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Flyways & Byways: Guiding restoration of wildlife corridors

Monitoring connectivity restoration in the Australian Capital Territory

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30 April 2014

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CSIRO Climate Adaptation Flagship

Citation

Doerr ED, Doerr VAJ, Davies MJ, Davey C and Allnutt J (2014) Flyways & Byways: guiding restoration of wildlife corridors – monitoring connectivity restoration in the Australian Capital Territory. A report prepared for the Australian Capital Territory Environment and Sustainable Development Directorate. CSIRO Climate Adaptation Flagship, Canberra.

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Acknowledgments

It is widely recognised that one of the main reasons there is insufficient knowledge about how to restore functional connectivity in fragmented landscapes is that movement of species is extraordinarily difficult to study, yet movement is exactly what this project was trying to observe and quantify. Thus, this project required substantial innovation and hard work from government, scientists, and volunteers who helped to collect the data. Special thanks go to:

- Serena Farrelly, Tim Wong, and Jason MacKenzie of the Australian Capital Territory Environment and Sustainable Development Directorate (ACT ESDD) for funding the work and being willing to discuss and trial new approaches to examining animal movement in the landscape
- Tom Barrett and Jamie Love (of New South Wales Office of Environment and Heritage) and Jason MacKenzie for sharing spatial data layers and the Barrett & Love model of habitat and connectivity in the ACT
- Lucy Wenger for helping to refine the connectivity tree watch protocols and collecting many days' worth of tree watch data as well as radiotelemetry data
- Fred Michna for collecting radiotelemetry data, especially capturing some of the significant movements of our radio-tracked birds into the broader landscape
- Canberra Ornithologists Group (COG), for working with us to source and support citizen scientists with bird identification skills for the connectivity tree watches
- The fantastic COG volunteers – Ian Baird, Lia Battisson, Terry Bell, Con Boekel, John Brannan, Jean Casburn, Sandra Henderson, Jack Holland, Alan Kuffer, Duncan McCaskill, Michael & Vikki Mulvaney, Terry Munro, Nick Nicholls, Jenny Pierson, Lucy Randall, Laura Rayner, Jenny Smits, John Waldron – who braved early mornings, hot sun, curious cows, and problematic locked gates to collect most of the connectivity tree watch data
- Nick Nicholls for working with Erik to determine the best approach to analysing our unique 'connectivity tree watch' data as well as the best way to build the models in R
- Sam Niedra and David Watson for organising the workshop to develop a framework for monitoring improvements in connectivity, and to the NSW Environmental Trust for funding the workshop
- David Watson, Sam Banks, Don Driscoll, Paul Sunnucks, and Rodney van der Ree for bringing diverse and useful insights to the process of developing the monitoring framework
- Staff of ACT ESDD, Greening Australia, the Great Eastern Ranges Initiative, and the Australian Government's Department of Sustainability, Environment, Water, Population and Communities (SEWPaC) for ensuring the monitoring framework was informed by the practical needs and constraints of practitioners

Executive summary

Habitat fragmentation and increasing intensification of urban and agricultural lands have reduced many native species to small, isolated populations which are more vulnerable to extinction. This is particularly true along Australia's east, southern and south-west coasts, and inland throughout the cropping zone. Increasingly, the emphasis for biodiversity conservation is thus on 'connectivity conservation' (or landscape-scale conservation), in which spatial planning is used to help ensure that areas managed primarily for biodiversity are close enough together and linked by connections of native vegetation such that movement processes like dispersal, migration and nomadism can occur between patches, allowing the populations in multiple patches to form one large population of each species. In addition, because larger, more functionally connected populations may be more resilient to climate change, and may be able to shift their distributions as climate pressures increase, connectivity conservation is also a common climate adaptation strategy for biodiversity management.

Within the Australian Capital Territory (ACT) Government, the Environment and Sustainable Development Directorate (ESDD) is currently undertaking a program of work to support adaptation of biodiversity under climate change. One component of this program of work involves connectivity conservation - developing large networks of connected patches of high-quality vegetation. These networks are being planned based on a spatial tool developed by Tom Barrett and Jamie Love from the New South Wales Office of Environment and Heritage which used least-cost path modelling approaches to model landscape connectivity, parameterised according to the 'CSIRO Functional Connectivity Model'. The CSIRO model, or 'The 100m/1.1km/10ha Rule' suggests that connections between patches of native vegetation will generally support most species' movements if the connection does not have any gaps in it >100m, if the inter-patch distance (the distance between patches being connected) is no longer than 1.1km, and if the patches at either end are at least 10ha in size. This model is also being used to plan a number of other connectivity initiatives in south-east Australia and while it is based on best-available information, our knowledge of how to design landscapes is still limited. This project was designed to test 'The 100m/1.1km/10ha Rule' in the ACT and develop an approach to long-term monitoring of on-ground works.

To test 'The 100m/1.1km/10ha Rule', we used two methods. First, we performed 'connectivity tree watches' in which movements of birds were recorded in and out of 93 scattered trees, which were selected in areas between remnant woodlands and forests that differed in the relevant parameters (gap distances to the next trees, inter-patch distances, and sizes of patches at either end of the potential connection). We then analysed whether the abundance of birds at each tree and the number of flights in and out of each tree in particular directions depended on those landscape characteristics. Separate analyses were performed for five species groups – woodland specialists, nomadic foragers, woodland generalists, open country species, and exotic invasive species. The first two groups were expected to be in these connecting areas only if they were actively moving through the landscape, while the latter three groups could be living in these scattered tree connections. Second, we radio tracked nine birds that originated in Kama Nature Reserve but that we anticipated might need to move throughout the broader landscape.

The connectivity tree watch results revealed that:

- Gap distance was more important than the other parameters. Woodland specialists almost exclusively moved into or out of connectivity trees in directions where gaps were <150m, nomadic foragers primarily moved in directions where gaps were <400m, and woodland generalists mostly moved in directions where gaps were <500m. This nested pattern suggests that **one set of actions in the landscape (keeping gaps <150m) could simultaneously improve prospects for the at-risk movement-limited species while helping to keep the common species common**.
- Inter-patch distance was also important, sometimes as an interaction with gap distances. For example, woodland specialists were present up to 550m from patches (equivalent of 1.1km inter-

patch distance) but only where gap distances between trees matched the 100m rule. This suggests that **gap distances and inter-patch distances (of <~1.1km) should be managed in concert**.

- Nomadic foragers and woodland generalists were still present at relatively large distances from patches as long as gap distances among the scattered trees between patches were relatively small. As the woodland generalists in particular were almost certainly living in the scattered trees, this tells us that **maintaining gap distances of <150m between scattered trees provides connections for woodland/forest specialists but also provides valuable habitat for woodland generalists**.
- Exotic invasive species were actually more abundant where inter-patch distances were greater (~1.4-2km), suggesting that **keeping inter-patch distances between ~1.0 and 1.3km could benefit woodland specialists while simultaneously limiting the abundance of exotic invasive species like starlings**.
- Sizes of the two patches linked by scattered trees were rarely good predictors of the abundance or movements of species in those scattered trees, suggesting that while patch size may be a critical parameter in terms of providing habitat, particularly for woodland and forest specialists, it is not an important contributor to connectivity per se.

The radio telemetry results were slightly different, with one woodland specialist and one woodland generalist crossing much larger gaps than expected based on the tree watch results (~300m and 600m+ respectively). This may suggest that landscape design recommendations arising from the tree watch results could be too conservative, but the very limited sample size of movements that occurred during the tracking period makes it difficult to draw any firm conclusions.

Considering our set of results, we recommend revising the CSIRO Functional Connectivity Model slightly to '**The 150m/1.0 to 1.3km/10ha Rule**', increasing the recommended maximum gap distance and applying the inter-patch distance rule flexibly, keeping most inter-patches between 1.0 and 1.3km. However, if woodland specialists are not the target of management, other species (nomadic foragers, woodland generalists, and even open country species) could be accommodated by a '**400m/2km/10ha Rule'**, though the larger inter-patch distances could be vulnerable to increased numbers of exotic invasive species like starlings. Given that the rule for woodland specialists may be too conservative, it would be useful to continue to research the inter-patch distance parameter in particular as reducing these distances requires restoration of whole patches which is much more costly than reducing gap distances.

This result confirms that the approach currently being used by ACT ESDD and as modelled by the Barrett and Love (2012) spatial tool appears to be valid and connectivity management or restoration planned using the tool will tend to be effective at providing benefits for birds in the landscape. However, the revisions to the CSIRO Functional Connectivity Model suggest the original approach could be slightly conservative. Rather than re-modelling connectivity in the ACT, we suggest that the spatial tool can be used in a slightly more flexible way to identify additional opportunities for connectivity management and restoration. Those opportunities should particularly emphasise the management and even restoration of scattered tree connections because of the substantial habitat benefits they provide for woodland generalists.

To begin to develop a long-term monitoring approach to test the effectiveness of the actual on-ground works to improve connectivity in the ACT, we drafted a monitoring framework. There are a large number of options available for how to assess improvements in connectivity and landscape-scale conservation outcomes. So the intention of the framework is to explain the ecological relationships between different approaches as a way to define potential levels of monitoring and highlight their measurement options and the trade-offs between them. The framework was developed through a workshop with experts who actively study landscape connectivity. We provide best-available instructions for using the framework, particularly for informing choices about monitoring options over long time frames, ensuring that primary options achieve an acceptable balance between accuracy, tractability, and a clear relationship to outcomes desired, while secondary options can be chosen when opportunities arise that will most effectively complement the primary approaches.

