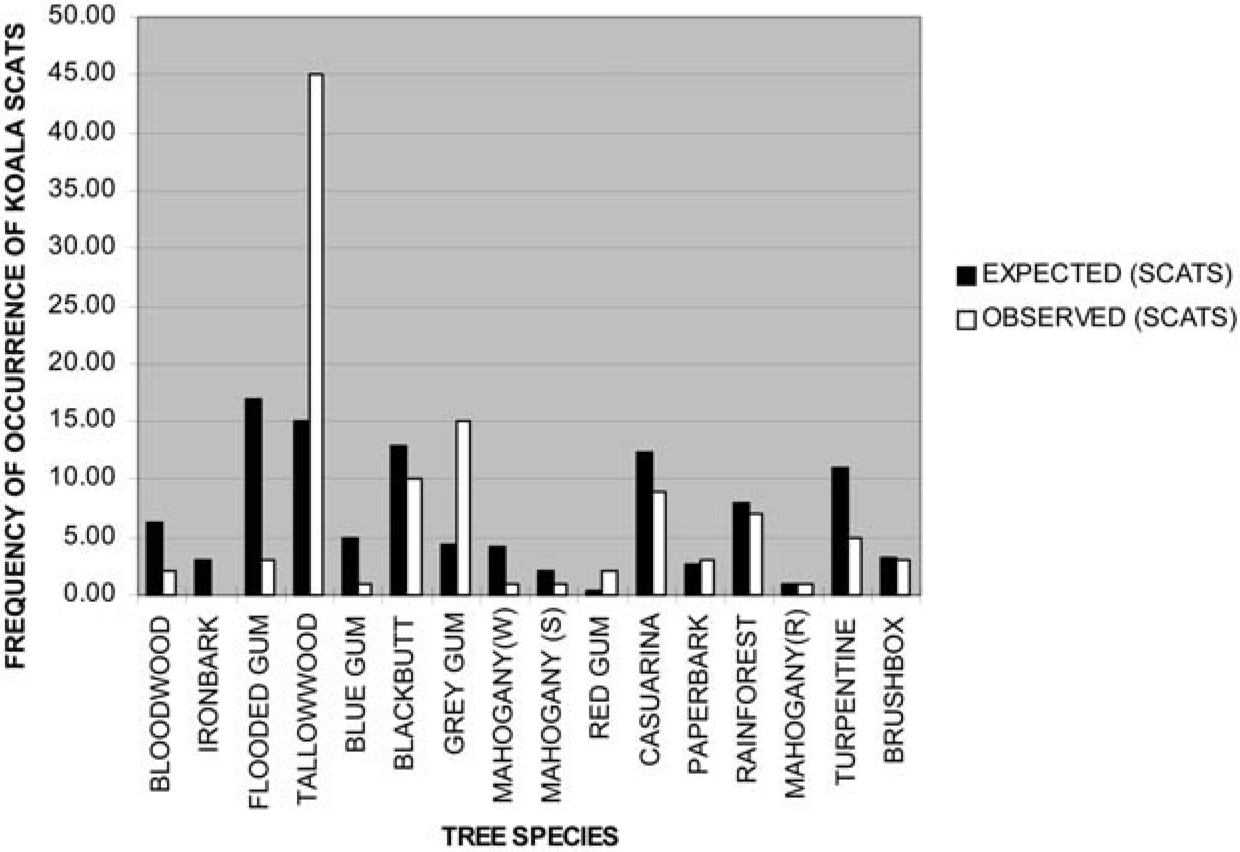


Figure 4. The observed and expected frequency of occurrence of koala scats beneath tree species in survey plots in the study area.

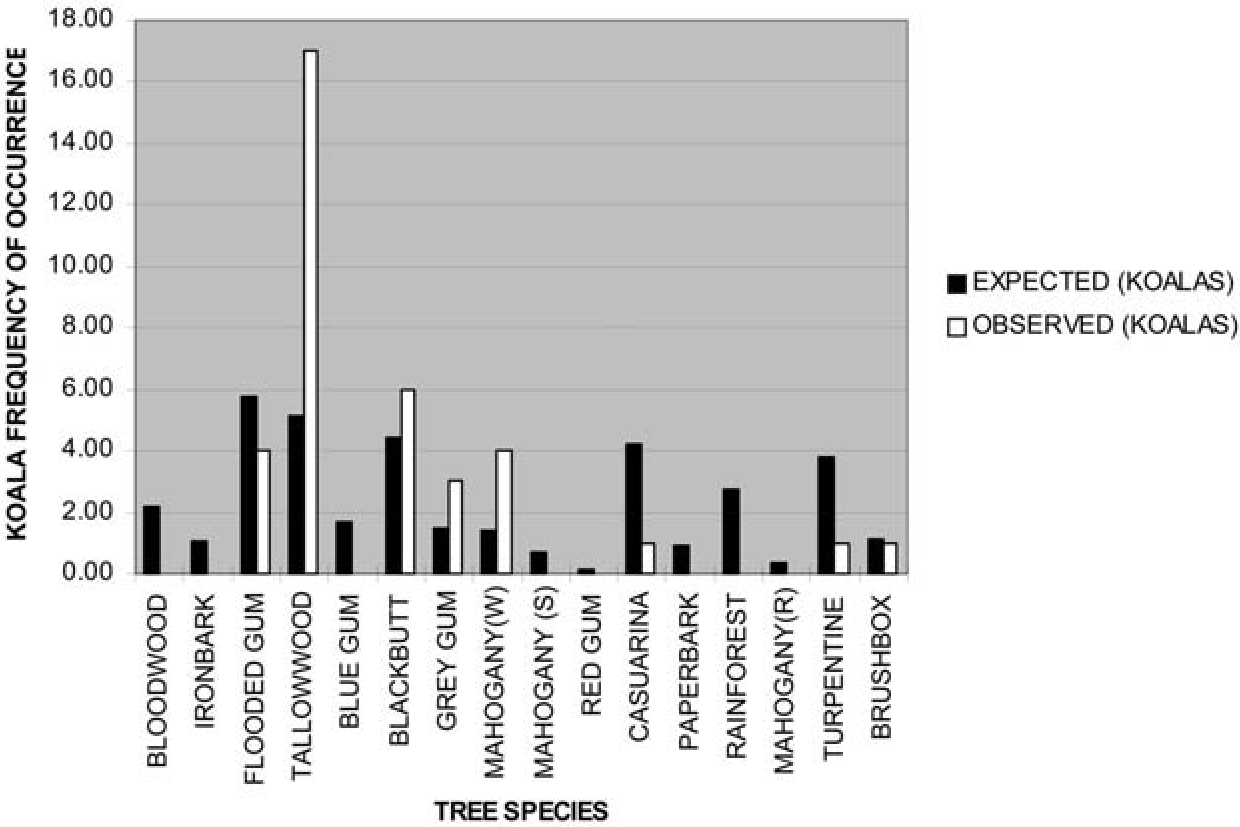


Figure 5. The observed frequency of occurrence of koalas in tree species in spotlight transects relative to the expected frequency based on tree species occurrence in survey plots in the study area.

No marked threshold effect was detected in associations with the number of forest oak. The mean number of scats averaged 0.56 on sites with 0-3 forest oak, 1.24 on sites with 4-10 forest oak, and 1.83 on sites with 10-33 forest oak per plot (P<0.01). A similar pattern was observed for grey gums. Koala scats occurred on 40% of sites with 0-1 grey gums per plot, 57% of sites with 2-4 grey gums per plot and 73% of sites with 5-21 grey gums per plot (Chi-square= 8, P<0.017). There appears to be a general increase in frequency or abundance of koala scats with increasing density of these food tree species.

Koala diet

Seventeen tree species were identified in scats collected on survey plots. The percentage frequency of occurrence of each tree species in scats compared with the expected frequency of occurrence based on the proportion (percentage) of each tree species in survey plots from which scats were collected is shown in figure 7. Tallowwood, grey gum, forest oak, swamp mahogany/ red mahogany and blue gum were the most frequent species in scats. Swamp mahogany and red mahogany could not be distinguished in scats but records of this group can be largely attributed to swamp mahogany as red mahogany was scarce or absent for survey sites. Grey gum, swamp mahogany/red mahogany and blue gum occurred in scats more frequently than expected on the basis of tree species abundance. Tallowwood occurred at levels consistent with abundance, and turpentine and blackbutt although eaten in some quantity occurred less that expected on the basis of tree abundance.

