MAPPING POTENTIAL HABITAT FOR VERTEBRATES IN FORESTS OF WESTERN AUSTRALIA

FINAL REPORT

For the Department of Conservation and Land Management, Western Australia

Bill McComb, Department of Forest Science, Oregon State University, Corvallis, OR 97331

10 August 1994

9 August 1994

MEMO TO:

Jim Armstrong
Paul Biggs
Jack Bradshaw
Neil Burrows
Per Christensen
Pat Collins
Karen Faunt
Gordon Friend
Barbara Jones
Rick Low
Jonathon Major
Keith Morris
Frank Podger
Martin Rayner
Denis Saunders
Peter Stirling
Geoff Stoneman
Dave Swain
Dave Ward

From: Bill McComb

Re: Final Report

Attached are the first few pages of a final report that I am leaving with Geoff Stoneman, SID, CALM, 50 Hayman Rd. Como. I am sending you this information so that if there are parts of the report that are of interest to you, you can contact Geoff, and arrange to have copies of made of those parts that you could use. The information in the report fills 2 large notebooks and includes 14 computer disks so it was not possible to provide each of you a copy.

I want to thank you for your help and hospitality during my stay in WA. I have felt most welcome here and would very much enjoy returning to WA again if an opportunity was available. Also, if any of you ever have the chance to visit the Pacific northwest of the U.S., be sure to stop in Corvallis for a few days. I'd be happy to show you the Oregon Coast, Coast Range, and Cascades, and introduce you to scientists and managers at Oregon State Univerisity, the USDI Research Center, The Environmental Protection Agency, and the USDA Forest Service Forest Experiment Station, all located in Corvallis.

Finally, if I can be of any help after I return to the U.S., I can be reached at the Department of Forest Science, Oregon State University, Corvallis, OR 97330 (503-737-2244), or over internet on mccombb@fsl.orst.edu. For you CALM folks, when (if) CALM is connected to internet, please drop me a message so I will have your e-mail address. Thanks for your help and for making a great year even better. I look forward to seeing each of you again someday.

Preface

The purpose of this report is to compile all of the manuscripts, models, model documentation, and raw data into one document that can be accessible to those individuals wishing to access this information in the future. The executive summary provides a brief synopsis of each section so that potential users can find the information that they need easily. In addition, I have offered my perceptions on the current and future state of forest research and management for multiple resources in the Department of Conservation and Land Management (CALM). These were sent to Dr. Syd Shea in a letter dated 28 July. These perceptions are my own and do not reflect those of any employee of CALM; indeed, I have not shared these perceptions with anyone in CALM until now.

I have thoroughly enjoyed my year working with scientists and land managers at CALM. I have been treated very well, and would welcome any opportunity to return to Western Australia to participate in land management planning, research projects, or continuing education activities. CALM is very fortunate to have well-trained, committed, and hard-working professionals in their employ.

Finally, I thank all those who have helped me during my stay here. Special thanks to Jack Bradshaw, Elaine Davison , Gordon Friend, Geoff Stoneman, and Dave Ward for inviting our family into their homes. Also to all of those above plus Kim Allen, Paul Biggs, Neil Burrows, Per Christensen, Pat Collins, Charles Downs, Karen Faunt, Barbara Jones, Matthew Jones, Keith Morris, Mike Pez, Kim Phillips-Jones, Martin Rayner, Greg Streline, Dave Swain, and John Webb for offering their assistance with my project despite having already very busy schedules.

Where to from here?

Neil Burrows and Per Christensen suggested that I offer my thoughts on continuation of the effort that has been initiated this past year on vertebrate persistence on managed lands. The data, models, and manuscripts contained in the final report represent only a first effort at the process of including estimates of population persistence for native fauna in managed forest lands. We have only begun to develop mapping rules and estimate demographic parameters for a few species. And even for those species, the process has resulted in identification of a number of research needs, particularly in habitat requirements of native fauna, estimates of habitat change as a result of fire and/or logging, and estimates of survival, reproduction and movement rates of species in various habitats. Clearly there is a need to add to the information that we have used in this effort for all of the species, and to begin to estimate those parameters for additional species.

For the process to continue, there must be commitment among forest planners to use the best available information to help them make decisions regarding where and how much to harvest AND there must be the commitment among the wildlife biologists to provide that information to the best of their abilities. Fortunately, all of the forest planners that I worked with, especially Paul Biggs and Pat Collins, seem willing to continue their work using PVA modeling to explicitly consider vertebrate persistence during development of management plans. Paul is attempting to follow through with this in the central jarrah forest and Pat has been assisting with production of maps from FMIS. Also fortunate is that Gordon Friend, Keith Morris, and Per Christensen have been very helpful in providing information needed to better consider vertebrates in forest plans. I would hope that these five people could form a core group to work on forest planning in the central jarrah forest and use the plans and processes from that area as a prototype for planning elsewhere in the region. Indeed, I expect that Peter Stirling will become more involved in developing an export protocol with in his integrated planning system that will produce map files that could be read directly into one or more PVA models for a series of species. Finally, it may be desirable for CALM to consider revising existing PVA models to be more compatible with FMIS and to more closely meet the assumptions for each species considered during forest planning. Source code for the OWL model is provided in the final report to facilitate revisions of that model if desired.

In summary, I see the materials included within the final report as of most utility to forest planners. Consequently, I expect Paul and Pat to take the lead in using these tools and approaches. Further, I expect that Paul and Pat will rely on advice from Gordon, Keith, and Per regarding species habitat requirements, demographic characteristics, or revisions to models. Finally, I believe that it is imperative that regular communication be established among all of these folks, to allow biologists to react to the results of the analyses (are they realistic?), and for biologists to be sure that when new information becomes available that can be used in this process that Paul and Pat can make those changes as soon as possible. Finally, if I can be of any help at any time, don't hesitate to e-mail (mccombb@fsl.orst.edu), FAX, phone (0011-1-503-737-2244), or write me at the Department of Forest Science, OSU, Corvallis, OR 97331. Please stay in touch.

EXECUTIVE SUMMARY OF FINAL REPORT

Study Plan

This section contains the study plan, a conceptual overview of forest wildlife habitat ecology, and an example questionnaire developed to acquire information needed to begin population viability analyses for selected forest vertebrates in the region. Sections that follow describe the results, data, and computer programs used to analyse data for each aspect of the study.

Tree Hollow Availability Study

Because several wildlife species use tree hollows as cover, I conducted a study to determine if tree inventory data collected by the inventory specialists within CALM could be used to predict the probability of occurrence of a hollow of a size suitable for each of several species in a jarrah or marri tree. I tested relationships based on these data with data collected by Karen Faunt. A manuscript describing the study was prepared and a draft copy is included as a WordPerfect document, and MS WORD document, and as a hard copy. Copies of field data sheets and DBase IV files are included. Karen Faunt's tree hollow data are also included as DBase files. A list of SAS programs is included as a hard copy and all SAS programs are contained on disk.

Woylie Population Viability Analyses

A manuscript was prepared to illustrate the utility of PVA to a management problem for a rare species. A copy of an early draft of the manuscript is included for reference. The likelihood of woylie persistence, predicted extinction time , and the rate of genetic loss were all predicted to improve for woylies if either foxes were baited or if burning cycles were extended from 10 to 20 years. Both strategies in combination virtually ensured the long term persistence of woylies. Data produced by the PVA model, SAS programs, FMIS map files, and a brief description of the process of transposing FMIS ASCII files into MAP files for the OWL program are included.

Chuditch Population Viability Analyses

Rules for mapping available habitat for chuditch in the northern jarrah forest were developed based on estimated hollow log availability for chuditch (from jarrah forest inventory data) and a preliminary set of maps reflecting past burn cycles (over 15 years) and bauxite mining were developed. These are currently being revised to estimate potential mine sites in the future. Consideration should also be given to the variability in hollow log estimates by assigning only a portion of all potential home ranges as adequate, similar to what Paul Biggs is considering for brush-tailed possums. Demographics parameters were estimated by Keith Morris and preliminary simulations were run. Refinement of estimates is under way. The preliminary maps, demographic rules, and simulations are included on disk.

Brush-tailed Possum Population Viability Analyses

Rules for mapping brush-tailed possum habitat were developed based on estimated hollow availability in forest strata in the Greenbushes supply area. Paul Biggs is currently developing an approach to estimating future harvest areas within FMIS. Demographic parameters were estimated based on information in the literature and from estimates provided by Barbara Jones. Preliminary simulations on a test map that includes projected harvests for 15 years into the future indicates that these rules seem to work fairly well. This is a large area, but preliminary tests indicate that the model can handle the size of the area. Wildlife biologists should be contacted to determine where in the supply area possums are known to occur. Additional harvest patterns will be developed by Paul.

Brush-tailed Phascogale Population Viability Analyses

Rules for mapping brush-tailed phascogale habitat were developed based on estimated tree size class distributions in forest strata in the Greenbushes supply area. Paul Biggs is currently developing an approach to estimating future harvest areas within FMIS. Demographic parameters were estimated based on information in the Todd Soderquist's dissertation and from estimates provided by Gordon Friend. Preliminary simulations on a test map indicates that these rules seem to work fairly well, but refinement may be necessary following finalisation of the mapping process, especially given the disparate survival rates between females and males for this species.

Appendices: Models available

VERTLIFE -- I included the documentation for VERTLIFE so that others will know of its availability. This is a habitat association model developed by Gordon Friend. See him for a copy of the model.

OWL -- PVA model developed by Kevin McKelvey, Barry Noon, and Jennifer Crocker to assess long term persistence, genetic loss, and habitat occupancy of northern spotted owls on dynamic forest landscapes. because the model is spatially explicit, has a GIS interface, and can model habitat dynamics, it is the one that I choose to use for all PVA analyses. I am leaving 2 copies of this model. The original mode l received from Kevin has the executable model (activated by typing OWL then <enter>) and the source code (PASCAL), and OWLW which has the OWL model with files that I used to model woylie population persistence. Kevin is working on a version of the model that incorporates predator prey relationships, which might be particularly useful for mammals in Western Australia, but as designed is probably most appropriate for territorial animals that form pair bonds. It does not explicitly consider catastrophic occurrences.

ALEX -- PVA model developed by Hugh Possingham, University of Adelaide, for general use with up to 50 populations. As yet, ALEX does not have a GIS interface, but is a general model that can be used with a variety of species. It does not yet handle dynamic landscapes. Possingham is developing a WINDOWS version of ALEX that will consider more populations and dynamic landscapes. It only models females., so for species such as Antechinus and Phascogales, where short-lived male populations may drive persistence, this model may not be suitable. However, it does consider catastrophic events

VORTEX -- PVA model developed by Robert Lacy that is a general model suitable for use for a variety of species. It does not consider dynamic landscapes and is limited to the total number of populations and number of individuals that can be considered. Genetics can be considered. It does a good job of allowing catastrophic events to occur.

HOLLOW -- A program written in C to predict the number of hollows available per hectare based on a tree diameter distribution for the area. The tree diameter distribution is provided as an external ascii file. Graphic and tabular output of the tree diameter distribution are available, graphic consideration of the size of several species home ranges relative to the size of the sampled area can be viewed, and tabular output of hollow availability can be viewed and/or saved.

UTOOLS -- A landscape planning tool developed in the U.S. Similar in some respects to SNAP II but not timber driven. See documentation for more details. It does allow interface with FRAGSTATS. David Swain has a copy of this program.

SNAPII+ -- A strategic planning tool developed by John and Bren Sessions and designed for modelling timber output and other resource values over a given area, over time. It produces a number of solutions to land management problems quickly while maximising present net worth of the timber resources within the planning area. David Swain has a copy of this program.

FRAGSTATS -- Developed by Kevin McGarigal and Barbara Marks, it calculates spatial statistics for areas of any size for raster or vector files. This program may be most useful in research initially to identify which landscape parameters seem to be associated with the abundance or fitness of certain organisms (or fire behaviour, or human aesthetics, etc) in jarrah and karri forests. Once those associations are identified, then interface of this program with land management planning tools can allow explicit consideration of spatial patterning, patch characteristics, and edge types in managed landscapes.

CAPTURE -- Developed by Eric Rexstad, initially designed by Otis and Burnham to calculate populations of animals based on mark recapture data on closed populations. Those researchers or those involved in monitoring population of species using mark-recapture techniques could benefit from use of this approach because it explicitly considers capture probability in calculating populations, and identifies the most appropriate estimator based on characteristics of the data.

ECOPRO -- Based on chapters by Brower and Zar's Laboratory Manual of Field Ecology, this is an interactive, menu-driven program written in BASIC to calculate simple statistics; conduct t-tests, nonparametric tests, regression and correlation; estimate animal abundance from mark-recapture, removal, or line transect samples; and calculate species diversity indices or community similarity indices from several samples. Particularly useful is few data need quick analyses.

STATECOL -- BASIC Programs written in association with the book, "Statistical Ecology" by Ludwig and Reynolds (1988). These programs calculate spatial dispersion, diversity, ordination of samples in multivariate space, and regression. Probably of most interest to plant and animal ecologists.

COMMUN -- Written in C, this model takes ASCII files containing species numbers for 2 communities and calculates species diversity indices for each community and community similarity indices for the pair of communities. Particularly useful for large data sets and repeated runs. Output can be saved to a common output file for later printing. Probably of most interest to plant and animal ecologists.

TELEM -- Calculates home ranges, includes ADKERN, for use of the adaptive kernel Method of home range calculation, the preferred approach these days. Source code is included. Useful for wildlife biologists.

TELEM89 -- Calculates home range area from coordinate data. Useful for wildlife biologists.

MCPAAL -- Calculates home range area from coordinate data. Useful for wildlife biologists.

CALHOME -- calculates home range area from coordinate data, including the adaptive kernel method. Useful for wildlife biologists.

November 26, 1993

STUDY PLAN

MAPPING POTENTIAL HABITAT FOR VERTEBRATES IN FORESTS OF WESTERN AUSTRALIA

William C. McComb, Professor, Department of Forest Science, Oregon State University and Science and Information, CALM, Como.

INTRODUCTION

Forest planners are faced with making decisions regarding resource allocation in the face of incomplete knowledge about the influence of timber management on other resources. There are over 350 species of vertebrates that occur in the portion of Western Australia that supports forest vegetation. Although a few species have been studied and habitat relationships are documented (e.g., woylie, *Bettongia penicillata*, Christensen 1980), most species have not received intensive study. However, the information that is available should be used to allow managers to more carefully consider the current and future needs of vertebrates in the region while maintaining an active timber management program. Appendix 1 provides a conceptual overview of wildlife-habitat relationships at multiple spatial scales (McGarigal 1993). I describe factors that could be used as a basis for forest planning.

Two interacting dynamic processes occur simultaneously over space that influence the abundance and distribution of vertebrate species: (1) population change as a function of reproduction, survival, and dispersal (King 1971, Kareiva 1990, Gilpin and Hanski 1991, Lamberson et al. 1992), and (2) change in habitat availability as a function of ecological succession and disturbance size, shape, frequency, intensity and pattern (Pickett and White 1985, Turner 1989) . Each species uses habitat over a range of spatial scales (Wiens 1989, Gilpin and Hanski 1991, fig. 1).