1 Introduction

1.1 The Rise of Connectivity Conservation

Biodiversity conservation and management used to be restricted to formal protected areas. A realisation that existing protected areas were unlikely to be comprehensive, adequate and representative (key goals of systematic conservation planning, Margules and Pressey 2000) stimulated a shift to thinking about biodiversity in all parts of the landscape, not just in protected areas (Norton 2000). However, in many broader landscapes, habitat fragmentation and increasing intensification of both urban and agricultural lands have reduced many native species to small, isolated populations (Collinge 2009; Lindenmayer and Fischer 2006). In Australia, this is particularly true along the east, southern and south-west coasts, and inland throughout the cropping zone (Robinson and Traill 1996).

Increasingly, the emphasis is thus on 'connectivity conservation' (or landscape-scale conservation), in which spatial planning is used to help manage biodiversity in protected areas and in the broader landscape in concert (Tabarelli and Gascon 2005). Drawing on theories from metapopulation biology and landscape ecology, the intention is to have protected areas and privately-managed patches of native vegetation managed in concert to provide high-quality habitat for native species. In addition, such areas should be close enough together and linked as necessary by small bits of native vegetation such that movement processes like dispersal, migration and nomadism can occur between patches, allowing the populations in each patch to be functionally linked so they form one large population of each species (Hanski and Ovaskainen 2000; Hilty et al. 2006). While this approach is clearly focussed on more than just connectivity (the physical links and actual movements between patches), it is the connectivity component that is largely new, and our understanding of how to manage and restore it is relatively limited.

Coinciding with the rise of connectivity conservation approaches, landscape managers have become more aware of the consequences of climate change for native species. Climate change has the potential to dramatically alter the suitability of environments and habitats for the majority of species (Araújo and Rahbek 2006; Pereira et al. 2010; Sommer et al. 2010). In turn, alterations in environmental and habitat suitability are expected to create pressure for significant changes in individual behaviour, population dynamics, species composition of communities, and ecosystem function (Chapin et al. 2000; van der Putten et al. 2004). These changes will occur either through local extinctions of native species (Lawler 2009), or through natural ecological and evolutionary mechanisms for responding to environmental change (Donnelly et al. 2012; Hughes et al. 2010; Lande 2009). Adaptation to climate change for biodiversity management thus emphasises ways in which policy-makers and managers can support natural mechanisms for responding to change (Doerr *et al.* 2011c; Dunlop *et al.* 2012b) such as genetic adaptation, phenotypic plasticity, and behavioural plasticity (including shifts in species' distributions). The result should be that species and ecosystems can adjust as much as possible to the changing environmental conditions they experience. This is referred to as 'managing the change to minimise the loss' – in other words, land managers can actually facilitate the process of change in order to reduce the number of local and/or global extinctions (Dunlop et al. 2012a).

Our knowledge of how policy-makers and land managers can actually influence processes like genetic adaptation and behavioural plasticity is limited. However, all of these processes appear to require variation among individuals, and greater variability is more likely in larger populations (Hartl and Clark 2007; Lacy 1997). Thus, a goal that policy-makers and land managers can include as part of a climate adaptation plan for terrestrial biodiversity is simply to strive for larger populations of native species, to provide the underlying variability on which natural processes for responding to environmental change can act. Given that this goal, functionally larger populations, is also the fundamental goal of connectivity conservation, and that connectivity conservation also has the potential to ensure pathways for likely shifts in species'distributions, it may be a useful approach to climate adaptation for biodiversity management.

1.2 Connectivity Restoration in the Australian Capital Territory

Within the Australian Capital Territory (ACT) Government, the Environment and Sustainable Development Directorate (ESDD) is currently undertaking a program of work to support adaptation of biodiversity under climate change. One component of this program of work involves developing large networks of connected patches of high-quality vegetation, with a particular emphasis on lower-lying woodland vegetation types. This is currently being pursued under the revised (draft) ACT Nature Conservation Strategy and other ACT Government initiatives (e.g. the ACT Woodlands Restoration Program). These initiatives are funding on-ground works to manage and restore specific links between patches of native vegetation in the ACT.

To decide where to focus efforts on on-ground works, ESDD commissioned Tom Barrett and Jamie Love of the New South Wales Office of Environment & Heritage to develop a spatial planning tool that modelled patches of woodland and forest and existing connectivity between them as well as areas where connectivity could easily be improved (Barrett and Love 2012). In this spatial tool, connectivity was incorporated using least-cost path modelling approaches, parameterised according to the 'CSIRO Functional Connectivity Model'. This model was built from both empirical research (radiotracking the dispersal and foraging movements of native birds in fragmented landscapes in south-east Australia) as well as a systematic review (Doerr *et al.* 2010; 2011b). The systematic review analysed data across all published and grey literature about the influence of structural features in between habitat patches (structural connectivity) on movements of native species (functional connectivity) for all species and ecosystem types in Australia. The results, analysed across 80 different studies of primarily mammals and birds in woodland and forest environments, supported some of the detailed conclusions from the radiotracking studies. The recommendations arising from these studies (as well as from existing literature on patch sizes) were to provide for dispersal and foraging movements for a majority of native species by ensuring that:

- woodland and/or forest patches are connected by woody vegetation with no more than 100m gaps between the trees
- such connections extend for no more than 1.1km (e.g. inter-patch distances are no greater than 1.1km)
- patches are at least 10ha in size

These recommendations are sometimes referred to as 'The 100m/1.1km/10ha Rule' and are shown graphically in Figure 1.

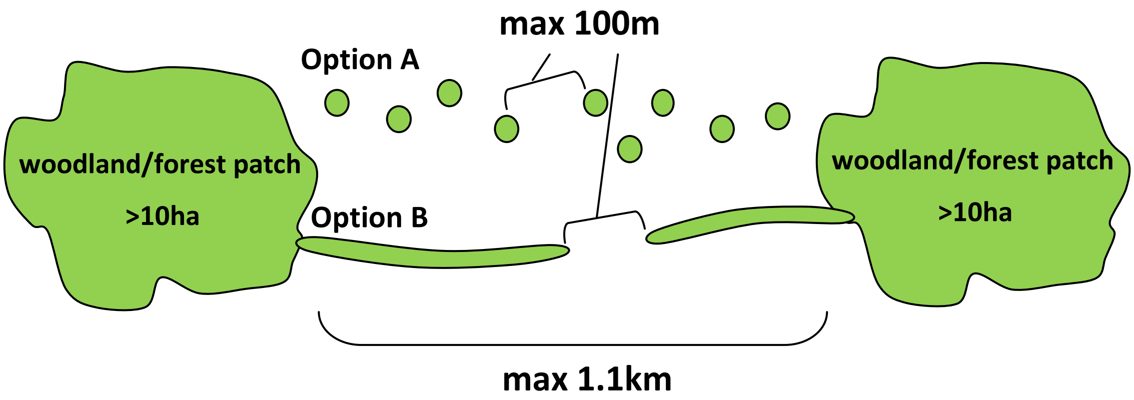

Figure 1. The spatial configuration of woodland and forest patches and connections between them (option A = scattered tree connection, option B = corridor connection) that the CSIRO Functional Connectivity Model suggests will provide for the majority of species movements in fragmented landscapes. Larger gaps in connections and/or longer distances between patches will be less effective at supporting species movements. Option A and option B may be equally effective.

The Barrett & Love spatial tool effectively modelled where such conditions currently exist in the ACT and some adjoining areas of New South Wales, with an emphasis on the maximum gap distance of 100m and the minimum patch size of 10ha (Barrett and Love 2012). The spatial tool also identified where gap distances between woody vegetation are currently too large but where a likely functional connection could be created with minimal restoration of scattered trees (i.e., areas where gaps were ~200m so in theory a single tree in the middle would restore a functional connection according to the CSIRO Functional Connectivity Model). This spatial tool is now being used to inform on-ground works in the ACT, albeit within the constraints involved in working on public land or with volunteer private land managers in a landscape heavily impacted by urban land uses. The emphasis is on improving the quality of patches of woodland or forest habitat >10ha in size, improving the quality of existing functional connections (i.e. those that meet the three criteria above), and restoring new functional connections according to The 100m/1.1km/10ha Rule (which may involve restoration of connections but also of patches >10ha in size where distances between existing patches are > 1.1km).

1.3 The Role of Monitoring

While monitoring is an increasingly important component of environmental management (Lindenmayer *et al.* 2012; Lindenmayer and Likens 2010), it may be particularly critical for connectivity conservation. At its most useful, monitoring involves evaluating the relative outcomes of management actions (including no action), not just whether the actions occurred, and provides an essential feedback mechanism to determine whether management is achieving its goals or whether it should be adjusted (Lindenmayer and Likens 2009). In connectivity conservation, our relatively scant knowledge specifically about landscape-scale movements of native species and how to support them (illustrated by the debate in Doerr *et al.* 2011a; Hodgson *et al.* 2009) suggests that even approaches that use the best-available knowledge (such as those employed by ACT ESDD) may still be inappropriate or insufficient to achieve the desired objectives. Thus, by monitoring actions particularly designed to improve functional connectivity (movements between patches of native vegetation), we can not only evaluate the success of individual projects, we can also improve our relatively small knowledge base about how to manage connectivity and engage in connectivity conservation, and thus improve actions over time through adaptive management (Westgate *et al.* 2013).

One of the greatest challenges involved in monitoring improvements to connectivity is the time lag that might be expected between physical restoration of a connection and its ability to fully support species' movements. For example, when connecting woody ecosystems, newly planted trees may not fully support movements of some species for many decades, possibly more than a century if movements are dependent on features of mature trees such as hollows. Thus, monitoring may need to be implemented at regular intervals over a very long time frame to truly evaluate the success of management actions.