Associations with tree species richness

One of the best predictors of koala scat abundance was the diversity (richness) or total number of potential koala food tree species per survey plot where potential food tree species were any of those species known to be taken by captive koalas (Table 3) including *Allocasuarin*a. Decision Tree Analysis identified both 3 or more food trees per plot and 4 or more food trees per plot as statistically significant cutoffs for distinguishing between high and low scat abundance sites. The mean number of scats averaged 0.2 on sites with 0-2 food tree species, 1.23 on sites with 3-5 tree species and 1.42 on sites with 6-7 tree species per plot (DTA P<0.008).

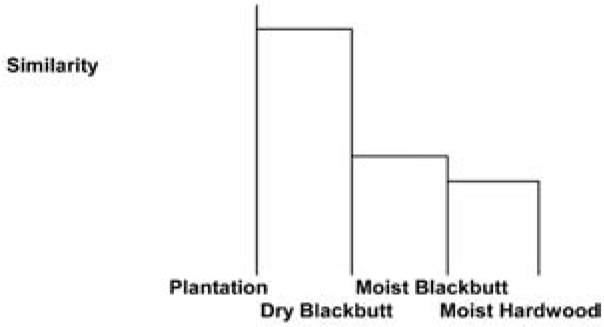
Associations with forest type

No significant or near significant association was found between mapped forest types (Baur 1965) and the abundance of trees with koala scats in survey plots. There was, however, a highly significant difference between the mean number of trees with scats in non plantation sites (average=1.23 trees per plot) and sites in plantations (average = 0.15 trees per plot, Mann-Whitney U test P< 0.001).

Table 3. Relative tree species preferences reported by four koala carers in the Coffs Harbour Region. - indicates no information provided on this species. The preferred species (those eaten most often) scored 4 points, species eaten consistently but not as often as preferred species scored 3, species eaten at some time but not consistently scored 2, species eaten occasionally scored 1 and species shunned or eaten only rarely scored 0. Individual scores for each species by the four carers were averaged to give an overall index of relative importance to captive koalas.

Species	Carer: M. Whackett	J&P. Wills	G. O'Shay	A. Coyle	Average Score
Tallowwood (*Eucalyptus microcorys*)	4	4	4	4	4
Swamp Mahogany (*Eucalyptus robusta*)	2	4	-	2	2.7
Flooded Gum (*Eucalyptus grandis*)	2	2	2	2	2
Grey Gum (*Eucalyptus propinqua*)	2	2	-	3	2.3
Forest Red Gum (*Eucalyptus tereticornis*)	-	2	-	3	2.5
Blue Gum (*Eucalyptus saligna*)	-	-	2	2	2
White Mahogany (*Eucalyptus acmenoides*)	-	-	-	2	2
Blackbutt (*Eucalyptus pilularis*)	0	2	0	0	0.5
Casuarina (*Allocasuarina torulosa*)	-	1	0	1	0.7
Swamp Paperbark (*Melaleuca quinquenervia*)	-	1	-	-	1

	Group 1	Group 2	Group 3	Group 4
No. Sites in Group	22	23	21	25
Koala Scat Trees/site	**0.32**	**1.00**	**1.67**	**1.24**
Food Tree Species/site	**1.90**	**4.20**	**5.00**	**3.90**



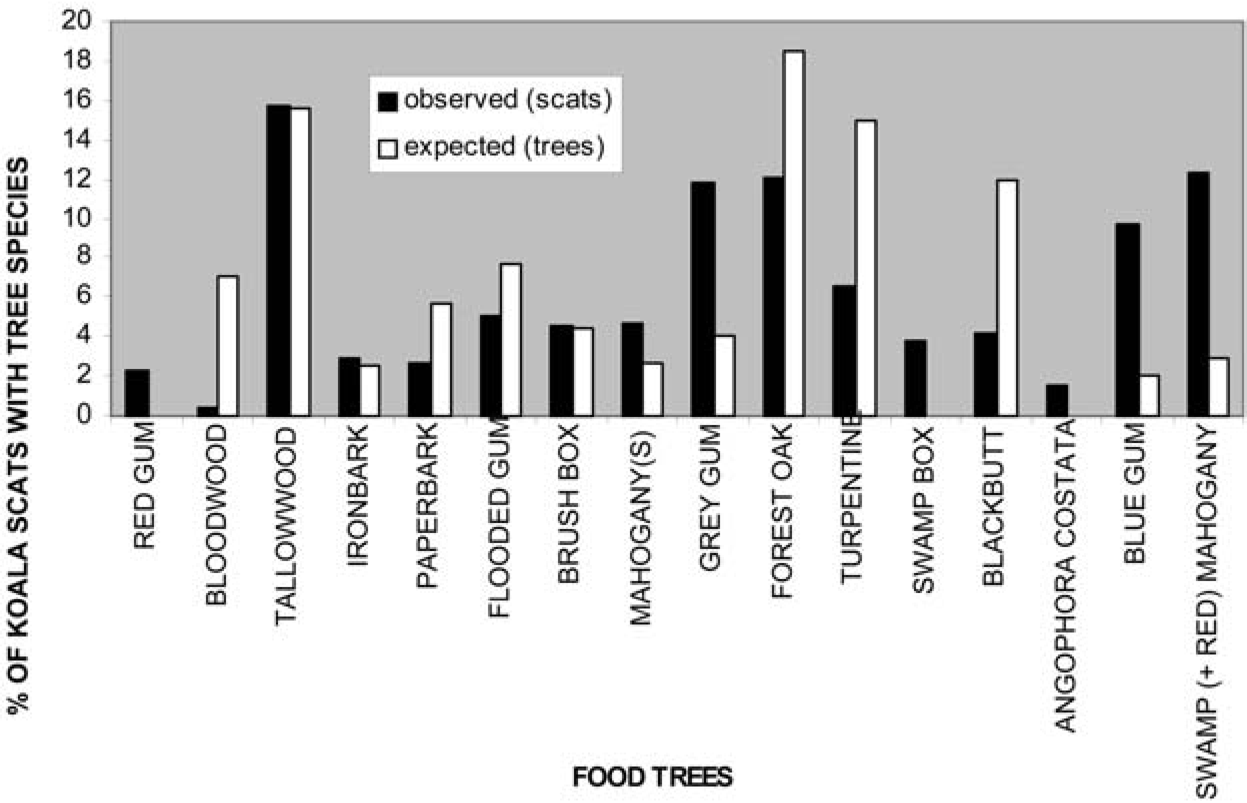
Tree Species (mean no.s per site)				
Blackbutt	5.10	11.20	5.00	1.20
Grey Gum	1.00	2.90	1.80	1.90
Tallowwood	2.90	9.60	7.90	6.30
Flooded Gum	12.20	0.80	4.80	10.70
Blue Gum	2.30	0.90	1.40	3.90
Brush Box	0.10	0.60	2.50	2.60
Turpentine	0.40	7.80	6.60	5.00
Palm	0.40	0.70	0.70	2.60
Forest Oak	0.90	7.10	8.10	6.00
White Mahogany	0.20	2.60	2.33	2.10
Swamp Mahogany	1.60	0.70	0.00	1.10
Bloodwood	1.70	4.30	3.10	2.20
Ironbark	1.40	1.30	1.20	1.40

Forest Types percentage of sites in type per group)				
Type 30 (5)	3	1	0	1
Type 36 (5)	1	0	4	0
Type 37 (21)	0	14	5	1
Type 46 (1)	0	0	0	1
Type 47 (10)	1	2	3	4
Type 48 (13)	3	1	2	7
Type 60 (19)	2	5	6	6
Plantation (18)	12	0	1	5

During field surveys, I observed a poor correlation between mapped forest types and tree species present, an effect that can be attributed to low topographic relief, uniform climate and a long history of logging (rather than fire) as the principal agent of disturbance and regeneration. For this reason survey sites were classified into floristic groups according to the relative abundance of blackbutt, flooded gum, tallowwood, turpentine, brushbox and bangalow palm *Archontophoenix cunninghamiana*, all species significantly associated with koala scat abundance or predominant in plantations. The resulting classification, using Wards algorithm and a percentage distance estimator, identified four major floristic groups which are described as follows: group 1, plantation (low tree species diversity, regrowth forest); group 2, dry blackbutt; group 3, tallowwood or moist blackbutt (mixed species), and group 4, moist hardwood.