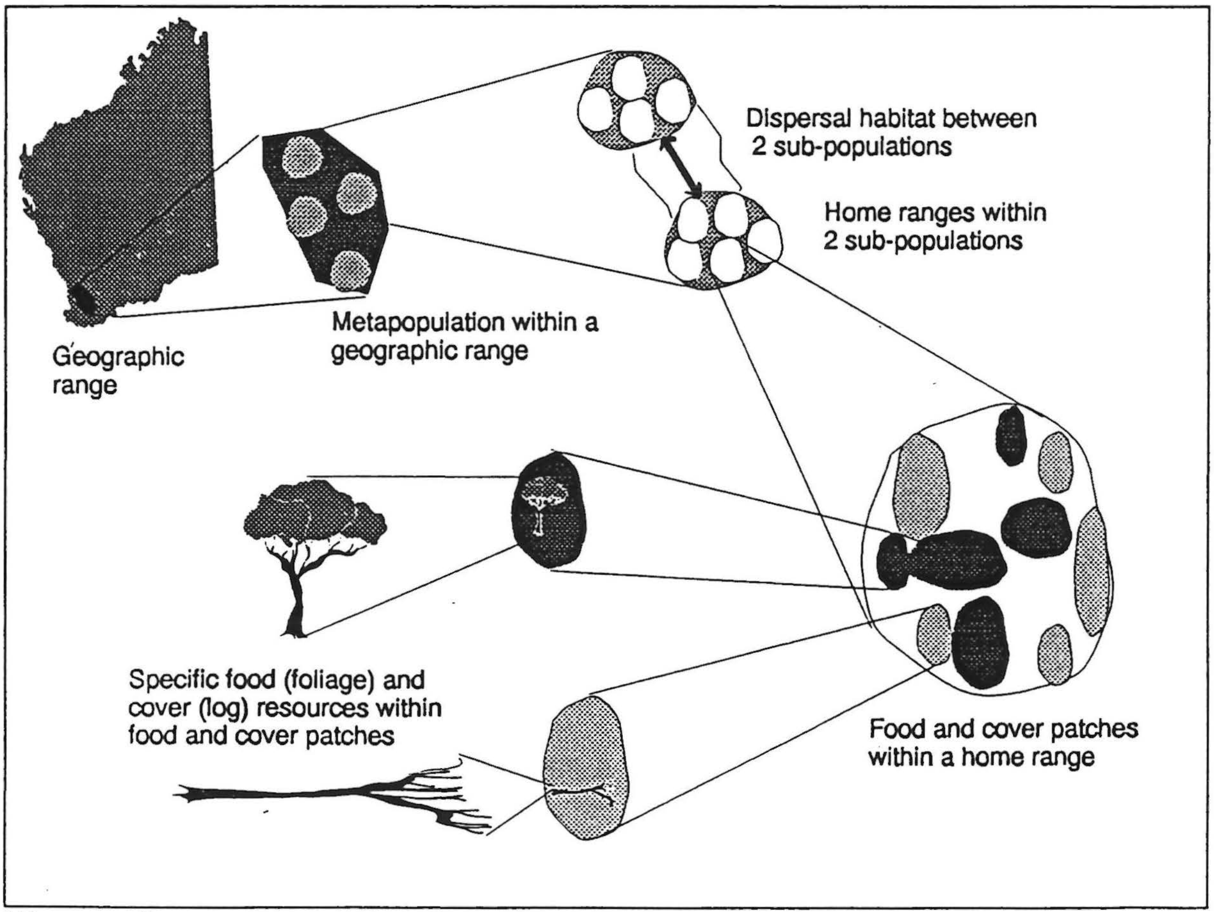

Figure 1. Range of spatial scales used by vertebrates. Note that each scale differs among species (figure 3).

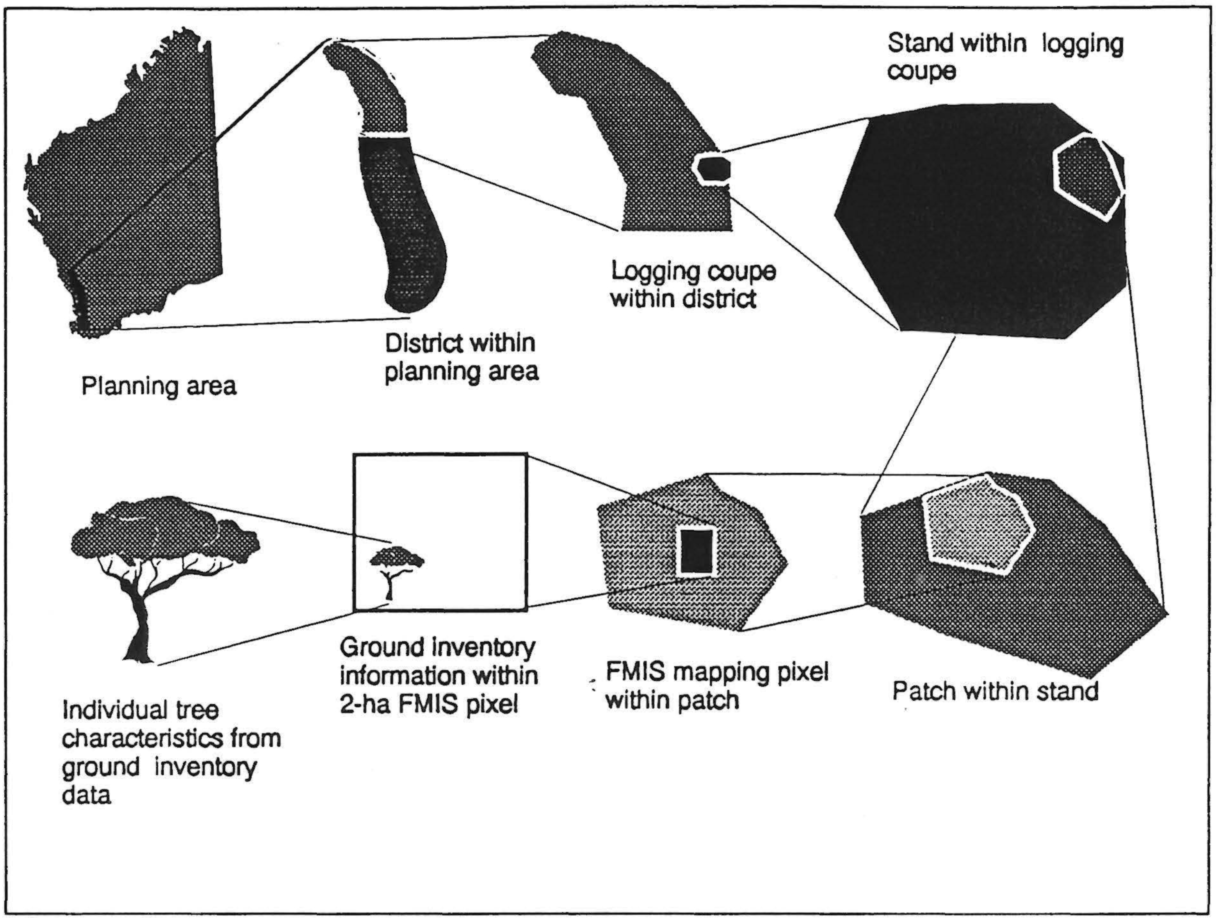

Figure 2. Spatial hierarchy of CALM management activities that can influence habitat abundance and pattern for vertebrates.

Vegetation change also occurs over a range of spatial scales that may or may not coincide with the spatial scales used by each vertebrate species (Allen and Starr 1982, Pickett and White 1985, Wiens 1989). Vegetation change in managed forests is primarily influenced by management activities (Wardell-Johnson and Nichols 1991, McComb et al. 1993, fig. 2), however natural disturbances may occur in managed stands over different scales of space and time (Pickett and White 1985, Stoneman et al. draft). The spatial scales illustrated in figure 1 represent a habitat selection hierarchy (Johnson 1980) that includes metapopulation theory (Gilpin and Hanski 1991) that must be considered before modeling of habitat availability for a species: (1) geographic range containing (2) metapopulation(s) containing (3) individuals occupying home ranges containing (4) habitat patch types used for feeding, reproducing, or dispersing, containing (5) specific food and cover resources used by the species. The spatial scales represented by each level of the hierarchy vary dramatically among species (fig. 3) as well as within a species over time (e.g., home range expansion and constriction from season to season or year to year), and space (e.g., home range sizes may be larger at the periphery of the geographic range than at the center). Recognition of the range in spatial scales used by organisms allows spatially explicit modeling of population dynamics while considering simultaneous changes in habitat availability (McKelvey et al. 1993).

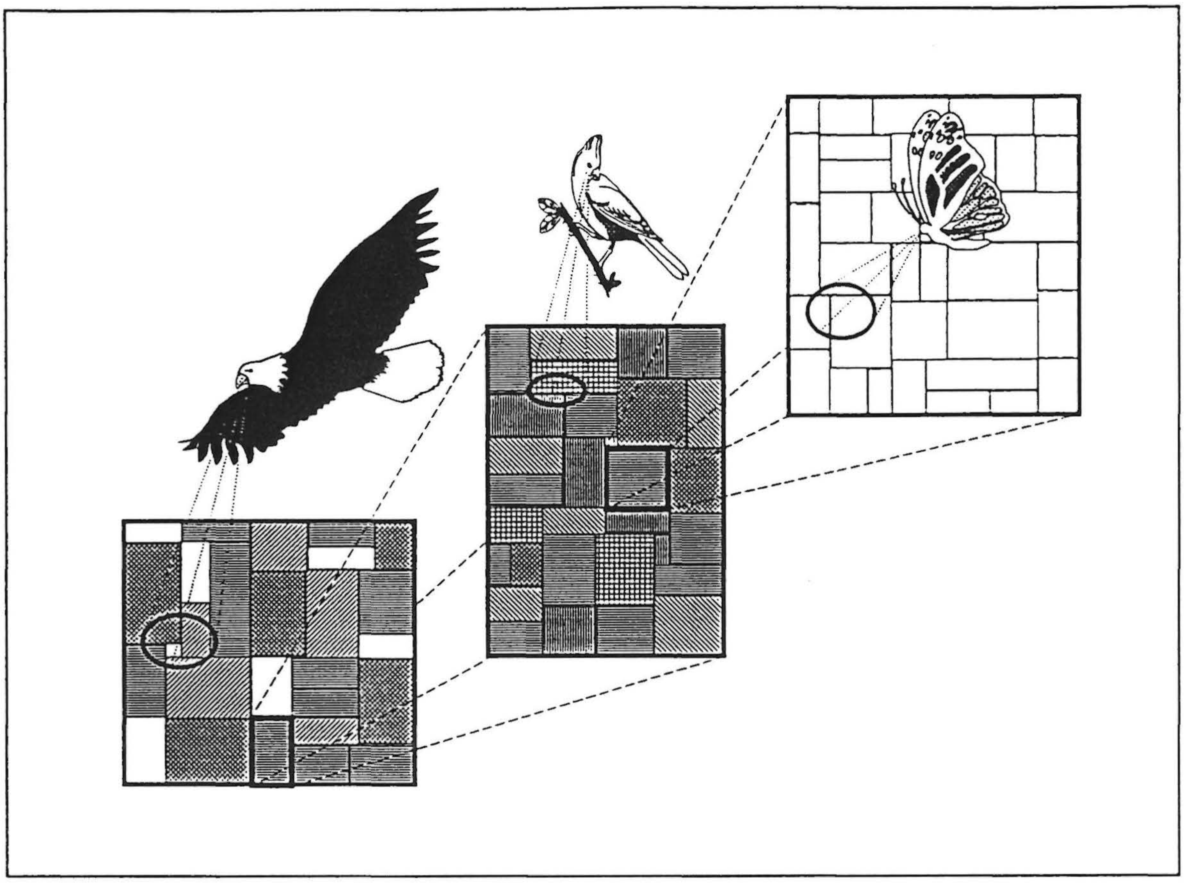

Figure 3. Multi-scale view of "landscape" from an organism-centered perspective. Because the eagle, cardinal, and butterfly perceive their environments differently and at different scales, what constitutes a single habitat patch for the eagle may constitute an entire landscape or patch-mosaic for the cardinal, and a single habitat patch for the cardinal may comprise an entire landscape for the butterfly that perceives patches on an even finer scale (from McGarigal 1993).

BACKGROUND

Spatial Organization of vertebrates

Geographic range.-- The geographic range for a species is the outer extent of habitat availability that should be considered during planning for each species (Scott et al. 1993). This extent probably is not known with certainty because of incomplete searches for the species over its range and low probability of observing the species where it occurs at low densities. Further, the extent can be over-estimated if dispersing individuals are observed in areas where self-sustaining populations cannot occur. This extent is dynamic and should be re-evaluated periodically as new information becomes available, where humans have translocated organisms, or after long-term changes in regional climate patterns. Within this geographic range, not all areas are occupied by the species.

Metapopulation structure.-- To Johnson's (1980) habitat selection hierarchy, I add another spatial scale that is the distribution of sub-populations comprising the metapopulation within the geographic range (Gilpin and Hanski 1991, McKelvey et al. 1993; see also, Appendix I, fig. 2.6). In the simplest form, there would be one population capable of sustaining itself over time within one habitat block. The population must be large enough to overcome the probability of extinction caused by stochastic variability in demographic parameters (reproduction and survival rates, dispersal success, probability of finding a mate, etc.) (Kareiva

1990). The variability in these parameters may be caused by chance, large scale fluctuations in weather, or by habitat change (succession and disturbance). In actuality, the metapopulation structure for most species provides variable opportunities for interaction among each sub-population as a function of the probability of successful dispersal among the sub-populations, depending on such things as distances between patches, patch size, dispersal rates and survival probabilities (Gilpin and Hanski 1991). Survival probabilities vary within a range over time and they are specific to a particular habitat patch type (fig. 4, table 1, McKelvey et al. 1993). Because the goal of management usually is to allow extraction of commodities while maintaining sufficient habitat to allow indigenous species to persist, these survival probabilities become important parameters driving the probability of persistence over dynamic landscapes (Kareiva 1990 McKelvey et al. 1993).

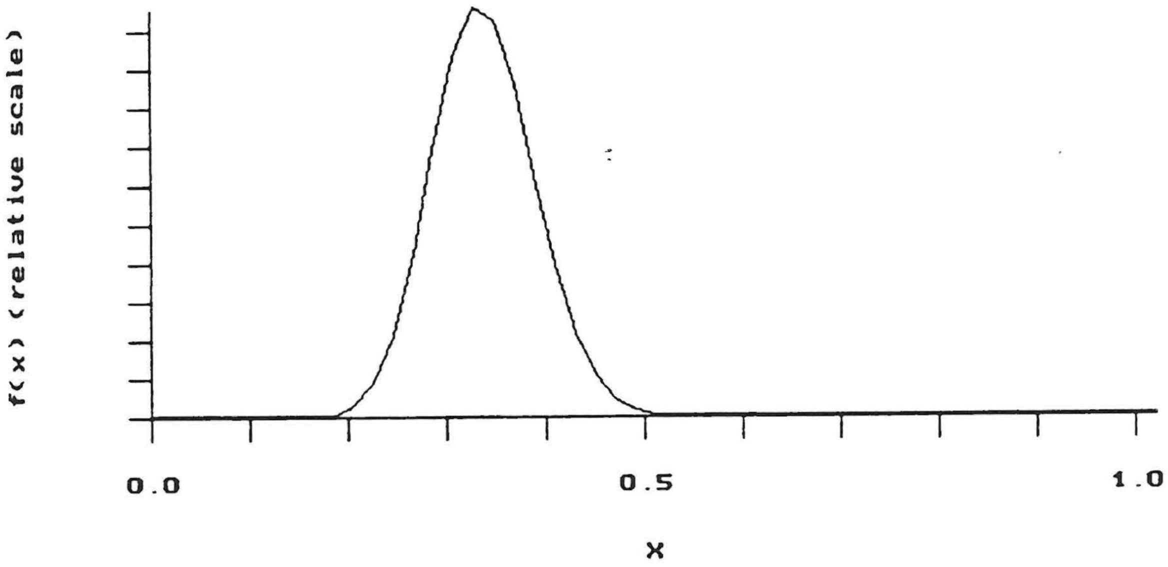

Figure 4. Example of the distribution of predicted probability of survival of juvenile woylies in foraging habitat in Western Australia jarrah forests, as estimated by Per Christensen.

Home range.-- Within each sub-population, individuals use space within which they secure the resources needed for survival (Johnson 1980). These home ranges vary in size among individuals within the population and over time as resource availability changes. Home ranges may also overlap substantially among members of the metapopulation for some species (e.g., woylies, Christensen 1980), or be nearly exclusive for some territorial species (Fretwell and Lucas 1969). Nonetheless, there are upper limits to home range size driven by the balance of energy gain and loss as a function of body mass. Indeed, within a trophic level, body mass and home range size seem to be related (Lindstedt et al. 1986). Home ranges become the basis for modeling interaction of individuals within sub-populations on dynamic landscapes (McKelvey et al. 1993, figure 5). Although home ranges are assumed to be of uniform size among individuals within a simulation, the actual size of the home range can be altered. For instance, if the model indicated that 30 home ranges were needed in one cluster to allow > 50% probability of survival for 100 years, and from field data we knew that home ranges varied in size from 20 to 40 ha, then we could estimate that habitat patches of 600-1200 ha would be needed to allow the sub-population to persist. Mapping of available habitat at the upper and lower ends of this range would provide optimistic or pessimistic estimates of habitat availability.

Table 1. Start-up parameters for simulation of woylie population persistence based on the distribution of individuals portrayed in figure 5.