As these long time frames limit the usefulness of monitoring for adaptive management, it is desirable to find alternative approaches that can increase our available knowledge about how to manage and restore connectivity within just a few years. One of the best options is to use 'space-for-time substitution', in which areas of the landscape that are thought to NOT provide connections are compared with areas that currently look like restoration/management sites are expected to look many decades from now. Examining species' movements using such a comparison provides an almost immediate assessment of whether restoration and management actions are likely to improve functional connectivity into the future. Furthermore, this approach allows comparison of many potential restoration approaches, potentially using much larger sample sizes than could be achieved purely through monitoring actual on-ground actions which may be expensive and relatively small in number. For example, the approach taken by ACT ESDD could be 'monitored' by testing 'The 100m/1.1km/10ha Rule', examining species' movements through areas in the landscape that possess these characteristics as well as areas where these values are slightly to substantially different. The results could be paired with long-term monitoring of actual on-ground works to provide on-going feedback and support adaptive management of landscape restoration in the ACT (Walsh *et al.* 2012).

1.4 Flyways & Byways Objectives

The Flyways & Byways project, guiding restoration of wildlife corridors, was designed to address both types of monitoring of improvements to connectivity in the ACT – immediate testing of 'The 100m/1.1km/10ha Rule' that was used to develop the spatial tool underpinning connectivity restoration and management, and putting in place a long-term monitoring framework and protocol for assessing actual on-ground works over time.

As most methods for studying species' movements are quite expensive and often species-specific (e.g. radiotelemetry, genetic analyses), they are not necessarily suitable for monitoring, in which the work may need to be repeated many times. Thus, the project was also designed to employ and test a novel method of assessing movements in connections – 'connectivity tree watches'. The specific objectives were to:

- Conduct 'connectivity tree watches': Collect data on movements of native species in and out of scattered trees in areas between more substantial woodland and forest habitat patches, but that differ in the parameters named in the CSIRO Functional Connectivity Model - gap distances to the next trees, inter-patch distances, and sizes of patches at either end of the potential connection
- Analyse those data to reveal whether adjustments could/should be made to the individual parameters in the CSIRO Functional Connectivity Model to most cost-effectively provide functional connectivity for native species
- Provide insights into whether the parameter needs differ across species groups that might need to use connectivity for different purposes, e.g. dispersal versus nomadic foraging movements
- Radiotrack a small number of birds of a range of species in one of the same study areas to provide more direct evidence of movement and assess the usefulness of the connectivity tree watch approach
- Develop a framework of options for long-term monitoring of connectivity restoration activities which identifies the advantages and disadvantages of a variety of different monitoring methods, and how multiple options might be combined to best effect
- Develop a specific long-term monitoring protocol for the ACT Government (including a handbook on data collection, storage and analysis) which is achievable within current practical constraints

- Collect baseline data according to this protocol for two regions in which connectivity is being restored and managed

To satisfy these objectives, three types of methods were employed:

- Connectivity tree watches (to test 'The 100m/1.1km/10ha Rule')
- Radiotelemetry (to test 'The 100m/1.1km/10ha Rule' and help validate the connectivity tree watch approach)
- Expert workshop to develop a monitoring framework (to support choices about long-term monitoring methods)

This report presents the results of the connectivity tree watches and radiotelemetry, along with the resulting conclusions about the CSIRO Functional Connectivity Model and the validity of the ACT ESDD approach to connectivity restoration. It also introduces the monitoring framework developed. Details of the final monitoring protocol and baseline data collected are presented in a separate Connectivity Monitoring Handbook.

2 Connectivity Tree Watches

2.1 Tree Watch Sites

The intent was to observe movements into and out of scattered trees associated with different gap distances, inter-patch distances, and patch sizes as they currently exist in the landscape (i.e., not just restricted to likely restoration sites). Thus, we first used Google Earth aerial imagery to select candidate regions of the ACT or north-east of the ACT into New South Wales (in an area where management and restoration will be occurring as part of the Greater Goorooyarroo project) where there were multiple patches of remnant native woodland or forest separated by scattered trees of varying densities. All scattered trees were embedded in a matrix of grazed pasture, variable in whether it was dominated by native or non-native grasses. We then used a combination of outputs from the Barrett and Love (2012) spatial tool and Google Earth to select 64 candidate inter-patch areas of various distances that contained scattered trees and had patches of varying sizes at one or both ends. The candidate inter-patch areas had distances (length of connection) that varied from 250m to 2400m to provide significant variation around the recommended maximum value of 1.1km. The patches at either end were at least 5ha in size to ensure we were including patches both smaller and larger than the recommended minimum size of 10ha. Note that we also defined patches using a combination of aerial imagery and the Barrett and Love (2012) spatial tool, as the tool used strict criteria to separate woodland, forest and scattered trees.

We then selected 31 of the 64 candidate inter-patch areas for final inclusion in the study based on: 1) confirming the accuracy of aerial imagery through a physical site visit, 2) gaining permission from land managers to conduct research there, and 3) achieving a relatively even spread of inter-patch distances from 250m to 2400m (Figure 2).

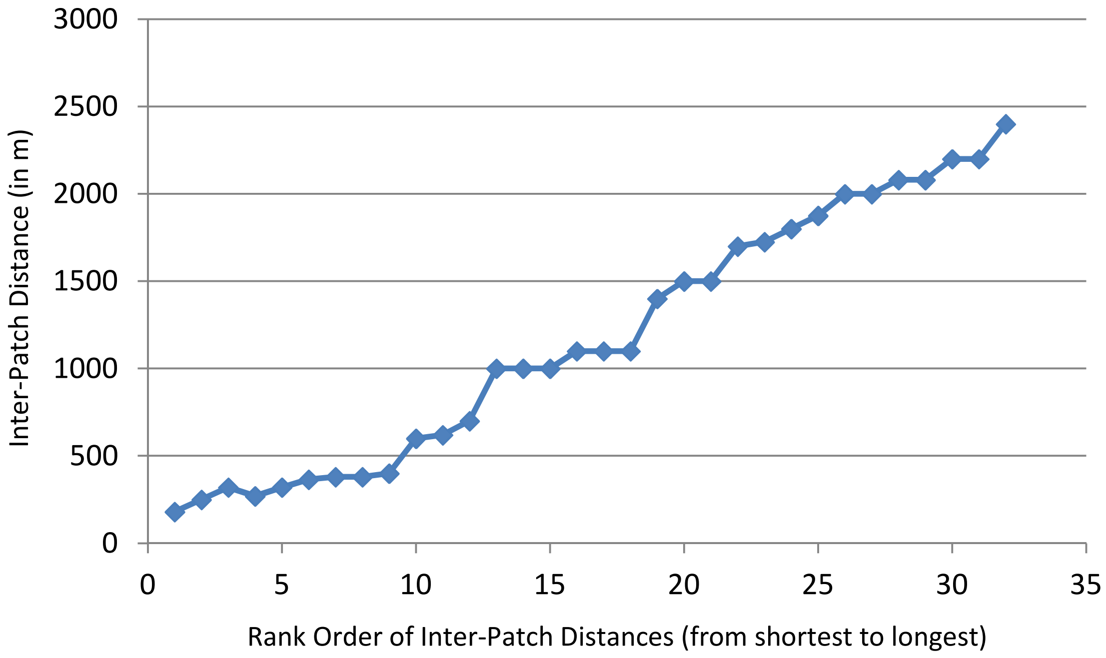

Figure 2. Relatively even distribution of distances of all inter-patch areas selected for inclusion in the study.

Finally, we selected three scattered trees within each inter-patch area to serve as our 'connectivity trees', making a total of 93 connectivity trees studied. We specifically selected trees that: 1) were at least pole stage (i.e., not seedlings or saplings), 2) had a distinct crown separate from other surrounding woody vegetation, 3) were varying distances from the edges of patches, and 4) had gaps to the nearest other trees in a variety of directions ranging from ~25m to 300m (Figure 3). For the second of these criteria, we occasionally selected a small clump of two or three trees that had a single distinct crown, and thus functioned like one larger scattered tree. For the last of these criteria, we measured gap distances to the next tree (again, excluding saplings and seedlings) using a range finder in the field in the four cardinal directions around each tree. We used this information to try to ensure that across all 93 connectivity trees, there were gap distances relatively evenly spread from 25-50m to 300+m, to provide significant variation around the recommended maximum value of 100m (Figure 4). Note that our ability to achieve an even distribution was somewhat limited by landscape condition – more widely spaced scattered trees are inherently fewer in number in the landscape.

Figure 3. Images of scattered trees selected for connectivity tree watches, showing distinct crown and range of tree ages and condition. Note that one is actually a clump of multiple trees but the clump has a distinct crown and thus was treated as a single tree.