Figure 6 (left). Hierarchical classification of survey sites into four major groups (plantation, dry blackbutt, tallowwood/moist blackbutt, moist hardwood) according to the number of stems (>10 cm dbh) of each species in survey plots. The mean number of stem/site for each of the dominant tree species in each group is listed to illustrate the principal floristic differences between groups. The number of survey sites in each group which fall within mapped SFNSW forest types (Baur 1965) is also listed to show the level of correspondence with floristic groups. Food tree species are those listed in Table 3.

Figure 7 (below). Comparison of the observed percentage of koala scats with remains of tree species and the expected frequency based on tree abundance in scat sample plots.



The mean abundance of all common tree species in each floristic group is shown in figure 6. This figure also shows the percentage of survey sites in each mapped (Baur 1965) forest type within each floristic group to illustrate the degree of correspondence between floristic groups defined in this study and State Forests of NSW forest types. The plantation group sites (group 1) were dominated by flooded gum and blackbutt plantations but also included some low diversity natural forest. Dry blackbutt forest sites (group 2) were dominated by natural stands of blackbutt and tallowwood. Tallowwood/ moist blackbutt forest sites (group 3) were dominated by tallowwood and blackbutt but with relatively high numbers of brush box and other moisture loving species. Moist hardwood forest sites (group 4) were dominated by naturally occurring flooded gum in association with moist forest species such as blue gum, brush box and bangalow palm.

The mean abundance of trees with koala scats differed significantly across floristic groups (AOV $P<0.05$). The mean number trees with scats was lowest in plantation (group 1) and highest in group 3 (tallowwood forest, Fig 6).

Soils and topography

It has been suggested that koalas are more abundant in forests and woodlands on high nutrient soils which typically occur on alluvium flats and fertile geologies (Reed and Lunney 1990). Soil type was not a significant predictor of koala scat abundance across all survey sites, but was a significant predictor within non-plantation forests (t test $p = 0.02$). Koala scats were more abundant in non-plantation sites on alluvial and transgressional soils than on erosional or marine soils.

Associations with roads

The association between the number of trees with koala scats in survey plots and proximity to the Pacific Highway was examined but no significant negative relationships or trends were found. Koalas appear to utilize habitats adjacent to the highway with a similar or higher frequency to habitats more distant from the highway.

Associations with logging history

The abundance of koala scats in non-plantation survey sites was correlated with aspects of logging history in the compartment surrounding survey sites including the number of timber stand improvement (TSI) events and the total number of logging events and the number of cross cut stumps (Table 2). TSI is the felling of dead and defective trees of no commercial value. The frequency of occurrence of koala scats was greatest in plots with 5 or more cross cut stumps, and within compartments subjected to 2 or more TSI events and 12 or more total logging events.

Decision tree analysis revealed that three additional logging history variables were significant predictors ($P<0.05$) of koala scat abundance in particular circumstances. Time since logging (as mapped by State Forests) and the number of old stumps were significant predictors of scat abundance in native forest compartments with a low total number of logging events (<14). Koala scats were more abundant in sites logged before 1985 and in sites with few or no stumps (<4 per hectare). In compartments with a high number of total logging events (>14) koala scats were significantly more abundant on sites with few or no new stumps (<4). These associations were difficult to interpret, but together they suggest that while koala scats are most abundant within compartments with a long, diverse or frequent logging history, they are only abundant in those portions of the compartment which had not been recently logged (within approximately 10 years). No significant correlations were apparent with the timber yield from compartments surrounding survey sites.

Associations with principal environmental gradients

A linear correlation matrix showing r values for all significant correlations between continuous predictor variables is shown in Table 4. This matrix shows that many of the environmental variables found to be good predictors of koala scat abundance are significantly correlated with one another. This effect, sometimes referred to as autocorrelation or confounding, can make the interpretation of causal associations between koala abundance and environmental variables difficult and speculative. A causal association with any one of

Table 4. Linear correlation matrix showing r values for all continuous predictor variables (from Table 2) that are significantly correlated with one another.

	1	2	3	4	5	6	7	8
1. Distance to Plantation								
2. CLASS	.48							
3. TSI	.48	.31						
4. TOTEVENT		.29	.60					
5. No of Stems 50-60 cm	.27	.5	.29					
6. No. of Stems 60-80cm	.33	.49	.27	.29				
7. No. of new logging stumps								
8. No. of Feed Tree Species	.42	.40		.27	.24	.38	.24	
9. No of Allocasuarina	.23	.29			.29	.24	.38	

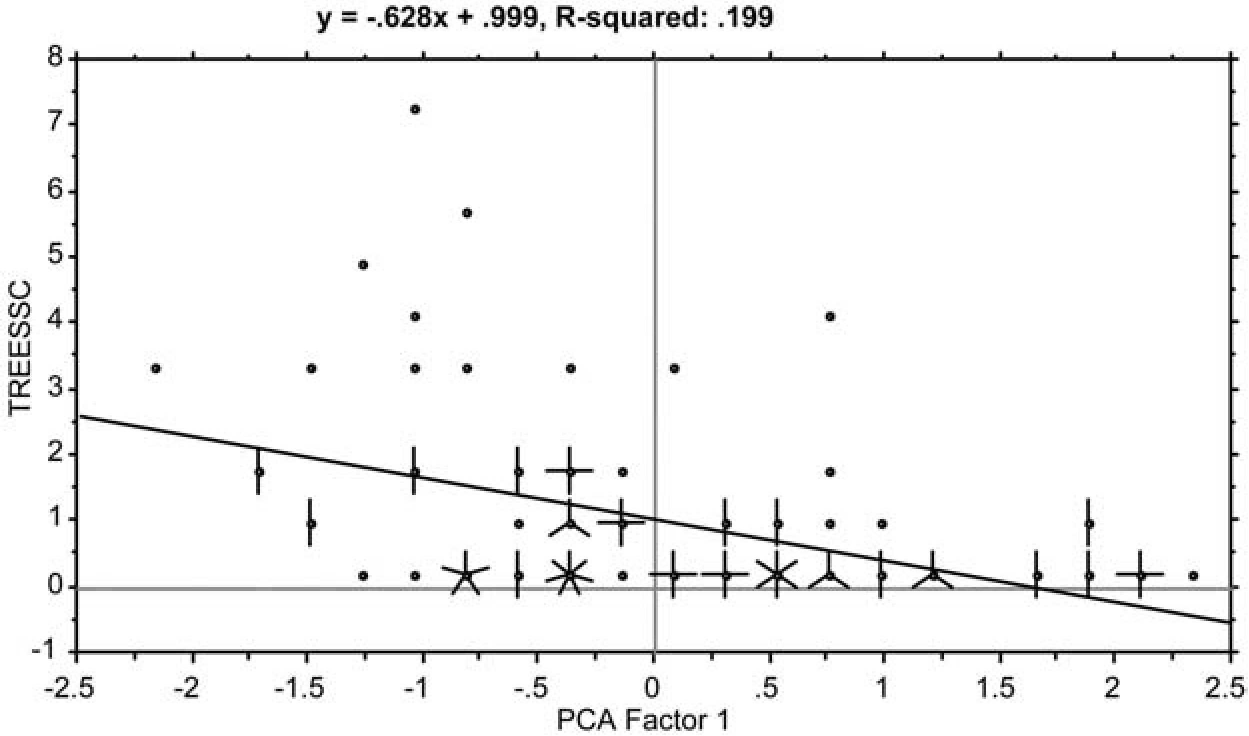


Figure 8. Linear relationship between koala scat abundance (TREESSC) and Factor 1 (see text for details).

these autocorrelated variable may automatically lead to associations with all other autocorrelated variables even in the absence of any real causal association.

Confounding often arises when predictor variables are all strongly influenced by the same underlying ecological or landuse gradients, such as primary productivity or past logging history. A Factor Analysis was applied to the data set to assist in the identification and interpretation of any underlying environmental gradients. Factor Analysis clustered all predictor variables onto a single principal gradient (Factor 1) with the exception of the number of new stumps and the number of stems in the 40-50 cm size class which were clustered onto a second principal gradient (Factor 2).

When the abundance of trees with koala scats was correlated with Factor Scores, Factor 1 was found to explain more of the variation in koala scat abundance than any single linear predictor variable on its own ($r = 0.45$, $p < 0.0001$, Fig 8). This result suggests that variation in koala scat abundance is best predicted by a combination of inter-related floristic, structural, and logging history variables. This gradient was interpreted to be one of increasing koala abundance with increasing tree stocking, increasing uneven-aged structure, increasing predominance of medium sized and mature stems, and increasing tree species richness, associated with a history of patchy and frequent low intensity selective logging and TSI. There was no significant association between Factor 2 and koala scat abundance.