Parameter	Foraging	Reproduction	Dispersal
Mean survival probabilities			
age 0	0.25	0.33	0.38
age 1	0.65	0.70	0.25
age 2	0.65	0.70	0.25
age 3	0.65	0.70	0.25
age 4	0.65	0.70	0.25
Variance in survival probabilities			
age 0	0.04	0.05	0.04
age 1	0.03	0.03	0.04
age 2	0.03	0.03	0.04
age 3	0.03	0.03	0.04
age 4	0.03	0.03	0.04
Mean probability of producing offspring			
age 0	0	0.50	0.50
age 1	0	0.81	0.81
age 2	0	0.81	0.81
age 3	0	0.81	0.81
age 4	0	0.81	0.81
Variance in probability of producing offspring			
age 0	0	0.03	0.03
age 1	0	0.02	0.02
age 2	0	0.02	0.02
age 3	0	0.02	0.02
age 4	0	0.02	0.02
MOVEMENT			
Probability of attempting to reproduce in this habitat	0	1.00	1.00
Aversion to crossing habitat	1.00	1.00	0.15

Number of young/female/year = 3
Probability of offspring being a male = 0.58

Prob. female finds male = 0.50
Male territorial aversion = 0.50
Directional weighting = 2.00

TIME SERIES

Total run length = 100 Years
Movements per year = 20

Habitat patch use.-- Within home ranges, vertebrates usually focus their activities on areas used for feeding, nesting, or escape from environmental extremes or predators (Johnson 1980). Most radio telemetry studies of organisms provide the empirical basis for habitat patch use by illustrating core areas (using harmonic mean estimators) where clusters of telemetry observations are observed (e.g., woylie use of heartleaf (*Gastrolobium bilobum*) patches, Christensen 1980, page 35).

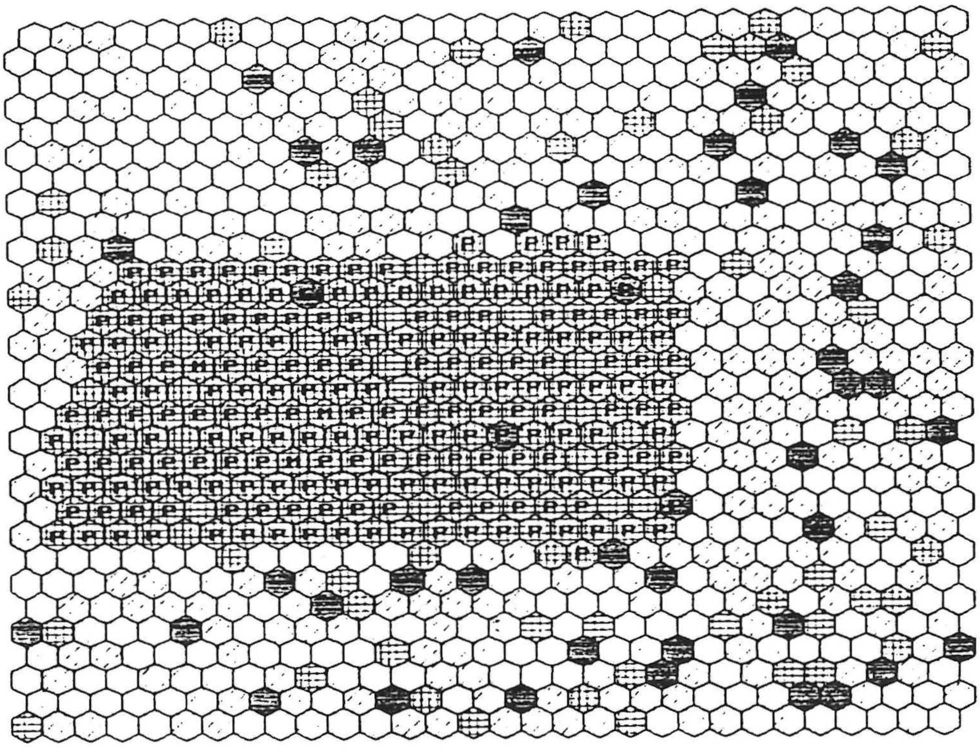

Figure 5. Example of arrangement of a cluster of home ranges for woylies. P=reproductively active individuals, M=non-reproductively active males, F=non-reproductively active females. Vertical cross-hatch=habitat used for feeding and reproduction, solid gray=habitat used for feeding, diagonal lines=dispersal habitat, and stippled cells=non-habitat. This arrangement was used in 10 simulations to test population viability for woylies in a single-cluster arrangement of home ranges.

Ultimate resources.-- Within each habitat patch are the resources used by the organism for reproduction and survival (Johnson 1980). Food, nest sites, escape cover, and resting cover are all essential to maintaining a positive energy balance within individuals, and ultimately within populations and the species. These ultimate resources provide the link between habitat structure and habitat function. Humans may manipulate structural components of the forest through silvicultural activities, however it is the provision of the ultimate resources that will influence the success or failure of such manipulations (e.g., do "habitat trees" provide the nesting and resting sites needed by hollow-using organisms?).

Temporal Organization of Vertebrate Populations

Population change may be predicted (often using Lotka-Leslie approaches) based on knowledge of age structure, sex ratio, life expectancy, reproductive rate, survival rate and rates of immigration and emigration (McKelvey et al. 1993). Typically each age cohort is assigned a sex ratio, reproduction and survival rate, and probability of dispersal. Population change is usually focussed on females, however, survival rates can vary between sexes. Further, the abundance and distribution of males must be explicitly considered especially for species in which males establish territories around nest sites and attract females to the territory (e.g., many passerine birds, Fretwell and Lucas 1969).

Reproduction, survival, and dispersal are not fixed rates, but range in value over time (e.g., fig. 4, table 1) among habitat types in response to environmental variability, competitors, or predators. Models of population change must provide the opportunity for variability in these rates from year to year. The results of such an approach is that (1) populations fluctuate over time (a stable carrying capacity is not reached, e.g., figure 6), and (2) occupancy of available habitat varies (rarely are all available home ranges occupied, e.g., fig. 7). Because interspecific interactions influence demographics of each species, the influence of competition and predation can be considered implicitly within models such as that developed by McKelvey et al. (1993) by providing estimates of demographic parameters that reflect effects of predators and competitors. Further, mapping of potential occupancy for many species simultaneously can provide an estimate of community diversity (Scott et al. 1993).

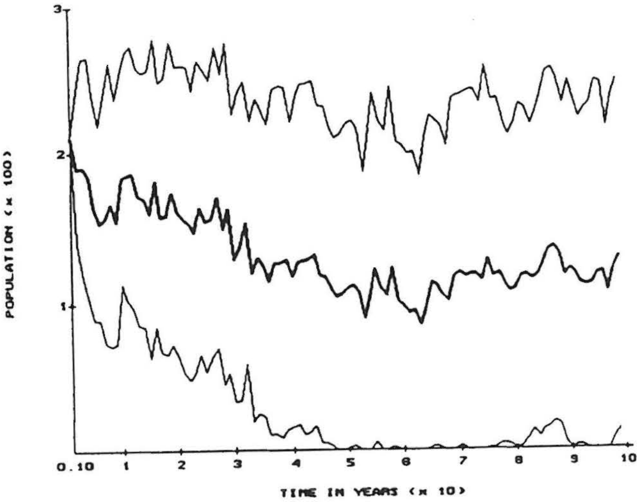

Figure 6. Example of average, maximum and minimum estimated populations of reproductively active woylies over 100 years using 10 simulations of populations distributed on one cluster (fig. 5).

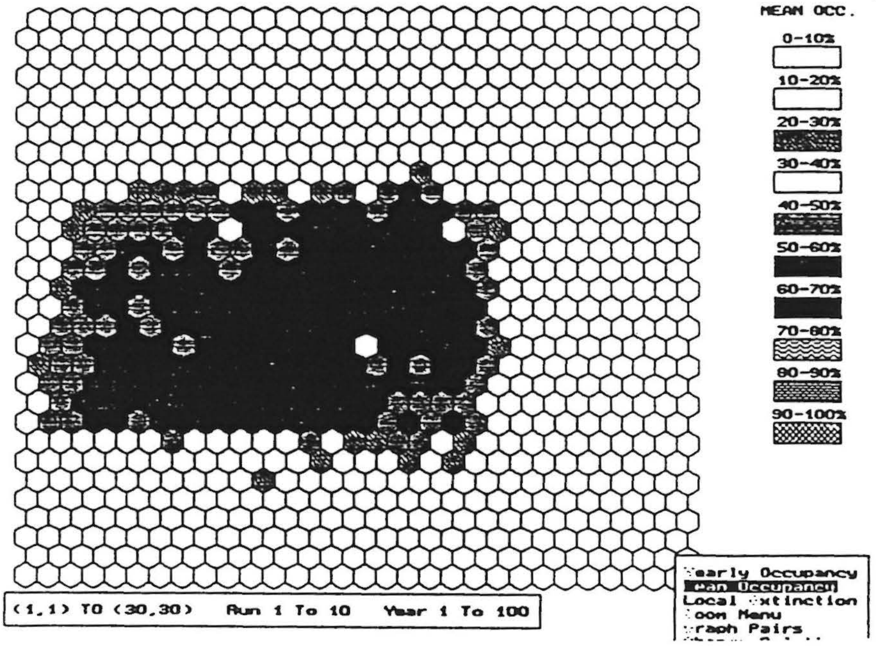

Figure 7. Example of mean occupancy rates of home ranges of woylies in the one cluster tests (fig. 5) over 10 simulations for 100 years (fig. 6). Note that no habitat patch (available home range) is predicted to always be occupied.

Spatial Organization of Vegetation

Logging operations influence both tree and shrub succession in jarrah (*Eucalyptus marginata*) and karri (*E. diversicolor*) forests (Wardell-Johnson and Nichols 1991, Wardell-Johnson and Christensen 199?) and pine (*Pinus* spp.) plantations. Gap and shelterwood approaches re-initiate ecological succession in these stages (Stoneman et al. 1991), producing a mosaic of developmental stages (Bradshaw 1993) on the landscape at any one time (figure 8). The arrangement of these patches is largely governed by the hierarchy of management planning described by Stirling (1993, fig. 2). Currently, harvest planning is rarely driven by the desire to maintain a specific arrangement of gaps and stands in particular developmental stages to meet the needs of certain wildlife species in managed areas. Rather, permanent exclusion zones, riparian buffer strips, visual management areas, and reserves in addition to a generalized requirement for a diversity of age classes are assumed to meet the needs of indigenous species outside of the land holdings managed for timber, though the managed areas could provide additional habitat for occupancy and connectivity for some species if the size, intensity, frequency, and arrangement of management actions is considered.

Within the forested region of southwestern Australia, the pattern of jarrah and karri forests seem to be largely influenced by patterns of rainfall, soil, and topography (Dell et al. 1989, Christensen 1992, Bradshaw and Lush 1981). This region has been designated into management districts that generally conform to northern, central, and southern jarrah forests and the karri belt. Within these areas, harvesting operations are designated to a harvesting operation containing coupes, stands and gaps (fig. 2). Specific information regarding the tree resource is based on inventory information from aerial photos (API maps, fig. 8) and ground inventories (Spencer 1992). Based on the species composition and size of the dominant trees in the stands, developmental stages can be categorized (Bradshaw 1985, 1986, 1993), although jarrah stands are often uneven-aged at the spatial scale of 2 ha, the smallest mappable unit in the Forest Management Information System (FMIS). Because of regeneration requirements of karri, gap sizes generally exceed 2 ha (Bradshaw 1992).

Within each managed gap or stand, shrub succession is largely influenced by the frequency and intensity of prescribed fire. Shrub succession occurs in the understory of each developmental stage of the overstory trees and it is the combination of shrub and tree developmental stages (overstory and understory) that seem to influence the community composition of some vertebrate groups (e.g., birds, Wardell-Johnson and Christensen 199?, Wardell-Johnson and Nichols 1991).

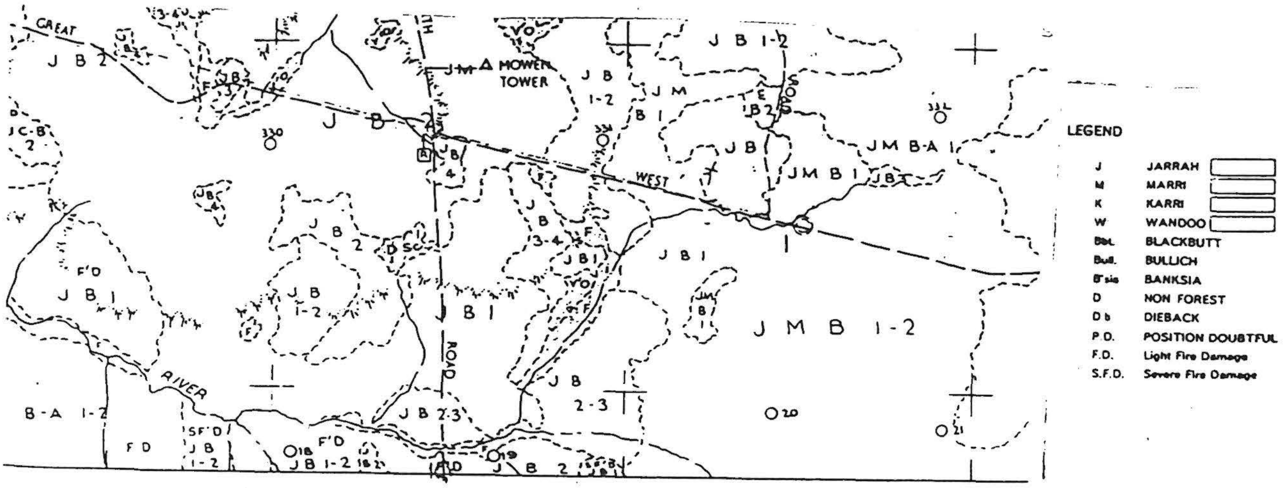

Figure 8. Aerial photo interpretation (API) map of an area in southwestern Australia.

Both tree and shrub developmental stages are influenced primarily by management activities in the managed portions of the forested landscapes (Wardell-Johnson and Nichols 1991), but natural disturbances (e.g., wildfire and wind,) are also influencing landscape pattern and they are the primary forces influencing the mosaic of developmental stages on reserve lands, though they certainly also affect patterns on managed lands (Stoneman et al. draft). Also, human-induced disturbances in addition to forest practices influence the landscape mosaic, such as jarrah die-back (*Phytphthora cinnamomi*), bauxite mining, agriculture, and urban and suburban development. Vegetative communities produced as a result of these disturbances must be considered (i.e., all land owners) during any attempts to estimate habitat availability for a species in the region.

Management intensity influences the components of a mature stand that persist into the early developmental stages following the disturbance (McComb et al. 1993). Retention of 3 habitat trees per hectare in jarrah forests is an example of altering management intensity in an effort to consider wildlife needs. The features of habitat trees, their arrangement within and among gaps or stands, and their longevity all may influence their function in developmental stages following logging (McComb et al. 1993). Similarly, widespread use of cool spring burns in forests (low intensity) may influence the succession of plants and the probability that tree and log hollows may be destroyed or created (Inions et al. 1989).

The pattern of developmental stages distributed across a landscape can influence connectivity among reserve areas by either enhancing connectivity or establishing barriers, depending on the habitat associations of the species being considered (Forman and Godron 1986). Connectivity can occur in 2 general forms: (1) dispersal that occurs within the life span of individuals leaving one habitat patch and encountering another (e.g., dispersing juveniles), or (2) dispersal that occurs over many generations within the connecting patches so that genes flow over time from reserve patch to reserve patch (Beier 1993). For small vertebrates with limited vagility, the latter approach is most common, consequently connectivity must be maintained over long periods if gene flow is to occur (Beier 1993). Large, mobile species may disperse effectively among reserves if connectivity is provided only periodically (depending on the inter-patch distances and proportion of dispersing members of the population). Sessions and Sessions (1992) provide a tool for land managers to allow optimization of timber production while maintaining connectivity (and other non-timber resource values) over a planning area (fig. 9).

Temporal Organization of Vegetation

The growth rate of trees in the region is largely influenced by precipitation, soils, and fire frequency and intensity, although Stoneman (1993) has demonstrated significant effects on growth rates of stand density management. Consequently, developmental stages of jarrah and karri may occur over a range of stand ages. From the standpoint of providing habitat for wildlife, generally age is less important that structure (e.g., tree size, log size, etc.), but time may be more important than tree size for development of tree hollows (Rose 1993).