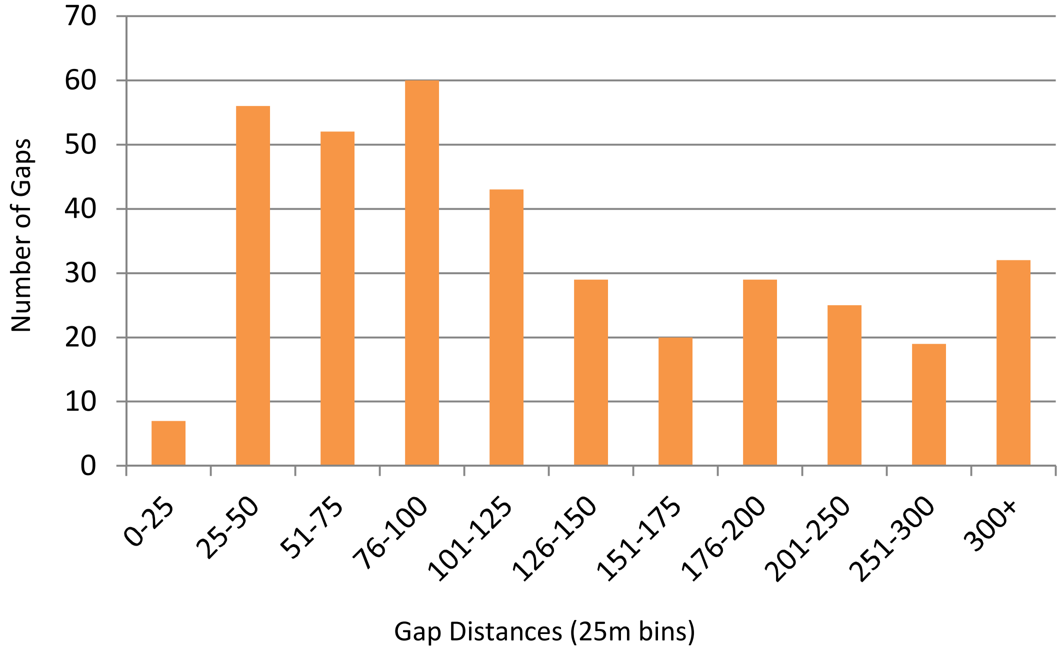

Figure 4. Spread of gap distances (distance from the connectivity tree to the next nearest tree) in four cardinal directions surrounding all 93 connectivity trees selected for watching in the study.

The final set of study sites for the connectivity tree watches thus consisted of 93 individual ‘connectivity trees’, clustered within 31 inter-patch areas, which were generally grouped within five regions: the area surrounding Kama Nature Reserve (Kama), the west side of Stromlo Forest Park (Stromlo), Goorooyarroo Nature Reserve and links to Mulligan’s Flat Nature Reserve (Gooroo), the Majura Valley (Majura), and the Greater Goorooyarroo landscape in New South Wales (NSW; Figure 7). See Appendix A for full details of inter-patch areas and connectivity trees.

a)

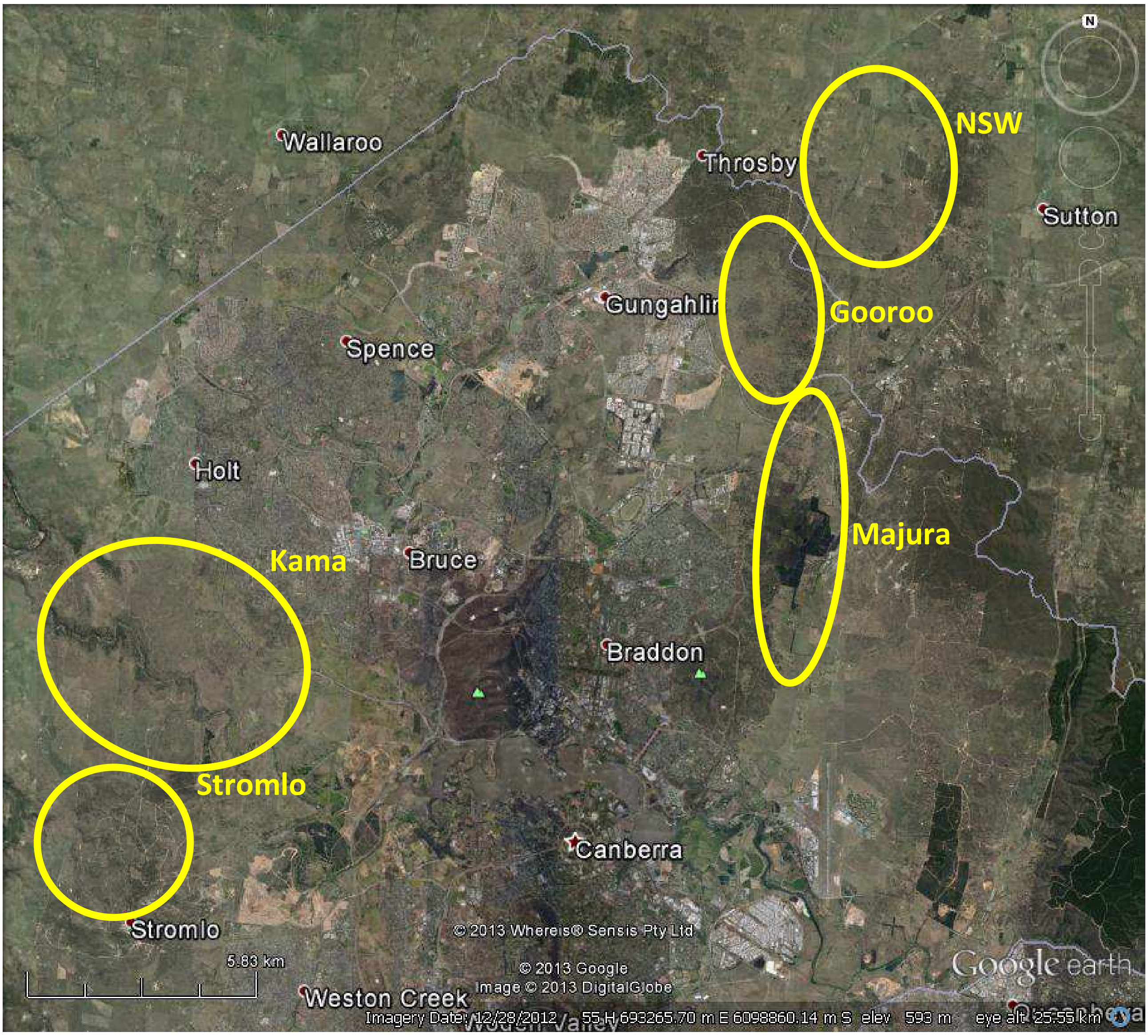

Figure 5a. The nested design of study sites for the connectivity tree watches - five broad regions within which inter-patch areas (sites) were selected.

b)

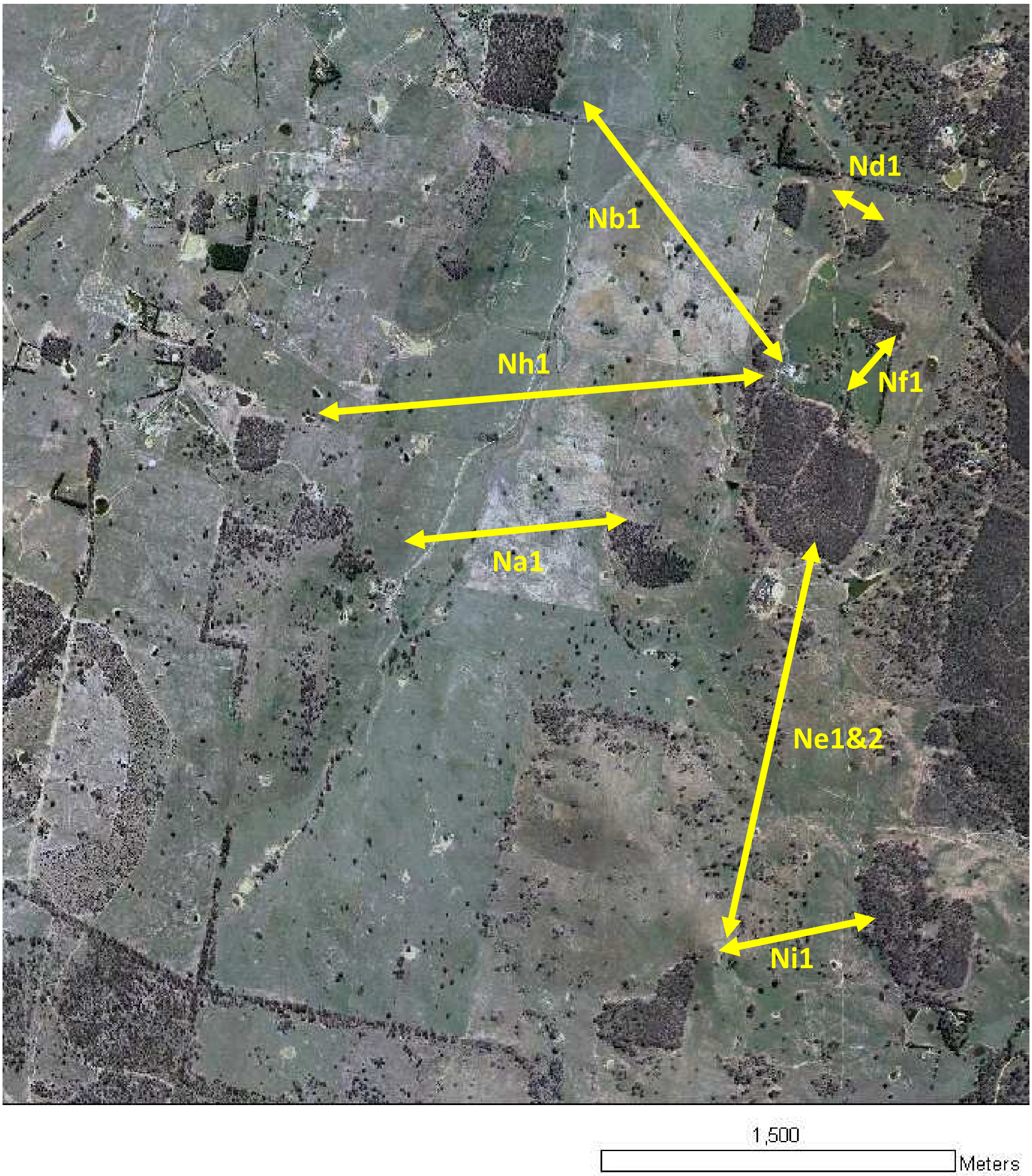

Figure 6b. The nested design of study sites for the connectivity tree watches - inter-patch areas (sites) showing distances and presence of scattered trees in the NSW region. See Appendix A for more details.