Habitat model

The primary decision tree model (Figure 9) was generated by entering the number of food tree species (FTREEDIV) on survey sites as the first predictor variable. The number of trees with koala scats averaged only 0.1 on sites with less than four food tree species compared with an average of 1.3 on the remaining sites and this difference was statistically significant at $P = 0.003$. Within those sites with more than three food tree species, the next best predictor of koala scat abundance was structural class (CLASS). CLASS was the variable generated by classifying survey sites according to the number of stems in increasing diameter classes and ranking the resulting groups into a pseudo-succession gradient from young regrowth to uneven-aged forest with oldgrowth on a scale of 1-6. Koala scats were most abundant in sites in the oldest two structural classes (classes 5 and 6). Within structurally mature and uneven-aged forests, koala scat abundance was greatest on sites located within compartments with a high number of logging events (12 or more) indicating a long, frequent or diverse logging history. The final step in the model revealed that, within high logging-event compartments, koala scats were only abundant within forest patches with few or no new stumps (those which have been subject to low intensity or no recent logging). An alternative model was generated by entering plantation vs non-plantation at the first step. This alternative model was identical to the primary model in all subsequent steps, indicating that plantation and food tree species richness are essentially interchangeable for modelling purposes.

The second model presented (Fig. 10) is based on frequency of occurrence of koala scats on survey plots. The best predictor of scat frequency of occurrence on survey plots ($P = 0.0019$) was the number of tallowwood trees per plot. Only 14% of sites with no tallowwood supported koala scats, compared with 53% of sites with between 1 and 6 tallowwood and 60% of sites with more 6 or more tallowwoods. On plots with between 1 and 6 tallowwoods, the number of grey gums was the next best

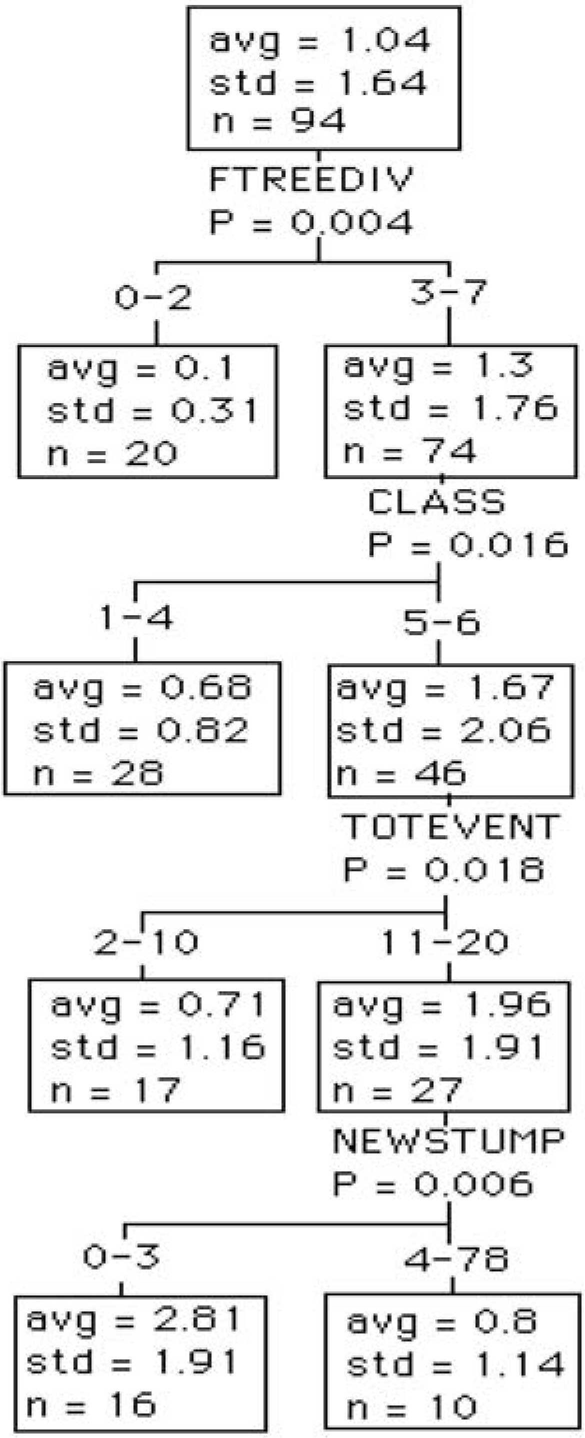


Figure 9. Decision tree habitat model that predicts relative koala abundance (as indicated by the abundance of trees with scats) in the study area as a function of environmental variables. Avg. = average scat abundance in survey sites; std = standard deviation of scat abundance; n = number of survey plots in sample; FTREEDIV = number of koala food tree species in survey plots (0-7); CLASS = forest structural class from regrowth (1) to uneven-aged forest with oldgrowth (6); TOTEVENT = the number of logging events in the compartment surrounding survey plots (from 2-20); NEWSTU = the density of new logging stumps (no per hectare) in survey plots (0-78); the probability value associated with each predictor variable is indicated below the variable name for each branch in the model.

predictor of scat occurrence, with scats present on 75% of plots with grey gum and tallowwood compared with only 31% of sites with tallowwood and no grey gum. On plots with 6 or more tallowwoods, soil type was the best predictor of scat frequency of occurrence, with the highest frequency of occurrence occurring on alluvial and colluvial rather than erosional or marine soils

Distribution model

The habitat model provides useful insights into the possible cause of koala distribution but has little value for koala distribution mapping because it incorporates unmapped habitat variables (variables measured at survey sites by ground survey but not available on maps of the study area). In order to predict and map koala distribution, an alternative, less rigorous model based only on mapped habitat variables was developed. The range of useful mapped habitat variables available in the study area was restricted to geology, topography, soils, forest type (Baur 1965), time since logging, and compartment number (including all logging history information summarized on a compartment basis).

Plantation vs non-plantation forest (PLANTSL) was the best overall mapped predictor of koala scat abundance. This variable was entered in the model first leaving a choice of two predictor variables, soil type (SOIL$) or the total number of logging events (TOTEVENT) for further subdividing non-plantation forests. Scat abundance was greater on alluvial soils and in high event (>14) compartments. When TOTEVENT was entered into the model after PLANTSL, then SOIL$ was an important predictor in the third step. Similarly if SOIL$ was entered into the model after PLANTSL then TOTEVENT was an important predictor in the third step indicating that both variables are important predictors of koala scat abundance. For the purpose of distribution modelling the model which entered TOTEVENT before SOIL$ was chosen because it exhibited a better fit with koala sighting records in the study area (see next section). No further splits were possible using additional mapped attributes.

Distribution map

The mapped attribute model was solved for all points in the study area (based on 100 m grid of mapped attributes) to generate a map of potential koala habitat which divided the study area into zones of low, medium and high relative scat abundance. The habitat map was tested by comparing the frequency of occurrence of koala scats at an additional 24 survey sites in the study area (8 sites randomly located within each of the three zones) with the expected number assuming a uniform scat distribution. This analysis showed the model to be accurate at the first level (plantation vs non-plantation), but the sample size was too small for evaluation of the model at the second and third levels.

The map was also tested using a combination of koala sightings from spotlight surveys (40 records) and Community Group records. The observed frequency of koala sightings was compared with the expected frequency, firstly assuming a uniform koala distribution and secondly assuming a koala distribution predicted under the model. Expected frequencies were calculated from the relative length of road survey transect passing through each habitat zone (Table 5).

The observed frequency of koalas in low, medium and high habitat quality zones differed significantly from the expected if koalas were distributed uniformly in all habitats (Chi-square = 9.5). The observed frequency of koalas also differed significantly from the predictions of the model when all three levels (PLANTSL$, TOTEVENT, SOIL$) were used for habitat prediction and mapping. Koalas were observed less frequently than expected on some alluvial soils and some compartments with more than 14 logging events. When the observed frequency of koala sightings was compared with the predictions of the model to the second tier only (using PLANTSL$ and TOTEVENT but not SOIL$ for mapping) there was no significant difference between the predictions of the model and the observed frequency of koala sightings (Table 5) but only when the non-plantation zone was expanded to include a 200 m wide strip of plantation adjacent to native forest. When conducting this analysis, it was noted that koala observation records in plantations were concentrated near the boundary with non-plantation forest. The predictions of the model were not consistent with the actual distribution of koala sightings unless this boundary effect was recognized.