The characterization of developmental stages of forest vegetation offer a powerful tool to forest planners because patches of forests can be mapped and the developmental stage can be changed over time as a function of tree growth rates (influenced by management activities and site characteristics) (Gagliuso and McComb 1992). The use of developmental stages by a wildlife species then can allow mapping of those stages used for feeding (a collection of developmental stages used by a species would be considered a habitat patch type), reproduction, or dispersal. Because developmental stages can be changed over time with knowledge of tree growth rates, habitat patch types can also be changed.

Developmental stages of trees and shrubs are considered discrete types of vegetation when in fact they represent a continuum of succession.

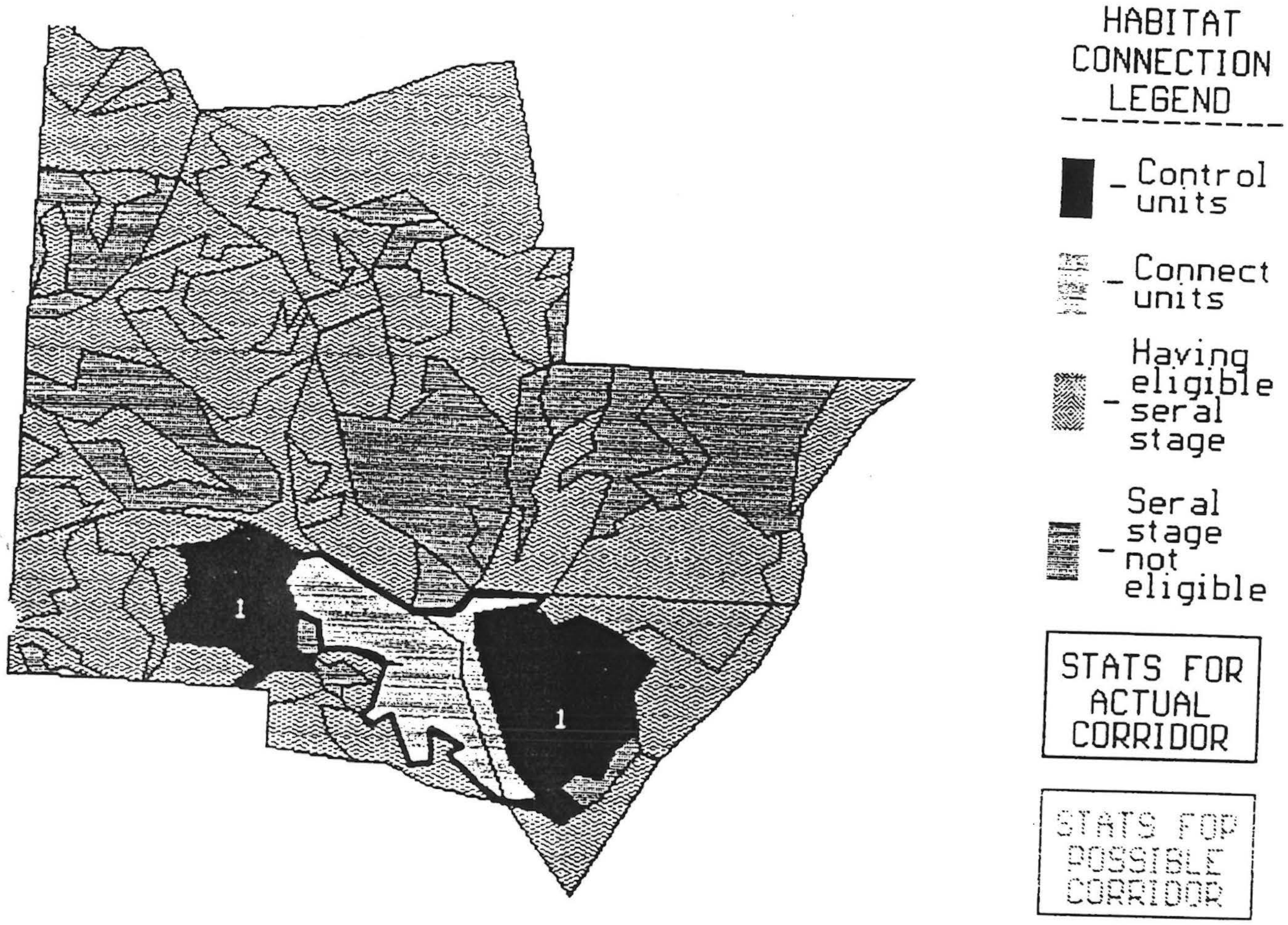

Figure 9. Example of providing connectivity using SNAP II+ through control of seral stages between 2 patches of old forest on the Oregon State University Research Forest. This connection could be maintained either as a fixed or floating corridor indefinitely while allowing timber harvest in the landscape.

Further, mapping of these stages over space and time is done based on discrete polygons when in fact there often are fuzzy borders (especially where natural disturbances have influenced the developmental stage) (Pickett and White 1985). For species that are influenced by edge contrast and/or edge density (see appendix 1), the width of the edge could be quite important. Tools such as FRAGSTATS (McGarigal and Marks 1993) can explicitly quantify edge characteristics as a function of development of adjacent habitat patches and tools such as SNAP II+ can optimize timber revenue while maintaining edge types on the landscape.

Several tools are available to explicitly consider the changes in developmental stages of trees, gaps and stands over time within a planning area (Rayner, pers. commun.: karri growth and yoield model; Sessions and Sessions 1992, SNAP II+), and Stirling is currently developing a spatially and temporally explicit planning system for hardwood management (HOPS). The link between the dynamics of vegetation and the dynamics of the animal populations that inhabit it has been attempted by several authors (McKelvey et al. 1993, Gagliuso and McComb 1992), but of the models of which I am aware, it is the spotted owl (*Strix occidentalis*) model of McKelvey et al. (1993) that seems to come the closest to considering long term persistence of a species on dynamic landscapes. This model has been used extensively in conservation planning for the spotted owl (Murphy and Noon 1992, McKelvey et al. 1993b, Verner et al. 1992). However, 7 papers to be presented at the

International Congress on Modelling and Simulation in Perth deal with population viability analysis (PVA) and biodiversity. I will write to these authors to inquire about the applicability of their approaches to Southwestern Australia vertebrates. In particular, Lindenmeyer et al.'s approach with mountain brushtailed possums (*Trichosurus caninus*) in the eastern states may have direct applicability to common brush-tail possums (*Trichosurus vulpecula*) in the southwest. Two other papers deal with PVA of indigenous marsupials.

PROPOSED APPROACH TO MAPPING HABITAT FOR VERTEBRATES

Given the above background on habitat relationships, population dynamics, and habitat dynamics, I propose that the following steps be taken to produce an estimate the availability of habitat for selected species of indigenous vertebrates, both with and without predations pressure from exotic predators, in the forests of western Australia:

1. Identify the spatial extent (i.e., geographic distribution) for the species within the planning area.

2. Identify the habitat patch size or configuration of patches that could allow the species a high probability (>50%) to persist over a reasonably long period of time (e.g., 100 years).

3. Identify the habitat patch types (forest developmental stages, shrub developmental stages, and soil types) that are used and adjacency requirements, if any.

4. Identify the within-habitat patch features that are needed (e.g., trees, shrubs, hollows, logs).

5. Develop decision rules for use in the GIS to allow depiction of polygons with appropriate attributes for the species and tally habitat area over the extent.

6. Change polygon attributes through time as a result of disturbance and forest regrowth affecting the developmental stages.

Each of the above steps (described in more detail below) requires knowledge of the habitat requirements, demographics, and distribution of each species for which mapping is attempted (McKelvey et al. 1993). I propose to accumulate this knowledge by having several experts on each species complete a questionnaire (appendix 2). The first set of information (item 1) allows identification of *habitat patch types* (patches used for feeding, reproduction, and/or dispersal) based on tree and shrub developmental stages. Habitat patch types are further refined based on underlying *substrates* (item 2), *adjacency* (item 3), and *within-patch features* (item 4a-4c). The probability of a population persisting for 100 years given the amount and distribution of habitat will be assessed using estimates of demographic parameters and spatial requirements for feeding and reproducing. Some parameters are general in nature and will be applied to all habitat patch types (item 5). Others are probably quite different among habitat patch types, so these require estimates for each habitat patch type (item 6). Dispersal habitat is only considered habitat that is not already classified as feeding or nesting habitat. Areas not classified as feeding, nesting, or dispersal habitat will be classified as "other" and I will assume that the species cannot survive in these areas.

I have provided opportunities to estimate both maximum and minimum values, as well as averages for each parameter on the questionnaire. These values should estimate the range in values of each parameter from year to year for populations of > 100 adults. The purpose of identifying ranges is to allow sensitivity analyses for habitat availability and for allowing stochastic variability in population responses to habitat arrangement over time as part of the population viability analysis.

Obviously, some of this information is not known. If possible I would like experts to estimate a value (or range of values) based on their experience with the species, because this information will probably be better than no information at all on which to base management activities. If information provided is based on experience and not data, it will be indicated as such. Where use of a habitat type or habitat feature is unknown ("?"), then it will be assigned to an "other" category for purposes of mapping and it will be considered "non-habitat" for this species. Where the respondent indicates "unknown" for demographic parameters requiring probabilities, then they will be set to 0.5 with a range of 0 to 1.0 (random chance, unless otherwise indicated) (table 1). Similarly, estimates requiring percentages will be set to 50 with a range of 0 - 100 for purposes of population viability analyses. Because information that is needed for mapping must be compatible with current GIS and dynamic models, I have attempted to structure the questionnaire to provide information that can be mapped based on themes in FMIS or ArcINFO.

Identifying the spatial extent for each species

Museum records for mammals have been accumulated and stored in a data base that includes latitude and longitude for each record (Kitchener and Vicker 1981). These museum records can be used to establish the outer bounds (extent) of the range of the species in the planning area. If a species range extends beyond the northern or eastern extent of forests in Western Australia, then the extent, for purposes for forest planning, will be terminated at that point. I have contacted Ken Aplan, Western Australian Museum regarding access to these data. If we are allowed access to these data, then they could be used to describe the geographic range of the species in the region. These data would need to be updated periodically to establish new extents as additional records become available. Further, there is uncertainty in this spatial extent, because (1) not all areas have been adequately searched for each species and (2) some species have been more thoroughly investigated than others.

The implications of overlooking habitat availability outside of the known range of each species could be investigated by increasing the known area of distribution out to the entire planning area and assessing the potential increase in habitat availability. Sensitivity analyses could be conducted to determine the potential for additional habitat availability elsewhere in the region given uncertainty in the true distribution of the species. BIOCLIM also could be assessed as a tool for predicting species occurrence in the region, but the cell sizes used in BIOCLIM are quite large and may not be of much value (Wardell-Johnson and Roberts 1993). Sensitivity analyses could be as simple as a curve illustrating the potential for additional habitat as a function of increasing area from the known distribution, to a Monte Carlo simulation of random point generation from known points of occurrence. In the latter example, random points following a Poisson distribution outward in a random direction away from the extent generated by the known points of distribution could be used to assess the probability of increased habitat availability as a function of distance from the current known distribution.

Identifying habitat patch sizes for persistence

Home ranges and/or territories have only been assessed for a few species, and some species have home range sizes that vary dramatically (e.g., chuditch home ranges with and without fox, *Vulpes vulpes*, baiting, K. Morris, pers. commun.). Consequently, I will ask experts to estimate average, minimum, and maximum home range sizes to allow sensitivity analyses. For species with home ranges or territories < 2 ha, the inherent FMIS grain of 2 ha will limit evaluation to a coarser scale than needed and potential habitat may be overlooked.

Simply portraying patches of home range size without regard to the probability of population persistence can overestimate habitat availability. Use of a population viability analysis (PVA) that is spatially explicit (Green 1991: 68), such as the model produced by McKelvey et al. (1993) may allow estimation of habitat patch sizes need for varying levels of population persistence. For instance, based on completion of an early draft of the questionnaire by Per Christensen for woylies, I used the McKelvey et al. (1993) model to identify (through several iterations) the size of a cluster of home ranges needed to allow a woylie population > 50% probability of persistence for > 100 years (n=10 simulations, figure 5). Smaller patches of habitat may very well be used and allow woylies opportunities for persistence < 100 years, especially in a metapopulation structure, but it is these large blocks of habitat that should be identified and considered during land management planning to increase the probability of persistence of the species throughout the planning area.

Unfortunately, the demographic parameters needed to evaluate probability of persistence (table 1) probably are not known for most of the vertebrates in the region (appendix 3). However, the McKelvey et al. (1993) model allows estimation of variability in many demographic parameters. Estimation of the range in parameters that is reasonable for the species (e.g., fig. 4) will simply increase the magnitude of annual fluctuation (fig. 6) and decrease the probability of persistence resulting in the need for larger patch sizes to meet the persistence criteria established for the species. Such an approach would provide a pessimistic estimate of habitat availability for a species until additional information is gained regarding demographic characteristics of the species.

Except for a few studies on other species in other systems, our knowledge of dispersal capabilities for indigenous vertebrates is very poor. For example, the probability of dispersal beyond 2-3 home range radii is unlikely for desert rodents (Buechner 1987). Some indigenous species are considered poor dispersers (e.g., splendid fairy wren, *Malurus splendens*, Wardell-Johnson and Christensen 199?), while others have dispersed widely and can colonize newly available habitat readily (e.g., bush rats, *Rattus fuscipes*, Wardell-Johnson and Nichols 1991); this knowledge must be taken into consideration when developing approaches to identifying areas of potential habitat in the region for each species. Obviously, maintaining connectivity among patches would help to overcome this problem (fig. 9), but all patch types cannot be connected at one time in any landscape.

Identify the habitat patch types that are used by each species

I am accumulating information on food and cover use, reproductive potential, patch type use, and within-patch feature associations for all vertebrates in the region in a LOTUS 1-2-3 spreadsheet (a draft version has been printed as appendix 3). These data are from general references and results of descriptive studies; additional references are being reviewed. The approach that I have chosen is to categorize use by developmental stage within dominant plant communities. This approach most closely matches the theme layers used by CALM in the GIS (forest type, overstory density, total density, tree height). These data are obviously preliminary and the results of the retrospective study on animal associations within managed stands within the jarrah (*Eucalyptus marginata*) region will provide the data needed to update this spreadsheet. Decisions regarding management of resources will not wait for the results of that study, however. The advantage of having the information in a spreadsheet is that information pertinent to a specific sale area (especially in combination with geographic distribution data) or group of species can be easily extracted by managers for use in planning and environmental assessments. Further, the spreadsheet could (and SHOULD) be updated as new information becomes available, allowing managers the ability to use current information in their forest planning. Note that I will complete this data base to the best of my ability during my 1-year sabbatical with CALM because of my own interest in the vertebrates of the region. I will leave a copy of the spreadsheet with CALM before I leave, but it should be reviewed and corrected by experts in the region (e.g., Per Christensen, Grant Wardell-Johnson, Gordon Friend, Norm McKenzie, J. D. Kitchener, Keith Morris, Tony Friend) before it is made available to managers.

Identifying the within-habitat patch features that are needed by each species

I have begun to develop a checklist of forest structure attributes (e.g., trees, tree hollows, logs (including log hollows), shrubs, leaf litter, and free water; Appendix 3) that are associated with each species of vertebrate in the region, if known. Specific parameters for each of these features must be known or estimated before patches can be evaluated regarding their potential as habitat for a species. For instance, chuditch (*Dasyurus geoffroi*) use logs that are > 50 cm diameter with a hollow from 8 to 20 cm in diameter (Serena et al. 1991). Tree hollows must be of sufficient size to allow use by several species of birds and mammals (Faunt 1992). Several species feed exclusively on certain food items (e.g., numbat [*Myrmecobius fasciatus*] on termites, Baudin's cockatoo [*Calyptorhynchus baudinii*] on marri [*E. calophylla*] seeds, honey-possum [*Tarsipes rostratus*] on banksias [*Banksia* spp.]) so the availability of these resources will need to be estimated within each patch type. Without knowledge of the availability of these attributes within patches, we could easily misclassify patches as potential habitat when in fact they did not contain a food or cover attribute needed by the species.