c)

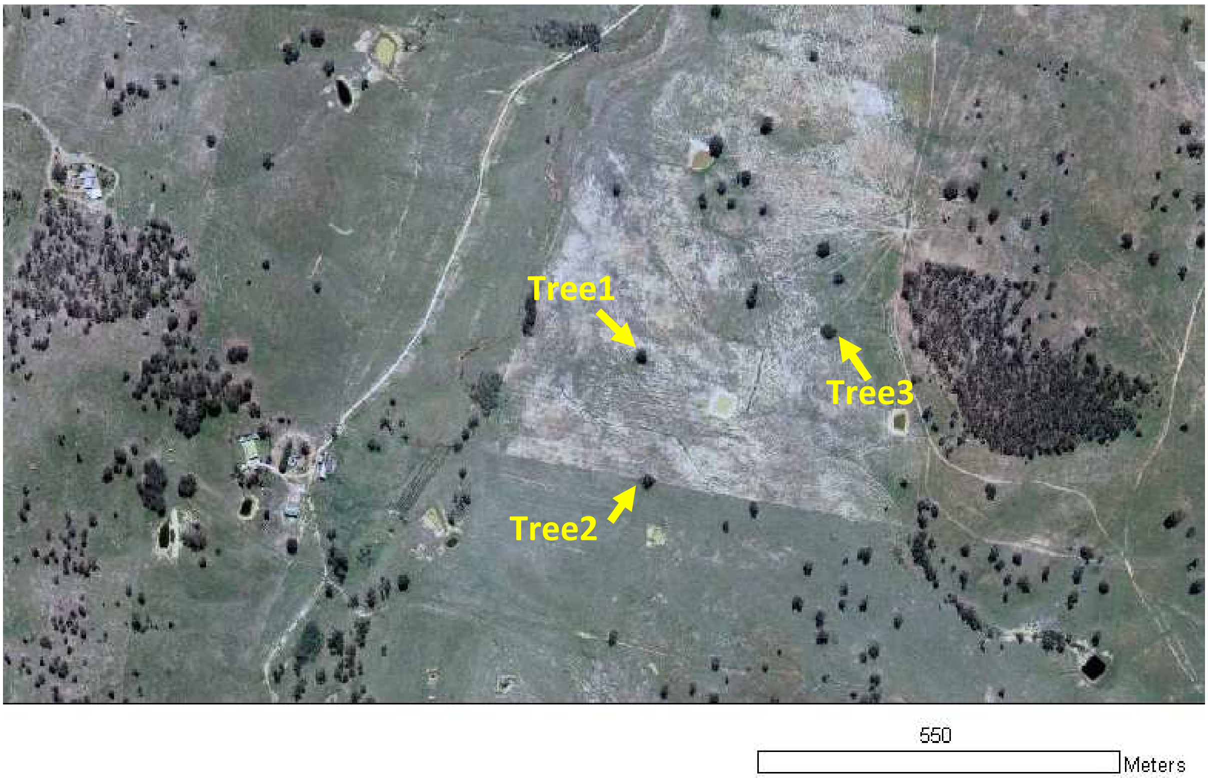

Figure 7c. The nested design of study sites for the connectivity tree watches - a single inter-patch area (site Na1) showing selection of three connectivity trees for observing movement of native species. See Appendix A for more details.

2.2 Tree Watch Data Collection

Each connectivity tree was watched five times for 30 minutes (a total of 2.5 hours per tree, 232.5 hours total). Watches were spread relatively evenly from 27 October to 22 December 2012, with approximately half the watches in the early morning (before 9am) and half in the late morning (after 9am). Four of the watches at each site (3 connectivity trees within a single inter-patch area) were performed by a volunteer from the Canberra Ornithologists Group (COG), with most volunteers offering to perform the watches at just one or two sites. One additional watch at each site was performed by a core tree-watching team (generally C. Davey and L. Wenger) to provide some consistency across sites. Watches were not performed in rainy or windy conditions.

All trees were watched from at least 40m away to the east or north-east, with the observer sitting at least 15m away from all other trees to avoid influencing tree-to-tree movement patterns (Figure 6). Observers recorded arrivals into and departures out of the tree by any species observed, with the tree considered to be a cylinder encompassing the full crown of the tree and extending down to the ground and up to 3x the height of the top of the canopy. If an animal passed through this cylinder (i.e., under, though or directly over the canopy of the tree) without stopping in the tree or on the ground, both an arrival and a departure were recorded but the lack of stopping was noted. Note that while all animal species were recorded, we expected the vast majority of observations to be of birds, given their relatively conspicuous nature.

For each arrival or departure, observers recorded the species involved, the number of individuals, and the approximate direction that the arrival came from or the departure left toward. For the direction, observers were provided with an aerial image of the tree being watched with eight numbered directions around it (Figure 9). Observers were simply asked to record the number of the octant involved for each movement. The average direction of the movement was used rather than the direction immediately prior to or after landing. If the observer noted the precise origin of an arrival flight or the exact landing of a destination flight, these additional details were also recorded. Fischer and Lindenmayer (2002) used a similar technique to study directional movement through scattered trees, albeit with much smaller sample sizes in terms of both numbers of trees and hours of observation, and they did not attempt to analyse their data in relation to the details of tree spacing and other aspects of landscape structure.

Figure 8. Volunteer performing a connectivity tree watch at an appropriate distance from the connectivity tree as well as all other trees in the inter-patch area.

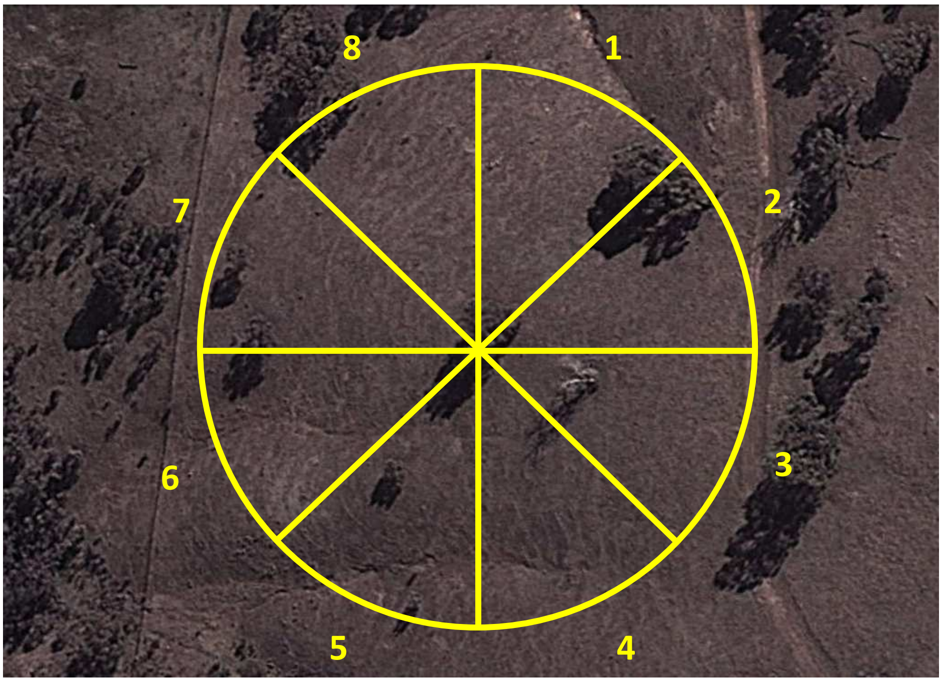

Figure 9. Aerial image of a connectivity tree overlaid with a compass with numbered octants for recording the directions of animal movement into and out of the tree.

2.3 Tree Watch Analyses

Data from tree watches were collated in an MS Excel database. All species recorded were assigned to one of 5 species groups: 1) Open country species such as galahs and magpies, which are not predicted to require connectivity; 2) Woodland generalists such as yellow-rumped thornbills and striated pardalotes which are predicted to live within connectivity areas; 3) Semi-nomadic and nomadic foragers such as white-plumed honeyeaters and red wattlebirds, which are predicted to use connectivity for foraging; 4) Sedentary woodland specialists such as white-throated treecreepers and buff-rumped thornbills, which are predicted to use connectivity for dispersal; and 5) Exotic invasive species such as starlings and mynas. Assignments were made based on general knowledge of habitat preferences (Appendix B).

Using a combination of ArcGIS and GoogleEarth™ we also recorded data on a number of spatial variables for each tree and site (i.e., inter-patch area). For each tree, we recorded the distance to and size of the nearest patch (hereafter referred to as the "near patch") and the distance to and size of the next nearest patch (hereafter referred to as the "far patch"). Patch sizes were estimated using a combination of the Barrett and Love (2012) spatial tool and recent GoogleEarth™ imagery. This was particularly necessary because a number of patches that we could clearly identify both on GoogleEarth™ and in the field were not picked up at all by the modelling. In cases where a patch was not identified or was identified as being under 1.5 ha, we simply used our own estimate of patch size. In all other cases, we averaged the two estimates (from the model and from our visual estimates on GoogleEarth™) to obtain a final estimate of patch size. For each site (consisting of 3 trees between a pair of patches) we also recorded the minimum inter-patch distance between the patches. Finally, we measured gap distances – the distance to the next nearest tree from each connectivity tree – in each of the octants surrounding each of our connectivity trees at which watches were performed.