Consequently the distribution model was used to the second tier only for the purposes of mapping potential koala habitat in the study area into zones of low, medium and high koala density. This model was a good predictor of relative koala density in plantation and non-plantation forest but a relatively poor predictor of relative koala abundance within non-plantation forests. Patterns revealed by habitat modelling indicated that koala habitat mapping could not be improved without first generating maps of forest structure and floristics (food plant density and distribution) and, to a lesser extent, logging history throughout the study area.

Koala density

The koala was the most frequently encountered arboreal marsupial in the study area. Koala scats were detected at 49% of survey sites and individual koalas were detected throughout the study area. The total numbers of each arboreal marsupial species detected during 161 km of road spotlight transects in the study area are listed in Table 6.

The number of koalas detected on spotlight transects decreased with increasing distance from the transect line (Figure 11). For this reason koala counts cannot be used for estimating density until a correction is made for the effects of decreasing detectability with increasing distance from the transect line. To estimate average koala density in the study area, a polynomial function ($p = 0.029$) was fitted to the decline data (Figure 10) and solved for zero distance to estimate koala density on the transect line, where koala detectability was assumed to be 100%. Koala density in a 161 km by 20 m wide strip (10 m either side) along the road transects through the study area was estimated to average 0.0665 animals per hectare (+/- 0.00834) or 15 hectares per koala. This density estimate is the average for the entire state forest, including plantations. It represents a minimum estimate of average koala density because not all animals are detectable by spotlight. Some individuals sleeping or looking away from the spotlight may have been missed.

The relative density of koalas in zones of mapped low, medium and high relative density was estimated in two different ways, from spotlight data and from scat data. Spotlight transects routes were overlaid on the koala habitat map to estimate relative koala density

Table 6. Total numbers of arboreal marsupials detected during 161 km of road spotlight surveys in the study area.

Common Name	Species	Number Seen
Koala	*Phascolarctos cinereus*	40
Greater glider	*Petauroides volans*	8
Common brushtail possum	*Trichosurus vulpecula*	7
Mountain brushtail possum	*Trichosurus caninus*	5
Sugar glider	*Petaurus breviceps*	4
Feathertail glider	*Acrobates pygmaeus*	2
Yellow-bellied glider	*Petaurus australis*	heard not seen

Table 5. Comparison of the frequency of actual koala observation records from spotlighting surveys (Spot) and community records (Community) in modelled koala habitat suitability zones (Habitat Suitability) with expected numbers, assuming that koalas were evenly distributed throughout the study area (Expected: uniform) and assuming that koalas are distributed in proportion to average scat densities measured in survey plots in each habitat suitability class (Expected: model).

Habitat Suitability Class		Observed Koala Records			Expected	
		Spot.	Community	Total	uniform	model
Low:	(plantation*)	3	4	7	19	5
Medium:	(non-plantation, totevent <15)	27	61	88	86	82
High:	(non-plantation, totevent >14)	10	28	38	28	46
Totals		40	93	133	133	133
Chi-square					9.5	2.6
Significance					S p<0.05	NS

* excluding 200m boundary adjacent to non plantation forest.

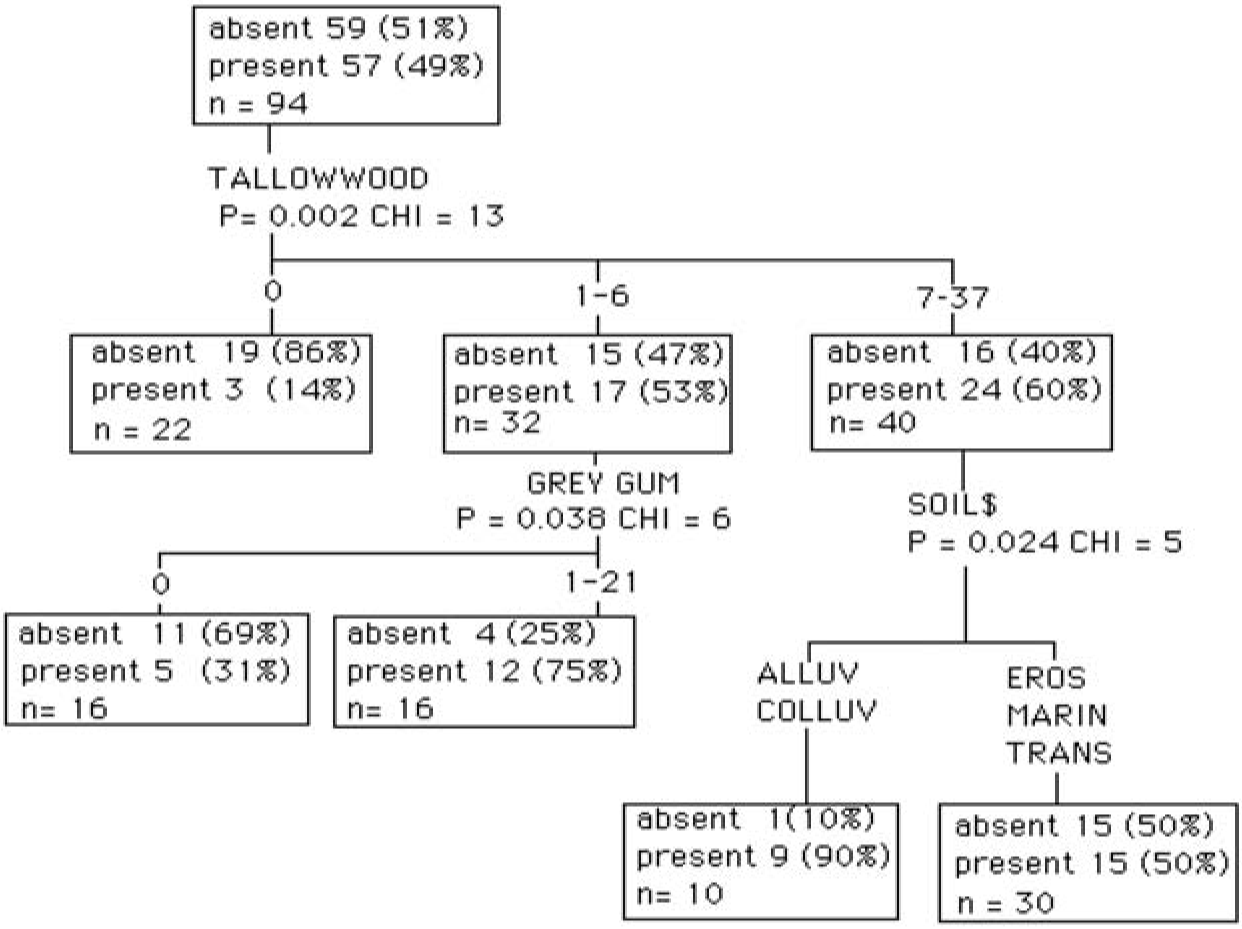


Figure 10. Decision tree habitat model that predicts the frequency of occurrence of koala scats in the study area as a function of environmental variables. absent = number and (percentage) of sites without koala scats, present = number and (percentage) of sites with koala scats. CHI = Chi-square. TALLOWWOOD and GREY GUM = number of stems of these species per plot. ALLUV/COLLUV indicates alluvial and colluvial soils, EROS, MARIN, TRANS, indicates erosional, marine and transgressional soils.