Jarrah forest inventory data contain information on timber availability and wood quality from > 2,000 sample points in the region. Perhaps these data can be used to assess the frequency of occurrence of habitat attributes or their means and variances. If this is possible and if resources are estimated to be insufficient within a home range area, then alteration of the minimum habitat patch size needed for persistence may be necessary for a species. For instance if hollow logs > 50 cm in diameter occur in only 50% of all jarrah forest ground inventory plots, or if the average density of these logs is < 1/ha (Serena et al. 1991), then the minimum habitat patch size used in analyses may need to be increased to have a high probability (e.g., > 95%) that a sufficient distribution and abundance of logs is likely over a patch of potential habitat. Alternatively, these sites could be targeted for artificial recruitment of hollow logs. The utility of the existing ground inventory data in estimating the availability of within-patch features such as tree hollows, logs, and plant species will be critical to the ability to predict potential habitat for species in the region. A preliminary visit to 1 inventory plot in the Jarrahdale region indicated that the wood quality information within the jarrah forest inventory data base could be quite useful in estimating the availability of hollow logs. Associations between jarrah forest inventory characteristics and the probability of a hollow occurring in a tree may be possible.

I worked with CALM inventory specialists to collect information on tree hollows in standing and felled trees within logging coupes in the Jarrahdale and Harvey Districts. My purpose was to determine if the presence or absence of a tree hollow of any size usable by some vertebrate or hollow abundance was predictable based on inventory information. If so, then the probability of hollow presence could be predicted for stands in the region using the jarrah forest inventory data base. To date, we have sampled 127 trees > 20 cm diameter at breast height (dbh) (99 jarrah, 28 marri) and measured 51 hollows in those trees. Analysis of these preliminary data indicate that the 51 hollows occurred in 22 trees. Hollow presence seemed to be associated with tree dbh ($\underline{P}=0.0001$) and the silvicultural class of the tree ($\underline{P}=0.0140$). Trees with hollows usable by some vertebrate were in trees larger in dbh ($\underline{x}=72.1$, SE=6.4, $\underline{n}=22$) than trees without hollows ($\underline{x}=46.1$, SE=3.8, $\underline{n}=77$, $\underline{P}=0.0014$). Trees with hollows were more likely classified as overmature old-growth or a regrowth non-crop trees than trees without hollows. Of the 55 hollows measured, 7 fell within the range of values presented by Inions et al. (1989) as suitable for brush-tailed possums entrance: diameter = 6-49 cm, height above ground= 0.5-10 m, interior diameter = 8-48 cm, interior depth = 0-390 cm). All hollows were in jarrah trees. The probability of a tree containing a hollow with the dimensions large enough to be used by a brush-tailed possum was predictable using logistic regression ($\underline{P}=0.0015$, $\underline{n}=99$ jarrahs, weighted by number of suitable hollows/tree). Bole length ($\underline{P}=0.0315$) seemed to most influence the probability of occurrence of a hollow of this size in a jarrah tree, but dbh ($\underline{P}$=0.1443) and silvicultural class ($\underline{P}$=0.1023) also contributed to predicting the probability of occurrence of a hollow in the tree. Trees with possum hollows (n=5) generally were larger in diameter (x=72.4 cm, SE=22.7) and had shorter boles (x=8.8 m, SE=2.1) than trees without possum hollows (n=94; dbhob=50.9, SE=34; bole length=10.4, SE=0.4), but many more samples are needed to confirm these relationships. I am planning to collect similar data in at least 3 additional logging coupes (Dwellingup, Margaret River, and Kirup).

Developing decision rules for use in the GIS

Within the planning area bounded by the geographic range of the species, identification of patches of potential habitat can only occur if the GIS is given decision rules based on polygon attributes. For instance in the case of the woylie, using information provided by Per Christensen, the following rules MAY apply:

1. The geographic range of woylies within the forest planning region was estimated based on Museum records available from Kitchener and Vickers (1981) and from descriptions by Per Christensen. I am awaiting additional records from Ken Aplan.

2. Within this area, we will attempt to identify potential breeding and reproduction habitat, and dispersal habitat by:

a. delete all polygons except those on gravel, sand, or loam substrates (or lateritic sites if gravel and/or sand may also be present).

b. from the remaining sites, delete all except jarrah- or wandoo-dominated polygons.

c. from the remaining sites, delete all polygons in seedling or sapling developmental stages.

d. from the remaining sites, delete all polygons burned < 5 years ago.

e. from the remaining sites, if possible, classify sites as follows:

1. shrub cover 50-80% = potential feeding/breeding habitat.
2. shrub cover 10-49% = potential dispersal habitat.
3. shrub cover < 10% or shrub cover > 80%, then delete.

f. from the remaining sites, delete all polygons within 200 m from a stream.

g. from the remaining sites classify all sites < 30 ha as potential dispersal habitat.

h. from the remaining sites, classify all sites that are < 2500 ha that are also < 3 km from another remaining site of any size as low quality breeding/feeding habitat (note 2500 ha is the size of habitat patch estimated to be needed to allow woylies > 50% chance of population persistence for > 100 years).

i. All remaining sites should be classified as potential breeding/feeding habitat.

Once the map of potential habitat is developed, a random subset of sites should be visited to ground-truth the map. Then the potential accuracy of the map could be evaluated by determining the percent of known locations of capture or collection of the species in the recent past (e.g., the past 20 years) that occurred in the predicted patches. Obviously errors will occur, because dispersing individuals will be collected in otherwise unsuitable habitats and not all patches of potential habitat will contain the species (because of predation, competition, or inadequate sampling for the species in the patch, see fig. 7).

Changing polygon attributes through time

The habitat patch types available for use by each species should be projected forward based on changes in developmental stages of vegetation as a function of regrowth and harvest (or fire). Simultaneously, the availability of within-patch features should be projected into the future. Because HOPS will be designed to link spatial information with forest growth and yield models, it will provide opportunities to produce maps of available habitat at various time periods (Stirling 1993). Although the McKelvey et al. (1993) model provides a GIS interface, the early version of the model that I have does not have a functional interface. I have sent a message back to Kevin McKelvey to see if that interface has been developed and if so, to acquire a copy of the new version of the program. If this interface is functional, then the probability of persistence of a population over the planning area could be estimated based on dynamic landscapes. If it is not functional, then 2 choices remain. First, periodic map files could be developed for incorporation into the McKelvey model (this is straight-forward with the model in its current form). Alternatively, the user could assume that if several patches of a size required to support a population with > 50% probability of persistence for 100 years is present in the region, then the population will probably persist. The latter assumption does not explicitly consider local extinctions and repopulation of patches, however (Lamberson et al. 1993).

PROPOSED SCHEDULE OF TASKS

1 September - 30 November 1993: Develop a study plan and attempt a trial mapping of woylies. Examine the utility of tree and log data from the jarrah forest inventory for estimating within-patch habitat availability. Begin collecting information on hollow availability in logging coupes to allow association between hollow presence in a tree and inventory characteristics collected during the jarrah forest inventory project (see page 14). This work has been completed.

1 December 1993 - 28 February 1994: Complete trial mapping of woylies, and, if this trial seemed successful, solicit additional information on woylies from other wildlife biologists to further refine the estimate of habitat availability. Attempt to solicit information on brush-tailed possums, chuditch, brush-tailed phascogale (*Phascogale tapoatafa*), and red-tailed black cockatoos (*Calyptorhynchus magnificus*) from experts for additional mapping. Continue to collect information on hollow availability in logging coupes in coordination with inventory specialists. Estimate the availability of logs as den sites for chuditch using the jarrah forest inventory data. Examine data collected by Inions (1989) and Faunt (1992) to determine if these data can be used in conjunction with the field data that I am collecting.

1 March - 31 May 1994: Examine continuous forest inventory data on tree mortality and fall rates of dead trees to allow development of a deterministic model to predict hollow development in jarrah stands as a function of: (1) stand diameter class distribution at time "t"; (2) probability of a hollow for species 'x' in a tree of a certain dbh; (3) probability of a tree of a certain dbh dying given basal area, dbh, and silvicultural class; (4) probability of a dead tree falling based on dbh and time since death. If experts provide questionnaires and field data allow estimation of within habitat patch habitat availability, then provide mapping rules for brush-tailed possums, chuditch, brush-tailed phascogale, and red-tailed black cockatoos to GIS specialists.

1 June 1994-15 August 1994: Develop the deterministic model (or portions for which information is available) on hollow development in jarrah stands. Prepare and submit a final report. Depart for U.S.

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A COMPARISON OF JARRAH HARVEST PLANS ON BRUSH-TAILED POSSUM (Trichosurus vulpecula) POPULATIONS IN CENTRAL JARRAH FORESTS

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We are assessing the probability of brush-tailed possum (Trichosurus vulpecula) population persistence, predicted time to extinction, average population size, and average genetic loss caused by inbreeding on the Greenbushes supply area in the central jarrah forest. These analyses will be the basis for comparison among jarrah harvest strategies that allow consideration of possum persistence in the region.

METHODS

We adapted a spatially explicit population viability model, originally developed for the northern spotted owl (Strix occidentalis caurina, McKelvey et al., 1994), to predict brush-tailed possum population response to harvest plans. Details of the model are provided by McKelvey et al. (1994). Briefly, this model considers each animal's home range as a spatially explicit location over an area encompassing up to 150,000 home ranges (McKelvey et al. 1994). Further, the model allows simulation of population responses on dynamic landscapes, such as those altered by logging disturbance and habitat recovery following the disturbance (McKelvey et al. 1994). We will focus on the relative gains or losses of persistence, population sizes, and genetic loss from inbreeding after imposing jarrah harvest strategies rather than the actual predicted values because of the uncertainty in estimating several demographic parameters.

We followed a 4-step process to predict the responses of brush-tailed possums to management over the area: 1. map habitat availability over the Greenbushes supply area; 2. produce one map for each 5-year period of timber harvest and regrowth over a 100-year period, with corresponding estimates of habitat suitability based on number of hollows expected to be present per hectare in each timber stratum; 3. estimate the brush-tailed possum demographic and movement parameters corresponding to habitat quality estimated for each forest stratum; and 4. predict the probability of extinction, time until extinction, population trends for brush-tailed possums, and genetic loss over 100 years over the region. Each of these are described in more detail below.

Mapping Available Habitat

The Forest Management Information System (FMIS) Geographic Information System (GIS) was used to map habitat over the central jarrah forest region. FMIS is a raster-based system with 2-ha pixel size and encompasses the managed jarrah forest. Brush-tailed possum use of habitat seems to be associated with presence of tree and shrub foliage in association with tree hollows as den sites (entrances 6 - 49 cm wide, internal diameter 8 - 48 cm, internal depth 68 - 390 cm). We estimated hollow availability for possums based on tree diameter distributions in each timber stratum in the region (table 1) using a logistic regression relationship developed from ground surveys for hollows throughout the jarrah forest region ($n = 363$ trees, Probability of a hollow $= 0.1 * (1/(1 + \exp(4.14 - dbhob * 0.056)))$, where dbhob = tree diameter at breast height outside bark, and 0.1 is a correction factor to include only hollows of adequate depth, McComb et al., unpubl. data). This model was tested on an independent data set representing 36 randomly selected trees from 3 forest blocks in the northern forest region. Results of the test were favourable (predicted 1.85 hollow, found 1 hollow).

Mapping Harvest and Regrowth Rates

Paul Biggs has developed 4 maps of habitat pattern on the Greenbushes supply area: 0, 5, 10, and 15 years from now. These maps were used as the basis for preliminary analyses over a 20-year period to assess model performance. Additional maps will be developed to encompass a longer period of time.

Estimates of Demographic and Movement Parameters

Estimates of the mean movement, and mean and variance of reproductive and survival rates in each of 6 brush-tailed possum age classes in each habitat quality class were made by Barbara Jones and from the literature (Table 2). We assumed a liner relationship between number of hollows for possums and probability of possum survival in the startum. The estimates in table 2 were used to predict persistence, population trends, extinction time, and genetic loss of possums among jarrah harvest plans.

Simulating Population Responses

Five response variables will be used to assess the relative value of harvest strategies toward maintenance or recovery of brush-tailed possum populations in the region: the probability of extinction during 100 years, the predicted time until extinction (based on the $\underline{x}$ intercept using a linear regression of populations over time), the probability of the adult population achieving an arbitrary goal of > 5,000 adults, average total populations over the region, and the average percent genetic loss as a function of inbreeding. Each simulation begins with 284 adults dispersed randomly in clusters of 20-24 animals each throughout the area. Consultation with wildlife biologists is needed to identify areas of known use by possums.

RESULTS

Preliminary tests of the model on the Greenbushes supply area over 20 years indicate reasonable predictions of persistence. Additonal information on possum distribution in the area needs to be included in ~~teh~~ the simulation. Also, future research is needed to more accurately estimate demographic parameters.

Table 1. Estimated hollow abundance per hectare available for brush-tailed possums, by forest stratum based on tree diameter distributions from stand tables, jarrah forest inventory.

Stratum	Hollows/ha	Hectares/stratum	Total hollows
CENTRAL REGION			
Mining	0.94	3227	307
Very high quality mature	2.33	14821	34533
Very high quality regrowth	1.87	54444	101810
Very high quality dieback affected	1.33	13148	17487
High quality mature	2.08	13444	27964
High quality regrowth	1.66	54462	90407
High quality dieback affected	1.36	13405	18231
Medium quality mature	2.14	52142	111584
Medium quality regrowth	1.66	97503	161855
Medium quality dieback affected	1.74	30940	53836
Low quality mature	2.00	17673	35346
Low quality saplings	2.37	32810	77760
Low quality regrowth	0.92	5609	5161
Low quality dieback affected	1.82	21219	38619
Sunklands	2.24	38647	86569
Sunklands dieback affected	1.89	14192	26823
Dieback unclassified	1.75	11393	19938
Wandoo (jarrah and marri only)	1.55	9138	14164
Eastern woodlands	1.85	78011	144320
NORTHERN REGION			
Mining	1.23	9546	11742
Very high quality mature	2.20	8543	18795
Very high quality regrowth	1.87	49005	91639
Very high quality dieback affected	1.75	6935	12136
High quality mature	2.03	14050	28522
High quality regrowth	1.46	64267	93830
High quality dieback affected	1.26	13946	17572
Medium quality mature	1.70	25928	44078
Medium quality regrowth	1.32	38129	50330
Medium quality dieback affected	0.84	3268	2745
Low quality mature	1.01	20494	20699
Low quality regrowth	1.00	9720	9720
Low quality dieback affected	0.76	14832	11272

Table 1. Continued.

Stratum	Hollows/ha		
Woodlands	1.11	31416	34872
Wandoo (jarrah and marri only)	0.57	44575	25408
Harvested forest with 3 100-cm dbhob habitat trees per ha	0.23		

Table 1. Demographic parameters estimated for brush-tailed possums. A linear relationship was assumed between low and high quality habitat.

		Jarrah and wandoo forests			
	Nonforest	Cutover 3 habitat trees/ha and < 1 hollow/ha	1-1.4 hollows/ha	1.5-1.9 hollows/ha	>2 hollows/ha
SURVIVAL PROBABILITIES					
Age 0-1	0.05 (0.01)	0.20(0.10)	0.37 (0.10)	0.53 (0.02)	0.68 (0.01)
range	0.0-0.10	0.0-0.35	0.20-0.80	0.30-0.90	0.65-0.80
Age 1-2	0.05 (0.01)	0.45(0.10)	0.58 (0.10)	0.71 (0.05)	0.85(0.02)
range	0.0-0.10	0.15-0.75	0.30-0.90	0.60-0.90	0.80-0.95
Age 2-3	0.05 (0.01)	0.45(0.10)	0.58 (0.10)	0.71 (0.05)	0.85(0.02)
range	0.0-0.10	0.15-0.75	0.30-0.90	0.60-0.90	0.80-0.95
Age 3-4	0.05 (0.01)	0.45(0.10)	0.58 (0.10)	0.71 (0.05)	0.85(0.02)
range	0.0-0.10	0.15-0.75	0.30-0.90	0.60-0.90	0.80-0.95
Age 4-5	0.05 (0.01)	0.45(0.10)	0.58 (0.10)	0.71 (0.05)	0.85(0.02)
range	0.0-0.10	0.15-0.75	0.30-0.90	0.60-0.90	0.80-0.95
Age 5-6	0.05 (0.01)	0.45(0.10)	0.58 (0.10)	0.71 (0.05)	0.85(0.02)
range	0.0-0.10	0.15-0.75	0.30-0.90	0.60-0.90	0.80-0.95

Table 1. Continued.