We also recorded whether the patches were linked or not through the inter-patch area according to the Barrett and Love modelling. For about a third of sites, it was difficult to judge whether the two patches were linked according to the modelling as the links were tenuous single-pixel-width threads that only just did (or did not) link the sites. To address this uncertainty, we created three alternate versions of this variable: 1) "Links" – a three-level version where each site was described with either "Y" (clearly linked), "N" (clearly not linked), or "?" (possibly barely linked); 2) "LinksC" – a conservative version where ambiguous sites were assumed to not be linked; and 3) "LinksL" – a liberal version where ambiguous sites were assumed to be linked. Preliminary results indicated that the "LinksC" version had the most predictive power so we renamed this variable "Connectivity" (CONN) for our detailed analyses.

For each of our five species groups, we then analysed: 1) whether simple abundance of individuals at each watch of each connectivity tree was influenced by landscape structure variables and 2) whether the number of flights to and from connectivity trees in each octant during each watch was influenced by landscape structure variables, including gap distance to the next nearest tree. Note that for the latter analyses, a group of individuals that arrived at or departed the tree together were considered one flight. For both sets of analyses, we also took into account the date and time of surveys (early vs. late morning) which could also have an influence on abundance and number of flights.

The analysis of these tree watch data presented significant challenges as the data were not normally distributed (primarily because they include a large number of zeros as is typical for count data) and they have a hierarchical or nested structure (i.e., data from watches are nested within trees and trees are nested within sites and sites are nested within regions). The most appropriate statistical approach for analysing such data is the use of generalised linear mixed models (GLMMs), in which random effects are incorporated for the identity of each tree, site and region to capture differences among these that may influence abundance and number of flights in ways other than the landscape structure variables and time and date. Software capable of running such models has only recently become available to ecologists and they are "challenging to use even for statisticians" (Bolker 2008). We constructed GLMMs using the 'glmmADMB' package (Skaug *et al.* 2013) in R (version 3.0.1; R Core Team 2013). Initial data exploration suggested that our response variables were significantly overdispersed (i.e., variances much larger than means), so we used a negative binomial model to construct our GLMMs. In constructing these GLMMs, we adopted a protocol very similar to that recommended by Zuur et al. (2009), which involves the following steps:

1. Construct a "beyond optimal model" that includes all fixed effects and interaction terms that may be important (i.e., that you believe could reasonably end up in a final model).

    a. For our abundance analyses, the beyond optimal model included:

        1. Time
        2. Date
        3. Near patch size (NPS)
        4. Far patch size (FPS)
        5. Near patch distance (NPD)
        6. Inter-patch distance (IPD)
        7. Interaction between patch sizes (NPS*FPS)
        8. Modelled connectivity (i.e., the binary variable CONN, see above)
        9. Interactions between CONN and each of variables 3-7 above

    b. For our analyses of flight direction, the beyond optimal model included:

        1. Patch presence (PP)
        2. Patch size (PS)
        3. Patch distance (PD)
        4. Gap distance (GAP)
        5. Interactions between GAP and each of variables 1-3
        6. A quadratic term produced by squaring GAP (GAP^2)
        7. An offset term equal to the logarithm of the total number of flights observed at the tree (in effect controlling for abundance which was analysed separately)

2. Identify the optimal random structure, by varying random components for the beyond optimal model. For our analyses, this involved a two-step process:

    a. The glmmADMB package offers both the "NB1" (variance = $\phi*\mu$) and the "NB2" (variance = μ (1+ μ /k)) parameterisations of the negative binomial function, so we first compared beyond optimal models that varied only in this parameterisation. Whichever parameterisation produced the better model (i.e. the one with the lowest AICc value), was used for all subsequent models.

    b. We then compared eight alterative models, identifying the optimal random structure by selecting the model with lowest AICc. Each of these models contained all of the fixed effects of the beyond optimal model, and random components as follows:

        1. No random structure
        2. Region identity only
        3. Site identity only
        4. Tree identity only
        5. Site nested within Region
        6. Tree nested within Region
        7. Tree nested within Site
        8. Tree nested within Site nested within Region

3. Attempt to identify an optimal model by comparing a range of models including various combinations of fixed effects and their interactions and using the optimal random structure identified in step 2.

    a. For the abundance analyses we began by comparing the following models:

        1. The full model created by combining all the fixed effects and interactions included in the beyond optimal model with the optimal random structure
        2. The full model minus connectivity variables (CONN and its interactions)
        3. The full model minus distance variables (NPD, IPD and their interactions)
        4. The full model minus patch size variables (NPS, FPS and their interactions)
        5. Model containing size variables only

6. Model containing distance variables only
7. Model containing the connectivity variable only
8. Model containing Date and Time only (note that these two variable are present in all of the above models as well)
9. Model containing only the optimal random structure (no fixed effects)

b. For the analyses of flight direction we began by comparing the following models:

1. The full model created by combining all the fixed effects and interactions included in the beyond optimal model with the optimal random structure
2. The full model minus the quadratic term (GAP^2)
3. The full model minus all the interaction terms involving GAP (except GAP^2)
4. The full model minus all interaction terms (including GAP^2)
5. Model containing only PP
6. Model containing only PS
7. Model containing only PD
8. Model containing only GAP and GAP^2
9. Model containing only GAP
10. Model containing only the offset term (which is present in all of the above)

4. Examine the two or three best models and try to improve these if possible. This involved either sequentially dropping terms with lowest significance levels or adding terms to the best model that were highly significant in the second or third best models. In many cases, this secondary model selection process allowed us to substantially improve on our previously best model.
5. Finally, check plots of the model residuals from our final best model plotted against each fixed effect variable in the model and against fitted values from the model (fitted values have had the effects of the optimal random structure incorporated into them). These checks revealed any potential problems with variance heterogeneity or influential outliers. Several issues were identified, with distributions of some variables as well as with the Majura sites, which were extreme outliers because of the very large sizes of the patches they connected. Thus, we log transformed several variables (see tables in Results) and excluded Majura sites from formal statistical analyses, and then repeated this modelling process from Step #1.

We followed the above protocol to produce a best model to predict abundance at watch trees for each of the five species groups and a best model to predict numbers of observed flights to or from watch trees in different directions for each of the five species groups.

2.4 Tree Watch Results

2.4.1 SUMMARY STATISTICS

A total of 6440 individual animals were recorded during tree watches (including the Majura sites), almost all of which were birds (barring a single group of 3 eastern grey kangaroos). Note that these numbers could include double-counting, as we had no way to determine whether individuals observed later in a watch or in watches later in the season were the same individuals observed and recorded earlier. These observations consisted of 2515 individuals of open country (OC) species, 2391 of woodland generalists (WG), 154 of nomadic foragers (NF), 191 of sedentary woodland specialists (WS), and 1189 of exotic invasive (EI) species (Figure 10; more details in Appendix B).

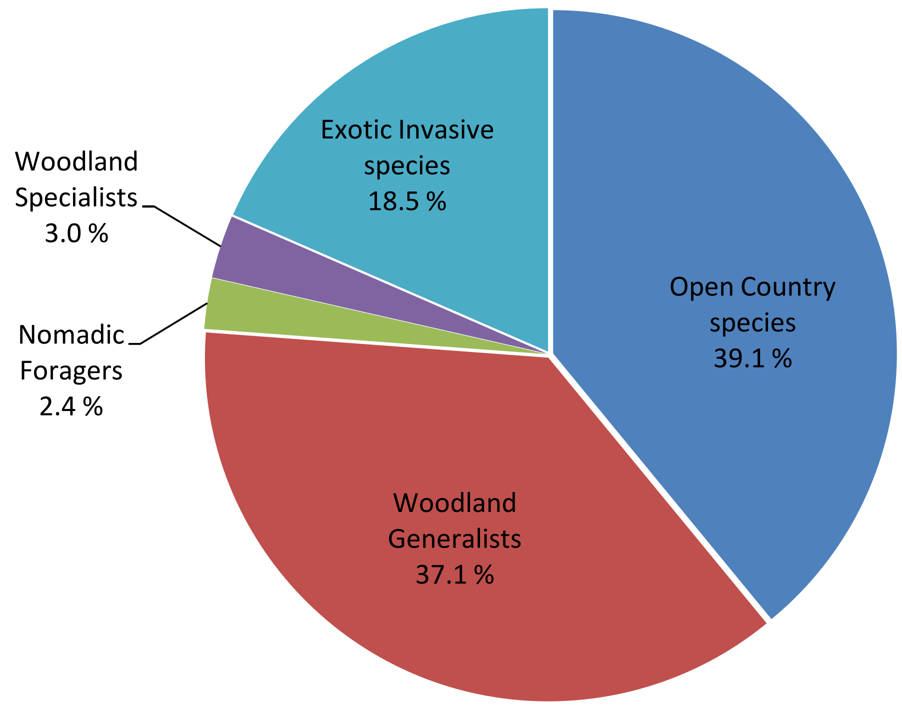

Figure 10. Species groups observed during tree watches (n = 6440 individuals).

2.4.2 ABUNDANCE ANALYSES

Woodland Specialists

The best model predicting abundance of woodland specialists at connectivity trees included all of the variables from the full model except for inter-patch distance. However, given the relative small number of observations of woodland specialists, this model was almost certainly overspecified. Residual plots suggested issues relating to the patch size variables in particular so we repeated model selection without any patch size variables. This indicated a best reliable model that included distance to the nearest patch, modelled connectivity, the interaction between those two variables, and inter-patch distance (Table 1). Woodland specialists were more abundant at trees that were both close to a patch AND predicted to be connected according to the Barrett & Love modelling (i.e., either one of these factors without the other did not lead to increased abundance of woodland specialists). They were also more abundant at trees between patches with shorter inter-patch distances.