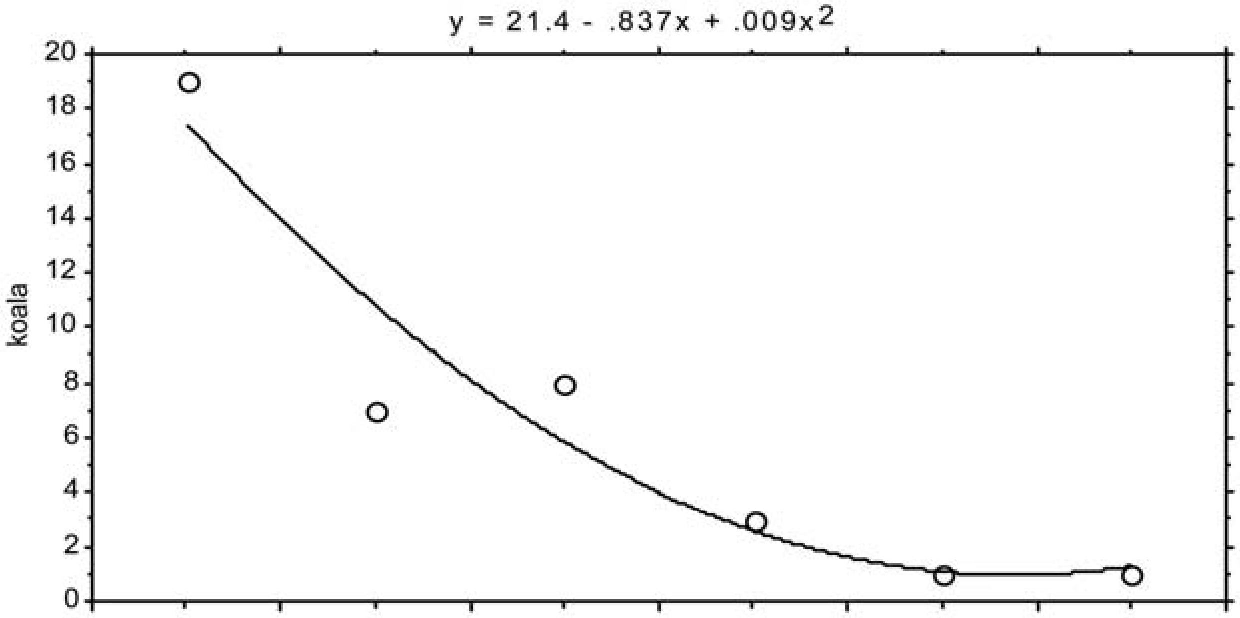


Figure 11. The number of koala sightings (koala) detected on both sides of 161 km of road spotlight transect in 10 metre right angle distance classes from the road edge is shown by open circles. The fitted curve was used to predict koala numbers at zero distance (where detectability is assumed to be 100%).

and minimum total population sizes in each habitat class. Total koala counts out to a distance of 50 m in each habitat class were multiplied by a correction factor (2.78) estimated from the detectability decline function, illustrated in Figure 11, to allow for animals not seen. This gave an overall estimate of 28 hectares per koala in low density habitat, 14 hectares per koala in medium density habitat and 12 hectares per koala in high density habitat.

The minimum population of koalas in the 6010 hectares of habitat in Pine Creek State Forest was estimated, from average spotlight density and habitat area, to be 400 +/- 50, or 350 to 450 individuals.

Variation in koala density in zones of low, medium and high koala density in the study area was also evaluated by assuming that the koala population of 400 animals was distributed in direct proportion to relative scat abundance in each zone. Using this approach, koala densities were estimated to average 73 hectares per animal in low density plantation habitat (0.013 animals per hectare), 14 hectares per animal in medium density habitat (0.071 animals per hectare) and 8 hectares per animal (0.12 animals per hectare) in high density habitat.

The discrepancy between koala densities in different habitat zones determined by spotlighting and scat abundance can be attributed to inherent biases in these alternative survey methods. Koala density is likely to be underestimated by spotlighting in high quality moist habitats, and over estimated in low quality plantations, due to differences in detectability. Visibility is generally greater in structurally uniform plantation forests with a sparse understorey and lower in uneven-aged forest with a dense understorey, thus leading to underestimation of density in high quality habitat and over-estimation in poor quality habitat when applying a single correction factor. Scat counts are likely to provide a more reliable indication of habitat use, but scats may be underestimated in plantations infested with lantana because of decreased visibility through to the ground layer, and in moist gullies due to increased moisture levels and higher decay rates after a period of heavy rain. Consequently the true minimum density of koalas in the study area was likely to fall between the extremes predicted by spotlighting and scat survey, that is approximately 50 hectares per koala in plantation, 14 hectares per koala in lower quality non-plantation and 9 hectares per koala in higher quality non-plantation forest.

Discussion

Koala distribution and abundance in Pine Creek State Forest in 1996 was best explained by a combination of environmental variables including food tree abundance, food tree species richness, forest structure, forest association, logging history, and soil type.

Food tree preferences

Koalas are well known to favour particular tree species for feeding in both captivity and the wild (Lee and Martin 1988, Phillips *et al*. 2000). Identification and mapping the distribution of preferred food trees and tree associations has been a common approach to mapping koala habitat for implementation of regional koala conservation management plans (Lunney *et al.* 2000). In this study, koala scats were found more often than expected (on the basis of tree species abundance) beneath tallowwood and grey gum. Scats were also found less often than expected below blackbutt, forest oak, turpentine and rainforest tree species. A comparison of the frequency of occurrence of tree species in koala scats from the study area, with the expected frequency based on the proportion of tree species in survey plots from which scats were sampled, indicated a similar but slightly different picture. Tallowwood occurred in the highest number of scats (16%) followed by grey gum, forest oak, blue gum and swamp mahogany/red mahogany. However, tallowwood occurred at the expected frequency based on tree abundance in survey plots while grey gum, blue gum and swamp mahogany/red mahogany were ingested more frequently than expected. Turpentine and blackbutt were less common in scats and occurred at less than the expected frequency based on tree abundance in survey plots.

Most of the tree species preferred by koalas in this study are known to be preferred by koalas in captivity or have been reported as preferred food trees in previous studies. An exception however, is the importance of forest oak in Pine Creek State forest. While koalas are occasionally known to feed on non-eucalypt species (Moore and Foley 2000) the presence of Allocasuarina in more scats than all other eucalypts with the exception of tallowwood is exceptional and may indicate an important dietary preference that should be taken into account in conservation planning. Smith *et al.* (1995) reported a similar correlation between the abundance of all arboreal marsupial species (predominantly eucalypt leaf eating possums and gliders) and *Allocasuarina* throughout the forests of the Coffs Harbour and Urunga region in a regional scale study. *Allocasuarina* is a nitrogen fixing plant which may be expected to have high foliage nitrogen levels. It may contribute directly to koala habitat as a high protein food supplement or indirectly by boosting soil fertility and enhancing foliage nutrient levels in adjacent *Eucalyptus* trees. *Allocasuarina* is thought to be fire sensitive and can be reduced or inhibited by frequent burning. *Allocasuarina* was scarce or absent in plantation forests in the study area which may, in conjunction with forest structure and low tree species diversity, account for the scarcity of koalas in native forest plantation.

Food tree species richness

Food tree diversity, or the total number of food tree species present in survey plots, explained a greater amount of variation in koala scat abundance than the abundance of any single food tree species. Smith *et al.* (1995) reported a similar association between eucalyptus species richness and the abundance of all arboreal mammals (principally leaf eating possums and gliders) in the State Forests of the Coffs Harbour region. Although food tree diversity has been alluded to as a potential predictor of koala habitat, this is the first study in which it has been identified as a primary determinant of koala abundance. Hindell and Lee (1987) observed that all koala home ranges in their

Brisbane Ranges study area contained at least four species of eucalypts. In this study, koala scat abundance peaked in sites with three or more preferred food trees (tree species listed in Table 3). This finding is consistent with the results of concurrent dietary studies in Pine Creek State Forest (C. MacGregor and A. Smith unpublished data) which identified a minimum 17 tree species in koala scats and an average of more than four tree species per scat.

Food tree diversity may be an important factor in forest habitats because it enables koalas to satisfy their nutritional requirements by selecting different tree species for different essential nutrients (water, protein, energy) and to avoid exceeding toxicity thresholds associated with individual tree species. Koalas are known to avoid tree species, individual trees and tree parts (mature leaves) which are high in toxins and to favour tree species, individual trees and tree parts (new leaf, flower) with high available protein and moisture levels (Moore and Foley 2000). Koala scats in the study area included remains of flowers of *Eucalyptus* and *Allocasuarina,* which are expected to be high in pollen nitrogen and low in fibre content and toxicity. *Eucalyptus* species commonly differ in the timing and duration of flowering and new leaf growth, so high diversity forests should offer high quality forage for a greater portion of the year.