		Jarrah and wandoo forests			
	Nonforest	Cutover 3 habitat trees/ha and < 1 hollow/ha	1-1.4 hollows/ha	1.5-1.9 hollows/ha	>2 hollows/ha
PROBABILITY OF PRODUCING YOUNG					
Age 0-1	0.00	0.00	0.00	0.00	0.00
Age 1-2	0.00	0.00	0.85 (0.10)	0.85 (0.10)	0.85 (0.10)
range			0.50-1.00	0.50-1.00	0.50-1.00
Age 2-3	0.00	0.00	0.85 (0.01)	0.85 (0.10)	0.85 (0.10)
range			0.90-1.00	0.90-1.00	0.90-1.00
Age 3-4	0.00	0.00	0.85 (0.01)	0.85 (0.10)	0.85 (0.10)
range			0.90-1.00	0.90-1.00	0.90-1.00
Age 4-5	0.00	0.00	0.85 (0.01)	0.85 (0.10)	0.85 (0.10)
range			0.90-1.00	0.90-1.00	0.90-1.00
Age 5-6	0.00	0.00	0.85 (0.01)	0.85 (0.10)	0.85 (0.10)
range			0.90-1.00	0.90-1.00	0.90-1.00
OK for reproducing	no	no	yes	yes	yes
Aversion to crossing	0.90	0.50	0.10	0.10	0.10
Probability of continuing	0.90	0.50	0.10	0.10	0.10

Table 1. Continued.

Young per adult female	1
Probability of a male offspring	0.50
Probability of male finding a female	0.99
Probability of a male avoiding another male's territory	0.50
Number of movements per year	20
Total number of runs	5
Total run length	20 Years

Results of preliminary analyses:

Mean population size : 86.16

Percent extinctions : 0.00
Mean time to extinction : undefined
Projected extinction time : undefined
Minimum population level : 248

A COMPARISON OF JARRAH HARVEST PLANS ON BRUSH-TAILED PHASCOGALE (Phascogale tapoatafa) POPULATIONS IN CENTRAL JARRAH FORESTS

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We will compare the probability of brush-tailed phascogale (Phascogale tapoatafa) population persistence, predicted time to extinction, average population size, and average genetic loss caused by inbreeding among jarrah harvest strategies in the Greenbushes supply area, central jarrah forest, using a spatially explicit population viability model. We adapted a spatially explicit population viability model, originally developed for the northern spotted owl (Strix occidentalis caurina, McKelvey et al., 1994), to predict brush-tailed phascogale population response to jarrah harvest plans. Details of the model are provided by McKelvey et al. (1994). Briefly, this model considers each animal's home range as a spatially explicit location over an area encompassing up to 150,000 home ranges (McKelvey et al. 1994). Further, the model allows simulation of population responses on dynamic landscapes, such as those altered by logging disturbance and habitat recovery following the disturbance (McKelvey et al. 1994). We will focus on the relative gains or losses of persistence, population sizes, and genetic loss from inbreeding after imposing jarrah harvest strategies in the Greenbushes supply area because of the uncertainty in estimating several demographic parameters.

We will follow a 5-step process to predict the responses of brush-tailed phascogales to management over the area: 1. map habitat availability over the central jarrah forest; 2. produce one map for each 5- or 10-year period of harvest of the jarrah forest, with corresponding estimates of habitat suitability based on predicted tree diameter distributions; 3. regrid the map into cells that correspond to brush-tailed phascogale home ranges (approximately 40 ha), 4. estimate the brush-tailed phascogale demographic and movement parameters corresponding to each habitat quality class, and 5. predict the probability of extinction, time until extinction, population trends for brush-tailed phascogales, and genetic loss over 100 years over the region. Each of these are described in more detail below.

Mapping Available Habitat

The Forest Management Information System (FMIS) Geographic Information System (GIS) was used to map habitat over the jarrah forest region. FMIS is a raster-based system with 2-ha pixel size and encompasses the managed jarrah forest. Brush-tailed phascogale use of habitat seems to be associated with large, rough-barked trees for foraging on bark-dwelling invertebrates, and hollows as den sites in trees. Following examination of 292 hollows in 363 trees throughout the jarrah forest region, no hollows of sufficient size for phascogales were found. Consequently we could not estimate hollow availability for this species. Rather we used estimates of the number of trees > 50 cm dbh and trees > 100 cm dbhob as indicators of potential feeding and den sites, respectively (table 1).

Mapping Harvest Cycles

Survival rates of brush-tailed phascogales are probably effected by food and cover availability. Consequently it we will impose a harvest strategy over the suitable habitat on the map for each 5- or 10-year period for the 100-year simulations.

Regridding Habitat Maps

The average home range size for brush-tailed phascogales is about 40 ha . Consequently, habitat maps will be regridded to 40-ha cells by assigning the cell to a habitat quality class based on the class present at the center of the 40-ha grid cell. Such regridding has the potential to alter the habitat mosaic (Schulz and Joyce 1992), so we will compare the area in each class between original maps and regridded maps using a paired t-test to determine if the average difference between maps departed significantly from zero. Pattern of all original and regridded maps also will be inspected visually to identify any gross errors made during regridding.

Estimates of Demographic and Movement Parameters

Estimates of the mean movement, and mean and variance of reproductive and survival rates in each of 2 female brush-tailed phascogale age classes in each habitat quality class were made based on work conducted by Todd Soderquist in eastern Australia (Table 1). The estimates in table 2 will used to predict persistence, population trends, extinction time, and genetic loss over harvest patterns in the Greenbushes Supply area.

Simulating Population Responses

To initiate each simulation, approximately 250 adults will be distributed on the map among areas known to support brush-tailed phascogales. Five response variables will used to assess the relative value of each harvest strategy toward maintenance or recovery of brush-tailed phascogale populations in the region: the probability of extinction during 100 years, the predicted time until extinction (based on the x intercept using a linear regression of populations over time), the probability of the adult population achieving an arbitrary goal of > 5,000 adults, average total populations over the region, and the average percent genetic loss as a function of inbreeding.

RESULTS

Maps have yet to be developed for this species in the Greenbushes area. Locations of known occurrences of phascogales in the supply area should be identified to provide more realistic simulations. Also, future research is needed to more accurately estimate demographic parameters. When Susan Rhind has completed her work, the results should be used to update this analysis.

Table 1. Habitat quality assignment for brush-tailed phascogales based on the number of trees/ha > 50 cm dbhob and number of trees/ha > 100 cm dbhob. Both conditions had to be satisfied for a stratum to be assigned to a habitat quality type.

Tree dbhob (cm)	Unsuitable	Poor	Good	Very good	Excellent
> 50	not jarrah forest	>5	>15	>25	>35
> 100	not jarrah forest	>0	>1	>2	>3

Table 2. Estimated demographic parameters for habitat patch types in jarrah forest, estimates for excellent habitat are from Soderquist, with a linear relationship assumed between unsuitable and excellent habitat types for intervening habitat types.

		Jarrah forests			
	Unsuitable	Poor	Good	Very good	Excellent
SURVIVAL PROBABILITIES					
Age 0-1	0.05 (0.01)	0.09 (0.05)	0.18 (0.03)	0.27 (0.01)	0.36 (0.01)
range	0.0-0.10	0.00-0.30	0.10-0.30	0.20-0.35	0.30-0.40
Age 1-2	0.05 (0.01)	0.13 (0.05)	0.26 (0.03)	0.39(0.01)	0.50 (0.01)
range	0.0-.10	0.00-0.30	0.20-0.40	0.35-0.45	0.45-0.55
PROBABILITY OF PRODUCING YOUNG					
Age 0-1	0.00	0.24 (0.10)	0.48 (0.05)	0.72 (0.02)	0.94 (0.01)
range		0.00-0.60	0.35-0.65	0.65-0.80	0.90-1.00
Age 1-2	0.00	0.24 (0.10)	0.48 (0.05)	0.72 (0.02)	0.94 (0.01)
range		0.00-0.60	0.35-0.65	0.65-0.80	0.90-1.00
OK for reproducing	no	yes	yes	yes	yes
Aversion to crossing	0.90	0.40	0.30	0.20	0.10
Probability of continuing	0.90	0.50	0.40	0.30	0.20

Young per adult female	6
Porbability of males	0.53
Probability of male finding a female	0.99
Probability of a male avoiding another male's territory	0.10
Number of movements per year	20
Total number of runs	3
Total run length	10 Years

Year	Average	SD
1	1894	166
2	1977	671
3	2056	901
4	2093	585
5	1924	443
6	1790	512
7	1770	503
8	2242	1231
9	2804	1407
10	3322	1250

HOLLOW AVAILABILITY FOR SELECTED VERTEBRATES IN JARRAH FORESTS, WESTERN AUSTRALIA

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Abstract: Availability of tree hollows for 9 vertebrate species was estimated based on a sample of 292 hollows in 363 trees along 18 strip transects in 9 logging coupes in jarrah forest. Felled and standing jarrah (*Eucalyptus marginata*) and marri (*E. callophylla*) trees > 20 cm diameter at breast height over bark (dbhob) within transects were searched for hollows. Hollows were assigned as suitable or unsuitable for occupancy for each of the 9 species based on internal and external hollow characteristics described during past studies. Each tree was assessed by an inventory forester for size, silvicultural class, condition, and wood defect. The probability of a hollow suitable for each species occurring in a tree was estimated using logistic regression with tree and site characteristics as predictor variables. Predictive equations developed for 4 species with sufficiently large sample sizes resulted in concordance between predicted and actual occurrence of hollows of 72-89%. Tree dbhob was the variable most strongly associated with the probability of a hollow in a tree for 3 of the 4 species. Models for 3 species produced reasonable predictions of hollow availability when tested on an independent sample of 36 randomly selected trees from 3 sites. Hollow availability was estimated for forest strata throughout the jarrah forest for these 3 species.

Key words: Forest wildlife, silviculture, forest inventory, forest habitat

INTRODUCTION

The Department of Conservation and Land Management (1992) proposed that "...three large trees per hectare will be retained to provide habitat for hollow nesting species on every hectare cutover.". Despite knowledge of the size of hollows used by some vertebrates inhabiting jarrah (Eucalyptus marginata) forests in southwestern Australia (table 1), only a few studies have attempted to assess hollow availability for these species within the jarrah forest region (Inions et al. 1989, Faunt 1992), and these studies were restricted in scope (2 study areas, Inions et al. 1989) or sample size (n = 36 trees examined, Faunt 1992). Land management planners must be able to assess the distribution of habitat features such as hollows over space and time if they are to consider needs of wildlife in managed forests. Such planning is especially important for features such as tree hollows that can take decades to develop and may only occur in large, old trees (Inions et al. 1989).

Spencer (1992) described a timber inventory system for the jarrah forest region that provided data on tree size, condition and defect. If the probability of a hollow in a tree for a species of vertebrate was related to features measured throughout the region as part of the timber inventory, then the availability of hollows for selected species could be predicted over the region. Further, given an estimate of the changes in densities of trees with certain characteristics over time as a function of forest management, tree death, and tree fall, changes in the availability of hollows for vertebrates could be estimated over both space and time.

Our objective was to measure hollows in trees throughout the managed jarrah forest region and determine if characteristics measured during the previous timber inventory could be used to predict the probability of occurrence of a hollow for each of 9 vertebrate species. Further, we wished to assess the effect of timber harvest on hollow availability for each of these species, both within the logging coupes that we studied, and more generally over the jarrah forest region.

METHODS

Model development

Felled and standing jarrah (n = 282) and marri (E. callophylla) (n = 81) trees were sampled along 18 transects in 9 logging coupes in the jarrah forest region in 1993-94 (figure 1). Logging coupes were selected opportunistically and sampling occurred in those areas where trees had been felled but not yet removed from the site. Upon arriving at a site, a 20- x 100-m (n = 10) or 40- x 100-m (n = 8) transect was established. Transect size was dependent on the size of the area available to sample and the time available to sample. An attempt was made to randomly locate the transect, but in some cases there was only one obvious location for a transect that would still sample fallen trees that had not yet been removed.

An attempt was made to sample all trees > 20 cm dbhob on each transect, but after sampling 6 transects, the minimum tree diameter searched for hollows was raised to 50 cm because > 50% of trees in each transect were < 50 cm dbhob and < 6% of these contained hollows large enough for the smallest hollow-user, striated pardalotes. We endeavoured to achieve a sample of at least 10 trees in each 10-cm dbhob category from 20 to 100 cm dbhob (figure 2).

Each tree within the transect was thoroughly searched for hollows by 2 people. Cut trees (n = 145) were inspected along their boles and all branches. Hollows that may have been missed would have been those on the underside of the tree and those that were destroyed when the tree hit the ground. All hollows > 10 cm deep and > 2 cm entrance diameter were measured. The following variables were measured to the nearest centimetre: entrance height, entrance width at the widest point, interior hollow depth from the lower edge of the entrance, interior diameter approximately 1 centimetre below the entrance, and diameter of the tree at the entrance of the hollow. In addition, binomial classification of evidence of burning and rot inside the hollow was recorded. Height above ground was measured to the nearest meter with a tape measure.

Standing trees (n = 218) were searched thoroughly with 7 x 50 binoculars along the bole and all branches from all sides of each tree. Hollows that were missed were probably those obscured by foliage and/or branches. Height above ground was estimated to the nearest meter with a clinometer. Entrance height and width, and tree diameter at the hollow was estimated with a Spiegl Relaskop.

Each tree on each transect that was examined for hollows was also assessed for quantity of wood defects by a timber assessor from CALM (Spencer 1992). Estimates of hollow availability across the jarrah forest region then could be based on data collected throughout the region on ground inventory plots used to assess timber availability. In addition to recording tree species, diameter at breast height outside bark (dbhob) and bole height were measured. Trees were classified by their condition (alive, dying, or dead), silvicultural class (regrowth, old-growth mature (vigorous), old-growth overmature (declining in vigour) on an ordinal scale), and marketability status (Spencer 1992). The vertical extent and the cross-sectional area of the tree bole affected by termites, rot, burn scars, pinholes, dryside, and unsound branches was visually estimated by the timber assessor (Spencer 1992). The annual rainfall at each site was estimated from CALM isohyet maps.

The above tree and site characteristics were used in a stepwise logistic regression analysis to identify the variable(s) that seemed to best predict the probability of occurrence in a tree of a hollow suitable for use by each of 9 species of vertebrates in the jarrah forest region (Table 1). Analyses were weighted by the number of suitable hollows per tree. Because internal dimensions of hollows in standing trees could not be measured, we used stepwise linear regression to predict internal dimensions based on external features of the hollow (entrance width and height, tree diameter at the hollow, and height above ground) and the tree (dbhob, bole height, wood defect amount). Unfortunately, no significant relationship was detected between hollow depth and external features ($R^2 < 0.075$), so a simple correction factor was used to estimate the proportion of hollows with adequate entrance dimensions and internal width and that also had adequate depth. For instance, 88% of hollows measured on the ground that had appropriate entrance and internal diameter for striated pardalotes also had adequate hollow depth, so only

88% (95% CI = 76 - 95%) of potential hollows in standing trees were considered suitable for striated pardalotes.

Model testing

A total of 36 randomly selected trees ranging in size from 30-160 cm were felled and dissected on 3 sites in the northern jarrah forest. The entrance diameter, depth, and internal width of each hollow in each tree was measured. Based on tree dbhob, silvicultural class and bole length, the number of hollows predicted to be present in the 36 trees was compared to the number actually found that were available for each of the vertebrate species for which models could be developed (table 1).

Hollow availability throughout the region

Hollow availability was estimated for timber strata throughout the northern and central jarrah forest where ground inventory data were collected (Spencer 1992). We only estimated hollow availability for those species with predictive models that seemed to produce reasonable results following testing. Estimated 95% confidence intervals reflect variability in logistic regression relationships and uncertainty in hollow depth estimates.

RESULTS AND DISCUSSION

Two hundred ninety-two hollows were found in 363 trees. Most (80%) occurred in tree limbs, so would not have been recorded during timber inventory (Spencer 1992). Fifty-four percent of the hollows had evidence of burning (table 2) and nearly all (99%) showed some evidence of rot. Inions et al. (1989) also illustrated the importance of fire to hollow development. The probability of a hollow showing evidence of burning was influenced by the height of the hollow in the tree ($\underline{n}$ = 226, $\underline{P}$ = 0.0014, P(burned) = 1/ (1 + exp(height above ground * 0.0979)) - 1.7662, concordance = 62%). Hollows with evidence of burning occurred lower in trees ($\underline{x}$ = 15.3 m, SE = 0.4, range 0.5 - 26) than hollows without evidence of burning ($\underline{x}$ = 17.4, SE = 0.5, range = 3.3 - 30.3, $\underline{t}$ = 3.34, $\underline{P}$ = 0.010, 224 df).