Table 1. Best model (lowest AICc value) predicting abundance of woodland specialists.

Predictor	Coefficient	Standard Error	Z value	P value
Intercept	2.519602	0.538440	4.68	2.9e-06
NPD	-0.006755	0.002875	-2.35	0.0188
CONN(Y)	-0.975849	0.614710	-1.59	0.1124
IPD	-0.001376	0.000584	-2.35	0.0185
NPD*CONN(Y)	0.008943	0.003026	2.96	0.0031

Nomadic Foragers

The best model predicting abundance of nomadic foragers at connectivity trees included inter-patch distance, modelled connectivity and an interaction between them (Table 2). If trees were located in an area that was predicted to lack connectivity then the abundance of nomadic forages was significantly higher between patches with shorter inter-patch distances. However in trees located between patches that were predicted to be connected, then the distance between them had no effect on the abundance of nomadic foragers.

Table 2. Best model (lowest AICc value) predicting abundance of nomadic foragers.

Predictor	Coefficient	Standard Error	Z value	P value
Intercept	1.215624	0.354300	3.43	0.0006
IPD	-0.000871	0.000351	-2.48	0.0131
CONN(Y)	-0.805269	0.508760	-1.58	0.1135
IPD*CONN(Y)	0.001139	0.000409	2.79	0.0053

Woodland Generalists

The best model predicting abundance of woodland generalists at connectivity trees included inter-patch distance and modelled connectivity, as well as time of day (Table 3). Woodland generalists were more abundant where trees were predicted to be functionally connected and where watches were conducted in the early morning. They also tended to be more abundant where inter-patch distances were shorter. Unlike the other woodland-dependant species (woodland specialists and nomadic foragers), there was no apparent interaction between the effects of modelled connectivity and distance on the abundance of woodland generalists.

Table 3. Best model (lowest AICc value) predicting abundance of woodland generalists.

Predictor	Coefficient	Standard Error	Z value	P value
Intercept	1.762644	0.242540	7.27	3.7e-13
TIME(L)	-0.296131	0.105530	-2.81	0.00501
IPD	-0.000233	0.000141	-1.66	0.09706
CONN(Y)	0.542945	0.155550	3.49	0.00048

Open Country Species

The best model predicting abundance of open country species at connectivity trees included time of survey, modelled connectivity, sizes of patches being connected, and interactions among these landscape structure variables (Table 4). This model possibly may suffer from some of the same issues experienced with the woodland specialists model (see above), however sample sizes for observations of open country species were much higher. Open country species were certainly more abundant when watches were conducted in the early morning. In terms of the landscape structure variables, the model suggests that they were most abundant at trees in areas with large patches (near or far) or with predicted connectivity. The significant positive three-way interaction between near patch size, far patch size and connectivity would indicate that abundance of open country species may be highest in areas between two patches that are both large and connected. However, visual examination of the data suggests that abundances may actually be highest in areas with intermediate-sized patches (which would have required a quadratic or higher order term to detect statistically).

Table 4. Best model (lowest AICc value) predicting abundance of open country species.

Predictor	Coefficient	Standard Error	Z value	P value
Intercept	-1.862	1.399	-1.33	0.18322
TIME(L)	-0.373	0.102	-3.64	0.00027
logNPS	1.671	1.203	1.39	0.16482
logFPS	2.574	1.302	1.98	0.04804
CONN(Y)	4.488	1.479	3.03	0.00241
logNPS*logFPS	-1.083	1.059	-1.02	0.30678
logNPS*CONN(Y)	-2.578	1.265	-2.04	0.04160
logFPS*CONN(Y)	-3.233	1.352	-2.39	0.01681
logNPS*logFPS*CONN(Y)	1.788	1.097	1.63	0.10291

Exotic Invasive Species

The best model predicting abundance of exotic invasive species at connectivity trees included date of watch, the size of the farther of the two patches being connected, and the inter-patch distance (Table 5). Exotic invasive species were more abundant when watches were conducted earlier in the season, where the far patch was larger, and where inter-patch distance was greater.

Table 5. Best model (lowest AICc value) predicting abundance of exotic invasive species.

Predictor	Coefficient	Standard Error	Z value	P value
Intercept	-1.261231	0.850040	-1.48	0.1379
DATE	-0.025685	0.007884	-3.26	0.0011
logFPS	1.189296	0.480830	2.47	0.0134
IPD	0.000980	0.000331	2.96	0.0031

2.4.3 DIRECTIONAL MOVEMENT ANALYSES

Woodland Specialists

The best model for predicting the direction of flights by woodland specialists included only the gap distance to the nearest tree and the gap distance squared. An alternative model with almost as much statistical support also included weak effect of patch presence and the interaction between patch presence and gap distance and we present this model below as the effects of the gap distance variables were nearly identical (Table 6). The combined effects of the gap distance and squared gap distance indicates that woodland specialists were most often observed flying across intermediate sized gaps. They were also more likely to fly in the direction of a patch and across somewhat longer gaps if those gaps were in the directions of a patch.

Table 6. Best model (lowest AICc value) predicting flight direction of woodland specialists.

Predictor	Coefficient	Standard Error	Z value	P value
Intercept	-14.52	3.92	-3.71	0.00021
PP(Y)	2.41	1.70	1.42	0.15597
logGAP	16.09	4.46	3.61	0.00030
logGAP^2	-5.16	1.27	-4.06	5e-05
logGAP*PP(Y)	-1.27	1.00	-1.26	0.20668

Nomadic Foragers

The best model for predicting the direction of flights by nomadic foragers included distance to the nearest patch, gap distance to the nearest tree, and the interaction of these two variables (Table 7). The positive coefficient values of the linear affects and the negative coefficient value of the interaction term indicate that nomadic foragers made the most flights towards intermediate-sized gaps (~30-180m) and towards patches at intermediate distances (~250-600m, equivalent of up to 1.2km inter-patch distance). They made few flights across very short gap distances or towards very near patches and the fewest flights in directions where both the distance to the nearest tree and the nearest patch were large.

Table 7. Best model (lowest AICc value) predicting flight direction of nomadic foragers.

Predictor	Coefficient	Standard Error	Z value	P value
Intercept	-6.320	2.825	-2.24	0.025
logPD	1.678	0.860	1.95	0.051
logGAP	2.534	1.479	1.71	0.087
logPD*logGAP	-0.989	0.458	-2.16	0.031

Woodland Generalists

The best model for predicting the direction of flights by woodland generalists included distance to the nearest patch, distance to the nearest tree, the interaction of these two variables, and the squared gap distance (Table 8). As with the model for nomadic foragers, the positive coefficient values for the linear affects and the negative coefficient values for the interaction and quadratic terms indicate that woodland generalists tended to fly most often towards intermediate-sized gaps and/or patches at intermediate distances. They also made few flights across very short gap distances or towards very near patches and the fewest flights of all in directions where both the distance to the nearest tree and the nearest patch were large.

Table 8. Best model (lowest AICc value) predicting flight direction of woodland generalists.

Predictor	Coefficient	Standard Error	Z value	P value
Intercept	-4.169	1.135	-3.67	0.00024
logPD	0.824	0.292	2.82	0.00477
logGAP	1.975	0.909	2.17	0.02975
logGAP^2	-0.339	0.214	-1.58	0.11380
logPD*logGAP	-0.492	0.160	-3.09	0.00203

Open Country Species

The best model for predicting the direction of flights by open country species included only distance to the nearest tree (Table 9). More flights by open country species were observed in directions with shorter gap distances.

Table 9. Best model (lowest AICc value) predicting flight direction of open country species.

Predictor	Coefficient	Standard Error	Z value	P value
Intercept	-1.321	0.203	-6.51	7.3e-11
logGAP	-0.371	0.103	-3.62	3e-04

Exotic Invasive Species

The best model for predicting the direction of flights by exotic invasive species included patch presence, patch size, patch distance, gap distance and squared gap distance, but no interaction terms (Table 10). As in previous models containing both linear and quadratic gap-distance terms, this suggests that exotic invasive species preferred to fly in directions where the nearest tree was at some intermediate distance, neither too far nor too close. These species preferred to fly towards patches, but particularly towards smaller and/or more distant patches.

Table 10. Best model (lowest AICc value) predicting flight direction of exotic invasive species.

Predictor	Coefficient	Standard Error	Z value	P value
Intercept	-6.358	1.868	-3.40	0.00066
PP(Y)	0.801	0.349	2.30	0.02157
logPS	-0.275	0.143	-1.93	0.05372
logPD	0.558	0.217	2.57	0.01003
logGAP	2.613	1.730	1.51	0.13087
logGAP^2	-0.727	0.435	-1.67	0.09500

2.4.4 EVALUATING THE CSIRO FUNCTIONAL CONNECTIVITY MODEL (THE 100M/1.1KM/10HA RULE)

The above model results tell us which factors helped predict abundance or number of flights in different directions for each species group, but they don't directly analyse the thresholds implied by The 100m/1.1km/10ha Rule. To evaluate those, we constructed a series of figures to examine the shape of the relationships where these factors were part of final models. The most relevant set is shown here, but the Discussion (sections 4.3 to 4.5 below) integrates these with the radio tracking results to provide full interpretations in terms of The 100m/1.1km/10ha Rule.