Structural preferences of the koala

This study identified forest structure to be a key predictor of koala scat density after food tree species and diversity. Koala scats were found to be more frequent than expected under trees with girths of 40-80 cm diameter. Lunney *et al*. (1996) also found koalas to prefer trees in the 51-70 cm diameter class at Iluka. These findings are also consistent with the results of recent studies in the outskirts of Sydney which showed koalas to prefer trees of 30-40 cm dbh (Ward 2003). This is approximately the distance between the outstretched paws of a koala suggesting that this preference may be at least partially related to the energetics of climbing. Koalas are reported to use approximately three trees per night (Hindell and Lee 1987). Because of their large size they cannot generally move from tree to tree through the forest canopy like other arboreal marsupials but must descend to the ground except in dense forest where leaping between trunks has been observed. This form of movement is likely to be more energetically expensive than gliding or intercanopy movement, so koalas can be expected to select individual trees which are either easy to climb or closely spaced within jumping reach. Koalas may also prefer larger trees because they provide larger branches or forks for day and night time sleeping.

Forest structural class was found to be a good predictor of koala scat abundance in Pine Creek State Forest in addition to tree size. Koala scats were most abundant in uneven-aged forests with some mature and oldgrowth elements and a spread of trees in all size classes from juvenile to oldgrowth. Preferred forests were also those with the greatest stocking or number of trees per hectare. In the Urbenville Forest Management Area of north east NSW (near the NSW Queensland border) koalas were found in all forest structural categories except young regrowth and uneven aged forests without an oldgrowth component, and uneven-aged forests without a regrowth component (Andrews *et al.* 1994). This finding is consistent with the pattern observed at Pine Creek in which koalas favoured dense structurally complex forests with young, mature and some older elements. Hindell and Lee (1987) reported similar findings in the Brisbane Ranges of Victoria where koalas favoured large trees and forests with more large trees, independent of floristics. They found koala density to be negatively correlated with the density of small trees (7-19 m high) and positively correlated with the number of tall trees (19-25 m) and trees of increasing size and foliage biomass. They attributed forest structural associations to the increased foliage biomass on large trees and improved shelter from adverse weather offered by larger trees.

I suggest that dense uneven-aged forest structure enhances foraging efficiency by providing greater access to eucalypt foliage. Koalas are unable to support themselves on the fine outer branches of trees because of their large body mass and they must reach out and pull small, outer branches toward them while seated on a nearby larger branch or trunk. This mode of feeding should be favoured in uneven aged forests with a complex structure and multiple foliage layers between the ground and canopy levels. Plantations with small diameter trunks, fine outer branches and a single exterior foliage canopy layer, and recently logged forests with a low basal area offer the least efficient foraging structure.

Koala density

Koala densities reported in this study in optimal habitat (9-12 hectares per koala) are low relative to densities previously reported in island and coastal woodland populations (Melzer and Houston 1997) but consistent with densities reported in moist New England Tableland forests (Smith 2001). Given the high foliage biomass and high site productivity of coastal and escarpment forests, the comparatively low density of koalas in forest habitats requires some explanation.

Koalas are known to prefer habitats on fertile soils which is consistent with the hypothesis that koalas are limited by a relative shortage of protein (Degabriele 1981). Attempts to explain variations in koala density have focused on the role of foliage nutrients (particularly water, protein and energy) and anti-nutrients (fibre and toxins) in food selection (Moore and Foley 2000). The importance of protein as a limiting nutrient in the diet of domestic and wild herbivores has long been recognized (White 1978, Harrop and Degabriele 1978). Smith and Lee (1984) calculated that percentage dietary protein requirements for growth and reproduction increase with increasing body size in arboreal marsupials and is likely to be limiting below 9-16% in animals the size of the koala (10,000 g). This prediction is consistent with the findings of laboratory studies by Pahl and Hume (1991) which showed that captive koalas select foliage with a leaf protein level of more than 12.5%. Protein levels in *Eucalyptus* foliage are highly variable but tend to fall below 12 % and near the bottom of the theoretically required range in mature eucalyptus leaves and near the top in juvenile leaves. This is presumably why captive koalas generally favour young or new leaves (Fleay 1937). A relative shortage of protein could limit koala distribution to habitats with abundant and year round supplies of new leaf growth, habitats with exceptional mature foliage protein levels such as those on fertile soils, or habitats with high nitrogen dietary supplements such as flowers and understorey casuarinas. Such habitats include partially cleared and dieback-affected rural lands where tree foliage is dominated by young and epicormic growth (Landsberg 1990); rural and urban lands treated with fertilizers; alluvial soils along rivers and drainage lines; escarpment forests on soils of moderate fertility with casuarina understoreys that have not been subject to frequent control burning; and forests and woodlands on fertile soils and geologies.

Alternatively the density of koalas in Pine Creek State Forest may have been reduced by the disease *Chlamydia* or other unidentified agents including predation by dogs and roadkill. *Chlamydia* is known to reduce fecundity in koalas (Mitchell and Martin 1990). The effect of *Chlamydia* was not investigated during this study, but about 22% of animals observed during spotlight surveys were juveniles or subadults indicating that the population was reproducing successfully. Koalas are vulnerable to predation by dogs when they descend to the ground to cross from one tree to another. It is noteworthy that the part of Pine Creek State Forest with the highest incidence of koala observations by local residents was particularly dense. In this area I observed koalas leaping from tree trunk to tree trunk avoiding the need to descend to the ground. This may be another possible explanation for apparent koala preference for structurally complex forests.

Koala mortality from roadkill in parts of Pine Creek State Forest was monitored annually by C. Moon (unpublished data). There were 8 reported cases of mortality along the Pacific Highway through Pine Creek in the first 10 months of 1996 and an average of more than 4 dead, sick or injured animals on roads in the vicinity of Pine Creek since 1988. Assuming an annual traffic mortality of 10 individuals per year, a healthy population of 40 individual koalas (or 580 hectares of habitat) would be required just to sustain this annual loss.

The importance of forest habitats to the koala in NSW may have been underestimated. State wide postal surveys of koala distribution are inherently biased toward partially cleared agricultural and urban lands in the vicinity of population centres. In arboreal mammal surveys of Urbenville forest management area, koalas were detected at more sites than any other arboreal mammal species (Andrews *et al.* 1994). In this study the koala was found to be the most abundant arboreal mammal in Pine Creek State Forest, exceeding the combined density of all other arboreal marsupials. Similarly, Lunney *et al.* (1997) concluded that State Forests contain the core of surviving populations in the Eden region of south-east NSW. Pine Creek State Forest is unusual in that it is one of the few forested areas remaining on fertile soils along the coast. Most of these forests have been cleared leaving coastal koala surveys to be biased toward urban and agricultural land, which is not the original habitat of the koala.

The scarcity of koalas in tall moist forests may also be partly attributable to structural foraging constraints and climatic constraints. Because koalas do not use tree hollows to reduce the energy demands of feeding and sleeping in adverse weather conditions like other arboreal mammals, they may be at risk of energy depletion in cold wet environments. The geographic ranges of Australia's two obligate eucalypt feeding arboreal mammals, the koala and the greater glider, are broadly complementary. The greater glider *Petauroides volans* lives in tree hollows and favours tall moist forests in cool climates and high elevations while the koala sleeps in the open and generally favours woodland and forest in warmer climates at lower elevations in north east NSW (NPWS 1994). Competition between these two species may be an important factor limiting densities of both species in the overlap zone such as the foothill and escarpment forests of north-east NSW. These findings suggest that in this zone, which includes Pine Creek State Forest, the koala will be advantaged in forests with few or no tree hollows.

Population size

The koala population estimate for Pine Creek of 400 +/- 50 is likely to be an underestimate because it was based on drive transect counts that may not detect all individuals. During the course of this study local residents pioneered a koala monitoring technique that involved walk spotlighting combined with call listening for 10 minutes every 200 m on still (quiet) nights. Whenever a call was heard, a search was undertaken and the exact location of the animal recorded. This method gave consistent returns and is recommended for future surveys.

Impacts of forestry

The likely effects of timber harvesting on koalas can be inferred from their habitat requirements and associations with logging history. Results of this study indicate that historical, low intensity forestry practices, such as selective removal of a limited number of large diameter trees are compatible with maintenance of natural koala density while intensive practices such as clearfelling, plantation development and Australian Group Selection which reduce forest structural complexity, reduce stand basal area, reduce food tree diversity and reduce or eliminate some preferred food trees also significantly reduce koala density.