The probability of occurrence of a hollow in a tree could not be based solely on data from cut trees, because this would have resulted in a biased sample. The probability of a tree being cut increased with increasing silvicultural class, increasing bole height, and decreasing extent of defect in the bole ($\underline{P}$ = 0.0001, concordance = 78.6%). Hollows in cut trees were farther above ground and had smaller entrance dimensions than hollows in standing trees (table 3). Hollows in cut trees occurred in branches or boles which were smaller in diameter at the hollow than in standing trees (table 3). Further, cut trees were larger in diameter and had longer boles than standing trees (table 3).

Internal hollow diameter was predictable based on external entrance width (R^2 = 0.614, 136 df, $\underline{P}$ = 0.0001: Internal diameter = 2.47 * (entrance width * 0.72). Because eucalyptus compartmentalise rot, decay columns similar in size to the external wound would be expected to develop down the bole (Wilkes 1982, Shigo 1984).

Brush-tailed possum

A total of 153 hollows had entrance sizes and internal diameters sufficient to allow use by brush-tailed possums. Of these hollows, 73 were measured in cut trees. Inions et al. (1989) associated 'fair', 'good', or 'very good' scratch track intensities on den trees with hollow depth. Hollows > 68 cm deep included the lower 95% CI estimate of depth for hollows in trees with 'fair' track intensities (Inions et al. 1989). Only 7 of the 73 hollows with adequate entrance size and internal diameter in cut trees were > 68 cm deep (table 4). The probability of a brush-tailed possum hollow occurring in a tree increased with increasing tree dbhob (_P_ = 0.0001, table 5). Tree species (binomial code), bole length, and internal defects were not selected in the stepwise analyses as associated with the probability of a possum hollow occurring in a tree. Only trees > 30.5 cm contained hollows suitable for brush-tailed possums, and average diameter of trees with suitable hollows was larger than trees without suitable hollows (table 6, _P_ = 0.0001). Of 153 suitable hollows, 81% were in old-growth overmature trees; 73% of these hollows showed evidence of burning (table 2). Most hollows (74%) were in limbs. Trees with possum hollows had longer boles than trees without suitable hollows (table 6, _P_ = 0.0042). Trees with suitable hollows were estimated by the timber assessors to contain more rot in the bole than trees without suitable hollows (table 6, P = 0.0001).

Of an initial density of 3.2 hollows > 68 cm deep per hectare, 1.5 per hectare were cut leaving 1.8 per hectare remaining after harvest (table 7). Because trees with possum hollows had more rot than unsuitable trees, there was a bias toward their retention during harvest. Hollow density prior to logging (range = 0 - 10.1 per ha) and following logging (range = 0 - 6.2) was highly variable among the 18 transects. Burning of the site after logging to prepare the site for regeneration may reduce food availability or expose foraging possums to predators, further limiting use of available hollows. However, high intensity burns could increase hollow availability (Inions et al. 1989).

Striated Pardalote

A total of 72 hollows was found which had entrance sizes and internal diameters sufficient to allow nesting by striated pardalotes. Of these 72 hollows, 59 were measured in fallen trees, and 88% had depths sufficient to allow use by striated pardalotes (table 4). The probability of occurrence of a hollow suitable for pardalotes occurring in a tree increased with increasing silvicultural class and increasing bole length (P = 0.0001, table 5). Seventy-one of the 72 hollows occurred in old growth trees, 48 in old-growth overmature trees (table 2). Only 25% of the suitable hollows showed evidence of burning and 94%

occurred in tree limbs (table 2). Only trees with bole lengths greater than 5.9 m and with dbhob > 43 cm contained hollows suitable for striated pardalotes. Tree dbhob, bole length and extent of rot in the bole were all greater in trees with suitable pardalote hollows than in trees without suitable hollows (*P* < 0.02, table 6).

An average of 13.8 hollows per hectare were available to striated pardalotes prior to harvest, but 3.6 hollows per hectare remained after harvest (table 7). Availability of hollows after logging was quite variable among the transects that we sampled (range 0 - 16 per ha). Pardalotes have small territories (1-2 ha), so the distribution and recruitment of remnant hollow-bearing trees should be considered during harvests. However, Abbott and Heurck (1985) did not detect an effect of thinning of jarrah forest on striated pardalote abundance.

Port Lincoln parrots

A total of 96 hollows had entrance sizes and internal diameters that met the requirements of Port Lincoln parrots. These occurred in 64 trees. Of these 96 hollows, 51 occurred in cut trees, and 10 had adequate depth for nesting by Port Lincoln parrots (table 4). The probability of occurrence of a hollow suitable for Port Lincoln parrots occurring in a tree increased with increasing dbhob (*P* = 0.0001, table 5). Suitable hollows only occurred in trees > 32 cm dbhob. Of the hollows found, 84% occurred in old-growth overmature trees, 68% had evidence of burning, and 79% were in tree limbs (table 2). Tree dbhob, bole length, and extent of rot in the bole were greater in trees with suitable hollows than in trees that lacked suitable hollows ($\underline{P}$ < 0.02, table 5). Tree species did not seem to influence the probability of a tree containing a hollow for Port Lincoln parrots.

Logging reduced the density of suitable hollows from 4.1 per hectare to 2.3 per hectare (table 7). Density of suitable hollows prior to logging was highly variable among the 18 transects both before (0 - 13.2 per hectare) and after (0 - 6.7 per hectare) logging. Port Lincoln parrots were not recorded in stands 1 year after thinning in jarrah forest, but this was not a statistically detectable decline (Abbott and Heurck 1985).

Galah

We found 90 hollows that had entrance and internal diameter dimensions suitable for use by galahs. These hollows occurred in 61 trees. Of the 90 hollows, 45 were in cut trees, and 14 had depths sufficient to allow use by galahs (table 4). The probability of occurrence of a suitable hollow for galahs increased with increasing dbhob ($\underline{P}$ = 0.0001, table 5). Only trees > 43 cm dbhob contained suitable hollows. Most suitable hollows (73%) were in limbs and 71% had evidence of burning (table 2). Tree dbhob, bole length, and extent of rot were all greater in trees with suitable galah hollows than in trees that lacked suitable hollows (table 6, $\underline{P}$ < 0.004). Tree species was not associated with the probability of a suitable hollow occurring in a tree.

Logging reduced hollow availability for galahs along transects from 6.0 per hectare to 3.4 per hectare (table 7), but availability was highly variable along the 18 transects prior to (0-17.1 per hectare) and after logging (0 - 9.3 per hectare). Given the mobility of this species and its association with agricultural lands, nest sites probably are not limiting its abundance.

Other Species

Too few observations were made of hollows of suitable size for mardos (4), red-tailed black cockatoos (1), corellas (1), and brush-tailed phascogales (0) to allow analyses. More intensive surveys should be conducted for hollows suitable for these species.

Model testing

Logistic models produced reasonable predictions of hollow availability in the independent sample of jarrah trees for brush-tailed possums (predicted = 1.85, 95% CI = 0.83 - 3.49; found = 1) and Port Lincoln parrots (predicted = 3.11, 95% CI = 1.76 - 4.49; found = 4). The model underestimated hollow abundance for galahs by 24% (predicted = 4.57, 95% CI = 2.64 - 5.44; found = 6). This error could be an error in the model or from the small sample of trees used to test the model. We suggest that a 24%

underestimation of hollows for galahs simply provides a conservative estimate of hollow availability. The model predicted 3.89 striated pardalote hollows (95% CI = 2.85-4.69), but 25 were found, a gross underestimate. This underestimate is probably a function of sampling error, simply having not found many potential pardalote hollows following destruction of the crowns after felling, or being obscured by foliage in standing trees.

Regional estimates of hollow availability

In general, high quality forest strata were predicted to contain more hollows for 3 species of vertebrates than low quality strata (table 8). Similarly, mature strata generally contained more hollows than regenerated strata. Patterns were generally consistent between the central and northern regions, except that hollow availability was predicted to be somewhat higher for most strata in the central than the northern region. These patterns were largely a function of tree diameter distributions containing more large trees in high quality stands, mature stands, and/or in the central region.

Habitat trees

Eleven of the trees we sampled were marked as habitat trees. They averaged 84.7 cm dbhob (SE = 8.4, range = 51.2 - 119.4). If 3 85-cm dbhob trees were retained per hectare, then we would predict the following number of hollows per hectare would be provided in those trees for each species: brush-tailed possum =

0.18, galah = 0.40 and Port Lincoln parrot = 0.27 (table 7). To provide at least 1 suitable hollow per 2-ha home range for brush-tailed possums, more trees would have to be retained (eg. 6 100-cm trees per hectare, or a combination of many smaller trees > 30 cm dbhob).

Conceptual Overview of Hollow Development

The diameter of the tree outside bark at breast height was the single best predictor of the probability of a hollow in a tree for 3 of the 4 species assessed. Implicit in this relationship is the influence of tree age on hollow development, but tree size and tree age are only crudely related. Rather it is probably a combination of tree age (time) and fire frequency and intensity during the time the tree remains standing that influences hollow availability for these species. Consider the following conceptual overview of hollow development in jarrah and marri trees. Following reestablishment after a disturbance, growth rates of many trees eventually decrease because of overstocking, though some may be released from intraspecific competition periodically by fires. Some trees eventually develop lateral branches of a diameter large enough to become an entrance to a hollow of a suitable size for one of the species in table 1. Because of death by intense fire or self-pruning, the branch dies, and decay enters the living tissue in the tree bole or larger branch to which the dead branch is attached. The tree may form callous over the branch and heal, or decay may be so great that it prevents callous formation until either another fire ignites the dead wood and forms a hollow or until rot proceeds to develop a hollow more slowly. Continued decay after a fire provides a substrate for ignition in subsequent fires, further increasing the depth of the hollow. Entrance size and internal dimensions of the hollow are largely determined by the size of the limb that died, because eucalypts compartmentalise rot, limiting its spread to healthy tissue surrounding the decay (Wilkes 1982, Shigo 1984). Columns of rot result. Consequently, without disturbance to allow tree growth (thinning or fire), and without self-pruning or disturbance to kill large limbs, and without fire to develop and accelerate hollow development, the number of hollows per hectare available for each species is likely to decline over time compared to current estimates of availability. Relationships presented in table 4 reflect the probability of hollows in trees that are a function of past disturbance regimes that may not occur in the future. Should future fire patterns be more frequent but less intense to reduce fuels (shorter flame heights and fewer embers carried up to 30 m into the crowns), then hollow densities might decline over time.

Management Implications

Managers should consider implementing strategies to maintain hollows in managed stands. Certainly selection of large diameter habitat trees (table 6) in the old-growth overmature silvicultural class (table 2) will increase the probability if hollow occurrence in managed stands following harvest. Currently marked habitat trees are rarely > 100 cm dbhob. It may be necessary to consider more intensive burning in some areas to allow enlargement of hollows in early stages of formation. But just assigning habitat trees with a high probability of hollows now may not be sufficient for long-term maintenance of hollows in managed stands, even if fire regimes are altered. Habitat trees will die and fall, decreasing hollow availability (Sedgwick and Knopf 1992). Replacements for habitat trees that fall should be considered now if hollows of sufficient size for large vertebrates are to be available in the future. Ideally trees of a range of sizes should be allocated now as habitat trees. These should be widely spaced to allow an open-grown form so large, lower limbs may die as they are overtopped by surrounding trees during stand regrowth or damaged during harvests. New replacement habitat trees should be recruited during each entry into a stand to replace those in small size classes that have grown and to replace larger trees that have fallen. Clumps or strips of trees reserved from harvest may be an operationally feasible strategy to achieve these goals.

However, it is not just hollows that will allow hollow-using species to persist in managed forests over time. Hollows provide one aspect of each species life-history needs, usually cover. Food resources, such as green leaves, insects, and/or fruits may be needed near the hollows to increase the likelihood that they will be used, depending on the food requirements of each species.

Finally the spatial arrangement of food and cover, and the dynamic responses of animal populations to the changing habitat mosaic should be considered more explicitly using a population viability model (eg., Possingham et al. 1993). If management strategies for hollow maintenance are not initiated, then habitat quality for some species may decline in the future as existing habitat trees fall and if prescribed burns change the rate of hollow development from that caused by past fire regimes.

Acknowledgments- We thank Mike Pez, John Webb, and Matthew Jones for assisting with field work; Kim Allen, Kim Phillips-Jones, and Charles Downs for providing field support; and the Department of Conservation and Land Management for supporting the study. P. Christensen, G. Friend, D. Saunders and K. Whitford provided comments on an early draft of the manuscript.

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Table 1. Hollow characteristics of selected hollow using vertebrates in that occur in jarrah forests.

Species	Entrance diameter (cm)		Height above ground (m)	Interior diameter (cm)		Interior depth (cm)		Source
	min.	max.	min.	min.	max.	min.	max.	
Red-tailed black cockatoo (*Calyptorhynchus magnificus*	14.7	53.5	4.4	19.0	54.0	45	725	Saunders et al. 1982
Corellas (*Cacatua sanguinea* or *C. tenuirostris*)	14.3		14.0	40.0		45	453	Saunders et al. 1982
Galah (*C. roseicapilla*)	6.5	30.0	4.7	10.0	31.0	32	377	Saunders et al. 1982
Port Lincoln parrot (*Barnardius zonarius*)	6.5	25.0	5.3	9.0	17.5	45	213	Saunders et al. 1982
Striated pardalote (*Pardalotus striatus*)	2.4	6.0	10.0	2.4	6.0	9	35	Haseler and Taylor 1993
Laughing kookaburra (*Dacelo gigas*)	8.5	11.0	15.0	20	30	30	62	Haseler and Taylor 1993
Brush-tailed possum (*Trichosurus vulpecula*)	6	49	0.5	8.0	48.0	68[a]	390	Inions et al. 1989

Table 1. Continued.

Table 1. Continued.

Species	Entrance diameter (cm)		Height above ground (m)	Interior volume (cm^3)		Source
	min.	max.	min.	min.	max.	
Mardo (<u>Antechinus</u> <u>flavipes</u>)	3.5	15.0	1.0	6000	17000	Wardell-Johnson 1986
Brush-tailed phascogale (<u>Phascogale</u> <u>tapoatafa</u>)	2.4	5.5	0.5	7000	31000	Soderquist 1993

[a] preferred hollows had depths > 68 cm (lower 95% confidence interval from Inions et al.), see text.

Table 2. Percent of hollows with height, entrance, and internal diameter characteristics acceptable for selected species (table 1) that occurred in old-growth overmature trees, in tree boles (as opposed to limbs), and which showed evidence of burning, jarrah and marri trees, Western Australia.

Species	Old-growth overmature(%)	Boles(%)	Burned(%)
All hollows (292)[1]	76[2]	20	54
Brush-tailed possum (153)	81	26	73
Striated pardalote (72)	67	6	25
Port Lincoln parrot (96)	84	21	68
Galah (90)	87	27	71

[1] Sample sizes indicated parenthetically.

[2] 45% of all 363 sampled trees were old-growth overmature.

Table 3. Average (SE) characteristics of jarrah and marri trees cut compared to those that were left standing along transects searched for hollows, jarrah forest, Western Australia.

Characteristic	Cut trees (_n_ = 160)	Standing trees (_n_ = 132)	_P_
Hollow height above ground (m)	17.1 (0.3)	14.0 (0.4)	0.0001
Hollow entrance width (cm)	8.1 (0.4)	12.4 (0.8)	0.0001
Hollow entrance height (cm)	10.6 (0.7)	14.8 (1.7)	0.0001
Diameter of tree at the hollow (cm)	25.4 (1.0)	36.3 (2.1)	0.0001
Tree dbhob (cm)	62.0 (1.6)	52.3 (2.1)	0.0003
Tree bole length (m)	12.4 (0.3)	9.7 (0.2)	0.0001

Table 4. Percent of hollows that met height, entrance and internal diameter requirements for selected species that also met depth requirements (see table 1), based on a sample of hollows measured in felled trees.

Species	n	Percent with adequate depth	95% CI
Brush-tailed possum	66	10	4-20
Striated pardalote	59	88	76-95
Port Lincoln parrot	51	20	10-34
Galah	45	31	16-43

Table 5. Logistic regression relationships to predict the probability of occurrence of a hollow in a jarrah or marri tree in the jarrah forest region, Western Australia (n = 363 trees).

Species	Probability of a hollow in a tree (P)	Concordance (%)
Brush-tailed possum	$1/(1 + \exp(4.14 - \text{dbhob} * 0.056))$[1]	86
Striated pardalote	$1/(1 + \exp(3.93 - \text{silvicultural class} * 1.029 - \text{bole length} * 0.094))$[2]	72
Port Lincoln parrot	$1/(1 + \exp(4.01 - \text{dbhob} * 0.045))$[3]	84
Galah	$1/(1 + \exp(4.33 - \text{dbhob} * 0.048))$[4]	86

[1] 95% CI = $P \pm (1.96 * \text{sqrt}\ (0.00003 * \text{dbhob}^2 - 0.00438 * \text{dbhob} + 0.15472))$.

[2] 95% CI = $P \pm (1.96 * \text{sqrt}\ (0.04136 * \text{silvicultural class}^2 + 0.00164 * \text{bole length}^2 - 0.1146 * \text{silvicultural class} - 0.0373 * \text{bole length} - 0.0001 * \text{silvicultural class} * \text{bole length} + 0.333)$

[3] 95% CI = $P \pm (1.96 * \text{sqrt}\ (0.00003 * \text{dbhob}^2 - 0.00422 * \text{dbhob} + 0.1596))$.

[4] 95% CI = $P \pm (1.96 * \text{sqrt}\ (0.00003 * \text{dbhob}^2 - 0.00469 * \text{dbhob} + 0.1803))$.

Table 6. Comparison of diameter at breast height outside bark (dbhob), commercial bole length, and estimated vertical extent of rot in the bole between jarrah and marri trees that contained suitable hollows for selected vertebrates and trees that lacked suitable hollows, jarrah forest region 1993-94, Western Australia.

Species	n	dbhob (cm)	bole length (m)	rot extent (m)
Brush-tailed possum				
Suitable trees	85	78.3(2.9)A[1]	11.7(3.5)A	5.9(0.6)A
Unsuitable trees	278	49.4(1.4)	10.5(0.2)	3.0(0.3)
Striated pardalote				
Suitable trees	49	67.3(2.7)A	12.1(0.4)A	5.6(0.9)B
Unsuitable trees	314	54.4(1.6)	10.6(0.2)	3.4(0.3)
Port Lincoln parrot				
Suitable trees	64	79.6(3.2)A	11.7(3.4)B	5.4(0.7)A
Unsuitable trees	299	51.1(1.4)	10.6(0.2)	3.3(0.3)
Galah				
Suitable trees	61	81.6(3.2)A	12.0(0.4)A	5.8(0.8)A
Unsuitable trees	302	51.0(1.4)	10.5(0.2)	3.3(0.3)

[1] A = difference between trees with suitable and unsuitable hollows, $P < 0.01$; B = difference, $P < 0.05$.

Table 7. Estimated densities of hollows suitable for use by 4 species prior to tree harvest (_n_ = 18 transects), after tree harvest (_n_ = 18 transects), and if three 85-cm dbhob trees were retained (based on logistic regression relationships[1]).

	Hollows/ha		
Species	Pre-cut[2]	Post-cut[2]	Habitat trees[3]
Brush-tailed possum	3.2 (0.3)	1.8 (0.4)	0.18 (0.09-0.34)
Striated pardalote	13.8 (1.4)	3.6 (1.3)	--[4]
Port Lincoln parrot	4.1 (0.5)	2.3 (0.5)	0.27 (0.16-0.37)
Galah	6.0 (0.8)	3.4 (0.7)	0.40 (0.25-0.46)

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[1] Calculated by summing probabilities of occurrence among 3 85-cm trees using equations in table 5, and then adjusting estimates based on the proportion of hollows of adequate depth from table 4. 95% CIs consider both variability in predicting occurrence and in depth.

[2] Average (SE).

[3] Predicted (95% CI).

[4] Model grossly underestimated hollow availability.

Table 8. Estimated hollow abundance per hectare (95% CI) by forest stratum based on average tree diameter distributions from stand tables, jarrah forest inventory.

Stratum	Brush-tailed possum	Galah	Port Lincoln parrot
CENTRAL REGION			
Very high quality			
mature	2.33 (1.14 - 4.09)	4.24 (2.65 - 4.74)	3.54 (2.19 - 4.76)
regrowth	1.87 (0.81 - 3.51)	2.94 (1.62 - 3.77)	2.64 (1.50 - 3.86)
dieback affected[1]	1.33 (0.68 - 2.25)	1.93 (1.23 - 2.13)	1.81 (1.15 - 2.38)
High quality			
mature	2.08 (1.02 - 3.64)	3.59 (2.21 - 4.07)	3.21 (1.99 - 4.32)
regrowth	1.66 (0.57 - 3.66)	2.71 (0.78 - 3.90)	2.34 (0.84 - 2.97)
dieback affected	1.36 (0.69 - 2.31)	2.02 (1.24 - 2.28)	1.90 (1.19 - 2.53)
Medium quality			
mature	2.14 (1.06 - 3.73)	3.79 (2.39 - 4.21)	3.21 (2.00 - 4.29)
regrowth	1.66 (0.70 - 3.85)	2.66 (1.22 - 4.27)	2.39 (1.34 - 4.29)
dieback affected	1.74 (0.86 - 3.02)	3.04 (1.91 - 3.39)	2.63 (1.64 - 3.51)

Table 8. Continued.

Stratum	Brush-tailed possum	Galah	Port Lincoln parrot
Low quality			
mature	2.00 (1.01 - 3.40)	3.16 (2.01 - 3.49)	2.82 (1.78 - 3.74)
saplings	2.37 (1.16 - 4.16)	4.37 (2.72 - 4.91)	3.44 (2.11 - 4.68)
regrowth	0.92 (0.46 - 1.57)	1.62 (1.05 - 1.76)	1.36 (0.86 - 1.79)
dieback affected	1.82 (0.91 - 3.20)	3.04 (1.89 - 3.41)	2.61 (1.62 - 3.51)
Sunklands	2.24 (1.11 - 3.88)	3.83 (2.40 - 4.27)	3.21 (2.00 - 4.31)
Sunklands dieback affected	1.89 (0.94 - 3.27)	3.14 (2.00 - 3.48)	2.78 (1.75 - 3.70)
Sites mined for bauxite	0.94 (0.47 - 1.61)	1.50 (0.96 - 1.66)	1.26 (0.79 - 1.70)
NORTHERN REGION			
Very high quality			
mature	2.20 (1.08 - 3.86)	4.09 (2.54 - 4.57)	3.24 (1.99 - 4.38)
regrowth	1.87 (0.78 - 3.68)	3.10 (1.46 - 4.10)	2.81 (1.48 - 4.22)
dieback affected	1.75 (0.86 - 3.05)	2.99 (1.86 - 3.34)	2.62 (1.63 - 3.51)

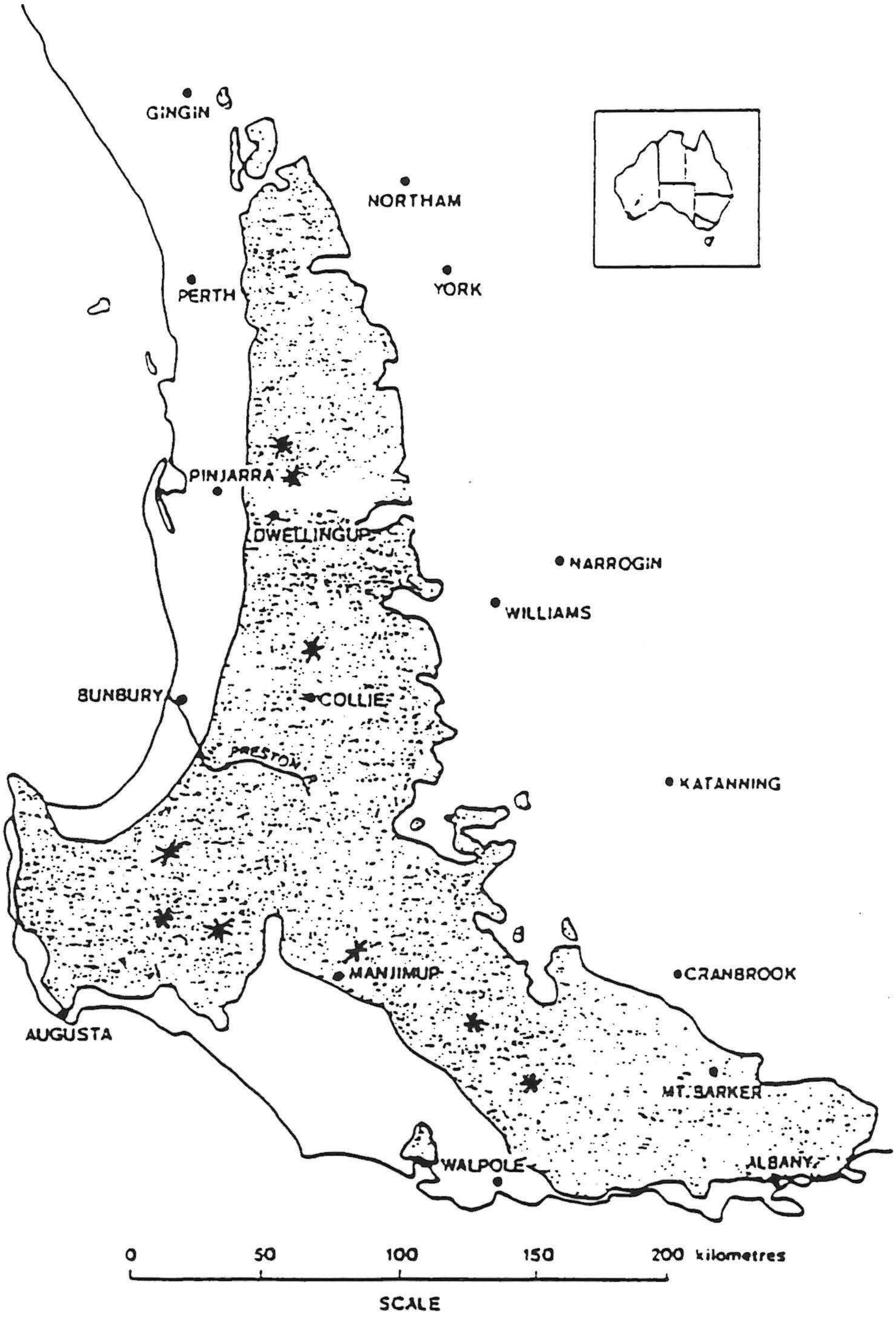
Table 8. Continued.

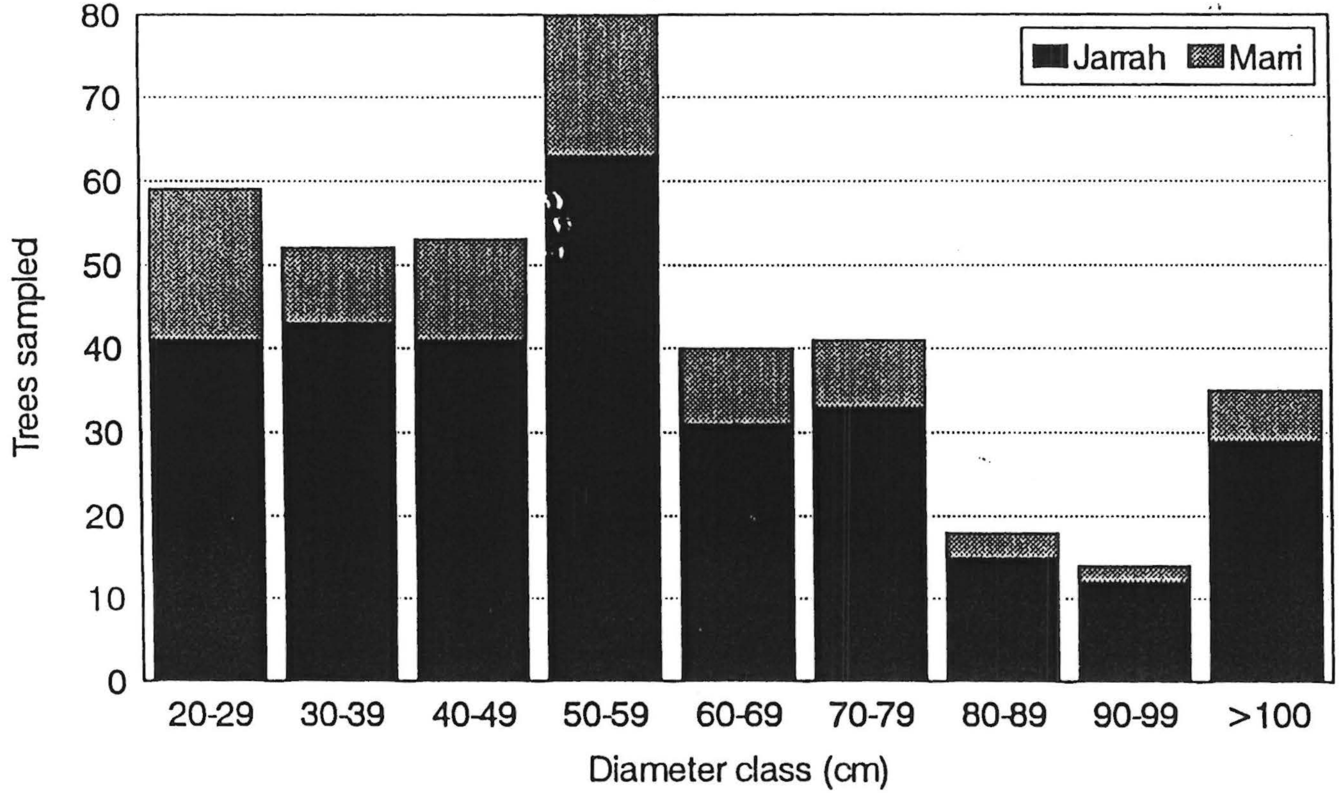
Stratum	Brush-tailed possum	Galah	Port Lincoln parrot
High quality			
mature	2.03 (0.97 - 3.63)	4.07 (2.49 - 4.63)	3.13 (1.90 - 4.30)
regrowth	1.46 (0.56 - 2.94)	2.58 (1.24 - 3.31)	2.17 (1.09 - 3.32)
dieback affected	1.26 (0.62 - 2.21)	2.25 (1.38 - 2.53)	1.95 (1.21 - 2.63)
Medium quality			
mature	1.70 (0.84 - 2.93)	2.92 (1.86 - 3.23)	2.45 (1.53 - 3.27)
regrowth	1.55 (0.45 - 3.75)	2.92 (0.50 - 5.20)	2.35 (0.79 - 4.30)
dieback affected	0.84 (0.40 - 1.50)	1.77 (1.11 - 1.97)	1.20 (0.73 - 1.66)
Low quality			
mature	1.01 (0.52 - 1.67)	1.40 (0.90 - 1.53)	1.44 (0.93 - 1.87)
regrowth	1.00 (0.52 - 1.67)	1.32 (0.83 - 1.47)	1.38 (0.88 - 1.81)
dieback affected	0.76 (0.38 - 1.30)	1.21 (0.75 - 1.36)	1.04 (0.65 - 1.40)
Sites mined for bauxite	1.23 (0.60 - 2.18)	2.20 (1.33 - 2.52)	1.93 (1.18 - 2.61)

[1] *Phytophtora cinnamomi*

Figure 1. Location of sites sampled for hollows in jarrah and marri trees, jarrah forest region, Western Australia.

Figure 2. Size class distribution of trees sampled for hollows, jarrah forest, Western Australia.


GINGIN
NORTHAM
PERTH
YORK
PINJARRA
DWELLINGUP
NARROGIN
WILLIAMS
BUNBURY
COLLIE
PRESTON
KATANNING
CRANBROOK
MANJIMUP
AUGUSTA
MT. BARKER
WALPOLE
ALBANY
0
50
100
150
200 kilometres
SCALE



Jarrah
Marri
Trees sampled
0
10
20
30
40
50
60
70
80
20-29
30-39
40-49
50-59
60-69
70-79
80-89
90-99
>100
Diameter class (cm)