The abundance of koala scats in production forests was found to increase linearly with the number of TSI events in the compartment surrounding survey sites. TSI is undertaken to promote the growth of regenerating and subdominant trees shaded by emergent oldgrowth stems of no commercial value. Culling also has the effect of reducing or removing tree hollows. Pine Creek State Forest has the lowest density of hollow-dependent arboreal marsupials yet recorded in a State Forest in north east NSW (Smith *et al.* 1992,1994, 1995). I attribute this exceptionally low density at least in part to a scarcity of tree hollows following a long history of TSI. This practice may have inadvertently advantaged the koala. A reduction in abundance of hollow-dependent possums and gliders, including the greater glider common and mountain brushtail possums *Trichosurus spp*. and common ringtail possum *Pseudocheirus peregrinus*, which all consume young eucalyptus leaves, is likely to have significantly reduced competition for koalas and may account in part for the increase in koala density in compartments which have been frequently culled.

Koala scat abundance was also found to be positively correlated with the total number of forestry events in compartments surrounding survey sites, including TSI, pole and sleeper harvesting, quota harvesting, gap clearfelling, thinning and replanting. I suggest two possible explanations for this association. Firstly, koalas may benefit from the structural diversity and stimulation of new leaf growth created by a long, frequent or diverse logging history. Secondly koalas may be displaced from portions of the compartment which have been intensively or frequently logged and become concentrated in remaining portions of the compartment which have not been disturbed. Results of this study suggest that both these factors are contributing to the pattern of koala distribution in Pine Creek State Forest. Koalas appear to favour uneven-aged forests which have developed after a long history of low intensity, single tree or large diameter-limited harvesting. Koala scats were also most abundant in portions of compartments with few or no new stumps or no evidence of recent logging (within the last 10 years). This observation is consistent with the predictions by Smith *et al.* (1995) that koalas may require long periods (10-20 years) for population growth and recovery after displacement by moderate to intense logging because of their low reproductive potential, particularly in populations infected with the reproductive tract disease *Chlamydia* which is known to reduce fecundity (Mitchell *et al*. 1988). No data were available on Chlamydia infection rates at Pine Creek during this study but the presence of juveniles and subadults indicated that recruitment was occurring. Very little information is currently available on the socio-demographic effects of logging and associated disturbance on koala populations. It is not known whether koalas are killed, displaced or relatively unaffected by logging disturbance. Neither is it known whether koalas displaced by logging disturbance cause stress and reduce fecundity and survival in koala populations inhabiting adjacent unlogged forest (due to overcrowding and territory invasion).

There are few other forestry impact studies with which to compare the findings of this study. Kavanagh *et al.* (1995) reported a positive correlation between koala occurrence and high intensity logging in the forests of north-east NSW based on regional scale surveys. This result needs to be interpreted with caution. Firstly Kavanagh *et al.* (1995) classified forests with a history of several logging cycles and few or no old trees with hollows as intensively logged, while we have classified forests with the same history in Pine Creek as selectively logged or logged at low to moderate intensity. A long history of logging does not necessarily equate with high logging intensity. Secondly, high intensity logging and elevation were confounded in Kavanagh's data set. Intensively logged sites occurred in coastal and subcoastal sites at elevations below 400 m where rainfall is higher and koalas were most abundant (NPWS 1994). Thus it is likely that their finding that koala abundance is correlated with a long logging history is an artefact of increased koala abundance in low elevation coastal and subcoastal habitats in north-east NSW forests.

Creation and maintenance of koala habitat in production forest will require a new approach to harvesting and silviculture based on the low intensity, single tree selection and diameter limited harvesting practices more typical of those carried out in the past. Plantation development and creation of plantation-like structure in native forest is not compatible with maintenance of natural koala densities. Australian Group Selection was proposed to the author as an acceptable form of silviculture for koala conservation. To evaluate the potential effect of Australian Group Selection harvesting on the structure of koala habitat, the distribution of trees by size class in an experimental blackbutt compartment in Pine Creek State Forest subjected to Australian Group Selection in 1955, 1969, and 1989 (Florence 1996), was compared with the structure preferred by koalas (Smith 1987). This comparison revealed that forests preferred by koalas (Class 5 and 6) have a greater stocking of trees in all diameter classes, particularly those over 50 cm dbh than forests subject to Australian Group Selection. Australian Group Selection harvesting produces a forest with a stocking density close to that preferred by the koala when stem distribution is averaged over a 5 hectare area. However, this is not the case when forest structure is considered at a finer (quarter hectare) scale. The experimental logging site with the stocking shown in Florence (1996) was inspected in the field and found to comprise a mosaic of small uniform–aged forest patches each of different age and structure. Some of these patches had a structure preferred by koalas but the majority tended to be even-aged cohorts dispersed in a patchy mosaic. Consequently it can be concluded that Australian Group Selection is equivalent to small gap clearfelling and, overall, should rank poorly as koala habitat.

Koala conservation in production forests

This study has shown that it is possible to conserve koala populations at current levels while at the same time allowing commercial timber production to continue at historical or slightly higher levels. The habitats least favoured by koalas, plantation and blackbutt forest, were those most important for timber production. Habitats most preferred by koalas can still be used for timber production by infrequent, low intensity removal of large diameter stems. Smith (1997) used these findings to recommend a zoning approach to koala conservation in Pine Creek State Forest based on implementation of different harvesting intensities in different structural and floristic zones. It was recommended that koala habitat carrying capacity be maintained at a target level of 400 individuals across three zones of approximately equal area. Zone 1 in which koala conservation would be a priority included preferred koala habitat, reserves and corridors. This occurred mainly in mature, mixed species forest down slope from blackbutt ridges and in moist hardwood forest in gullies. Zone 2 in which koala conservation and timber production would have equal priority (resulting in a reduction in koala numbers and a reduction in timber production) occurred mainly in heavily logged blackbutt dominated forests on ridges. Zone 3 in which timber production would be a priority included plantations and poor quality koala habitat. It was intended that information provided by this study be used to evaluate the likely effects of alternative zone boundaries on koala population size, thus providing an objective tool for comparing planning and management options and achieving conservation and timber production targets.

Findings and recommendations arising from this study were not welcomed with enthusiasm by State Forests of NSW. Reports arising from the study (Smith and Andrews 1997, Smith 1997) were subject to more review, scrutiny and intensive criticism than any of the other 60 scientific papers or 50 major reports that I have prepared during my career with the exception of studies on the Hastings River Mouse which have attracted a similar level of criticism from SFNSW. The Pine Creek koala survey data set was sent, without my knowledge, to a statistician in a Queensland central coast university for independent re-analysis after the study had been completed. This is why the data set may appear to have been over–analysed. I concluded that SFNSW, at that time, was not an appropriate authority for independent review of threatened forest species research. It stood to benefit financially by finding reviewers that would reject findings that might constrain wood production.

A package of recommendations to sustain koala populations within production forests, including the setting of limits to timber yields, maintaining a minimum stocking of mature and older trees and feed trees, reservation of a minimum 15% of koala habitat in each logging compartment and harvesting at intervals of not less than 15 years in timber production zones, was presented to SFNSW (Smith 1997). However, the author had no say in preparation of the final Koala Plan of Management for Pine Creek State Forest (SFNSW 2000) or decisions regarding the final balance between wood production and koala conservation. Key recommendations for integration of koala conservation and wood, particularly the need to maintain the low intensity harvesting instead of Australian Group Selection and gap harvesting were rejected. Approximately 12 months later, dissatisfaction with the Pine Creek Koala Plan of Management and insensitivity in its implementation prompted the local community (Pine Creek Koala Support Group) and NEFA (North East Forest Alliance) to put forward a proposal in 1998 to transfer the best koala habitat in Pine Creek to national park. This proposal was in large part adopted by the NSW Government in 2003 when 3000 hectares of non-plantation koala habitat in Pine Creek, including areas previously subject to clearfelling, was transferred to the adjoining Bongil Bongil National Park (Fig. 1).

In 1991 the author published a forest policy study (Smith 1991) which opened with the words " failure of forest management agencies in Australia to introduce silvicultural practices sympathetic to ecological patterns and processes has increased pressure for transfer of limited remaining areas of old growth forests from State Forests to National Parks. The timber industry already faced with declining wood quality and quantity, shrinking market share and operational deficits, has responded by intensification of hardwood production methods and gradual conversion of natural forests into tree farms. This polarized approach to planning and management of the forest is fostering conflict in the timber industry and achieving one of the lowest possible net benefits to society." These words were prophetic, accurately forecasting events in Pine Creek State Forest and more widely throughout north east New South Wales. In my opinion, this result is almost entirely due to failure of SFNSW to reverse timber over supply commitments and adopt new, low intensity harvesting practices and minimum stocking standards that prevent over-cutting of natural forests and their conversion to tree farms.

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