Figure 11 suggests that woodland specialists depended on both gap distances and inter-patch distances. Individuals of these species were never found >180m away from woodland or forest patches where scattered trees were too limited to provide connectivity according to the Barrett and Love spatial tool (see orange line). However, they were found up to 550m away from patches (equivalent of an inter-patch distance of 1.1km) and occasionally a bit further where scattered trees were sufficiently spaced to provide connectivity according to the Barrett and Love spatial tool (see red line).

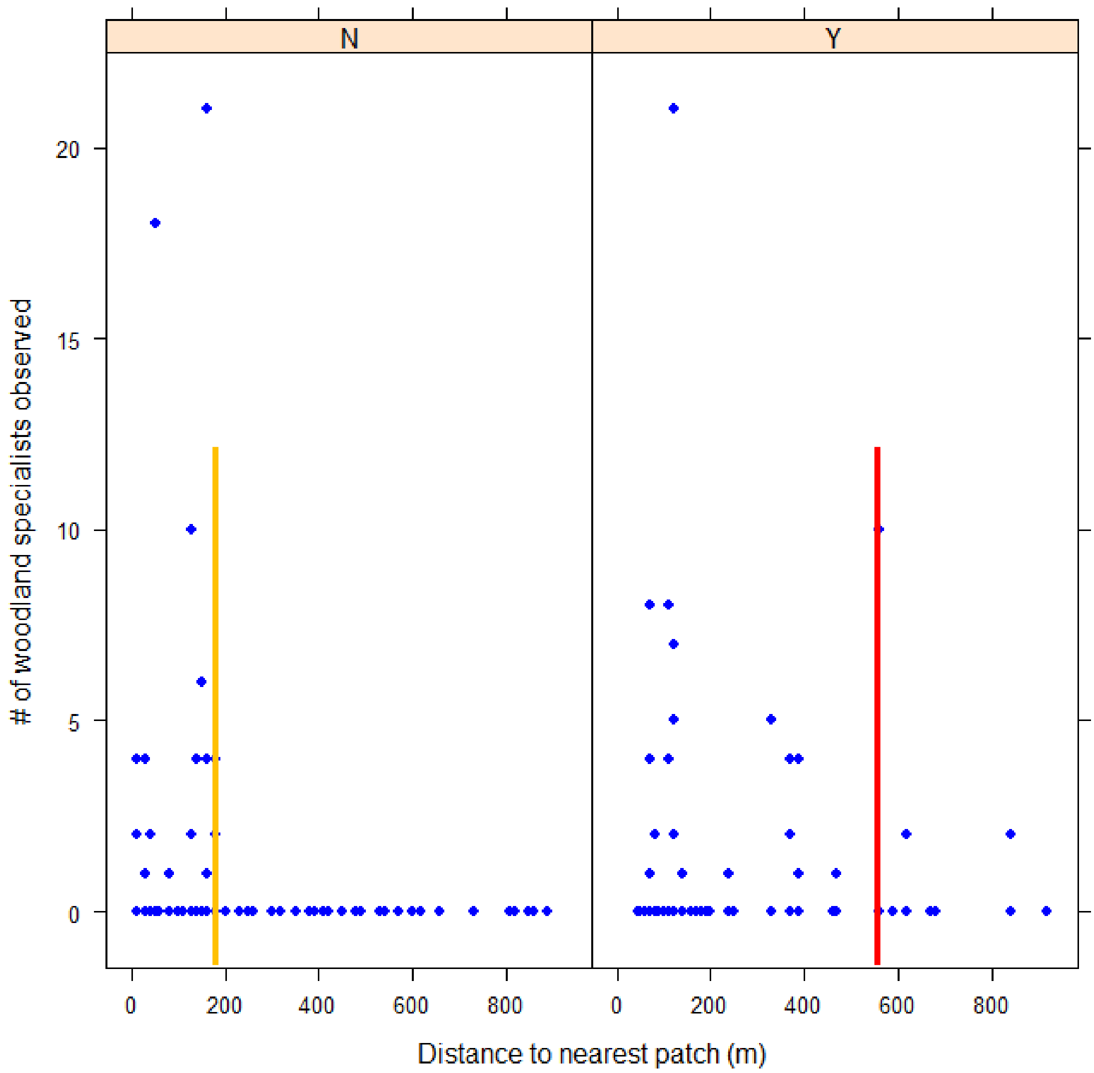

Figure 11. Abundance of woodland specialists as a function of both the distance to the nearest patch (x-axis) and whether the Barrett & Love spatial tool predicted the area was a functional connection based on gap distances or not (N/Y columns as labelled at the top). Abundances of zero represent the distances to the nearest patches around connectivity trees at which these species were not observed.

Examining the same interaction for nomadic foragers, Figure 12 shows that they were rarely found >500m away from woodland or forest patches (equivalent of a 1.0km inter-patch distance) where scattered trees were too limited to provide connectivity according to the Barrett and Love spatial tool (see orange line). However, where scattered trees were sufficiently spaced in the inter-patch area to provide connectivity according to the Barrett and Love spatial tool, these species could be observed at any distance to the nearest patch (up to the equivalent of a 2.0km inter-patch distance).

A similar but weaker pattern was observed for woodland generalists (Figure 13), though these species were regularly observed up to about 600m away from woodland or forest patches (equivalent of a 1.2km inter-patch distance) where scattered trees were too limited to provide connectivity according to the Barrett and Love spatial tool (see orange line). Where scattered trees were sufficiently spaced in the inter-patch area to provide connectivity according to the Barrett and Love spatial tool, these species could be observed at any distance to the nearest patch (up to the equivalent of a 2.0km inter-patch distance).

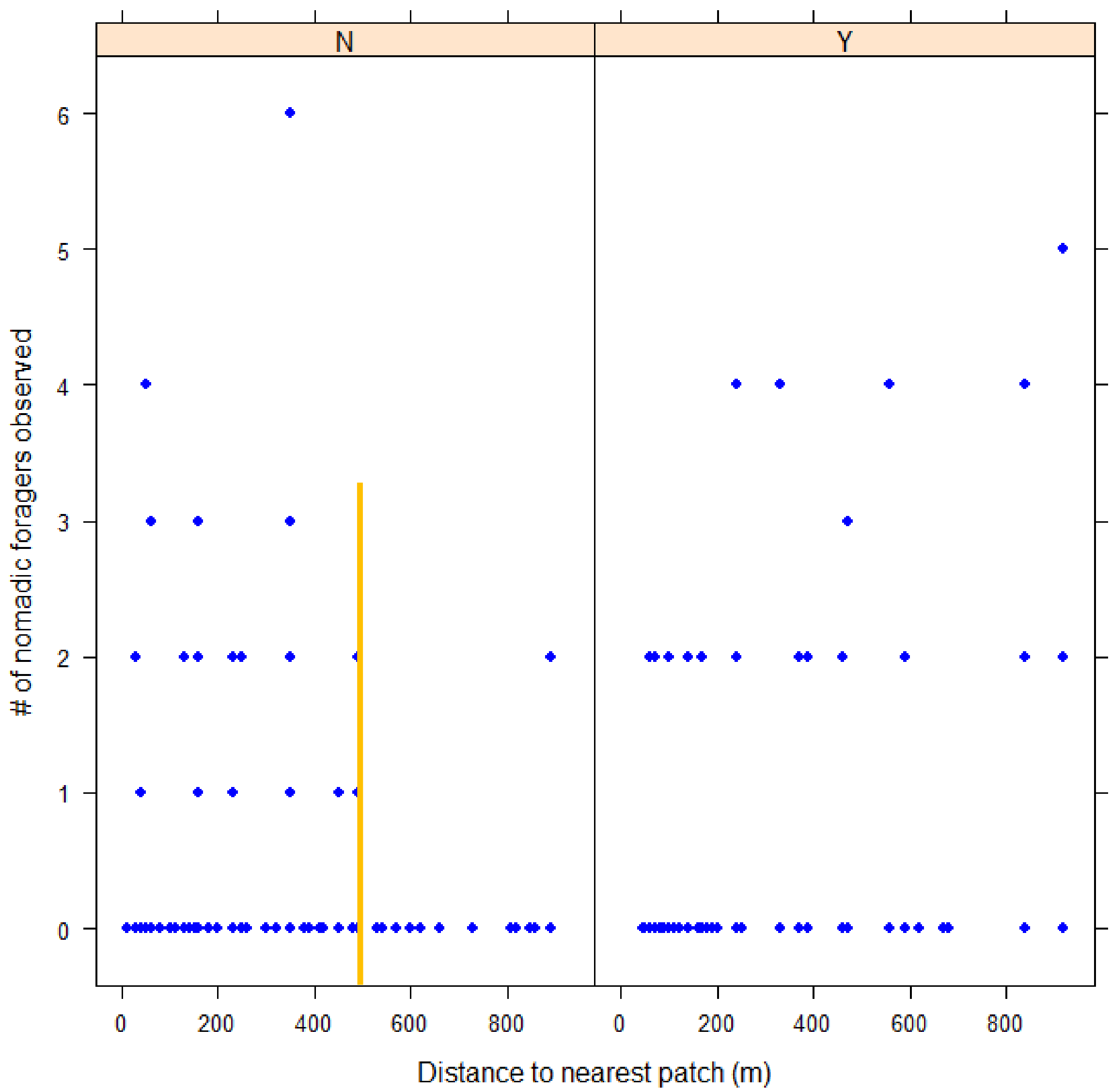

Figure 12. Abundance of nomadic foragers as a function of both the distance to the nearest patch (x-axis) and whether the Barrett & Love spatial tool predicted the area was a functional connection based on gap distances or not (N/Y columns as labelled at the top). Abundances of zero represent the distances to the nearest patches around connectivity trees at which these species were not observed.

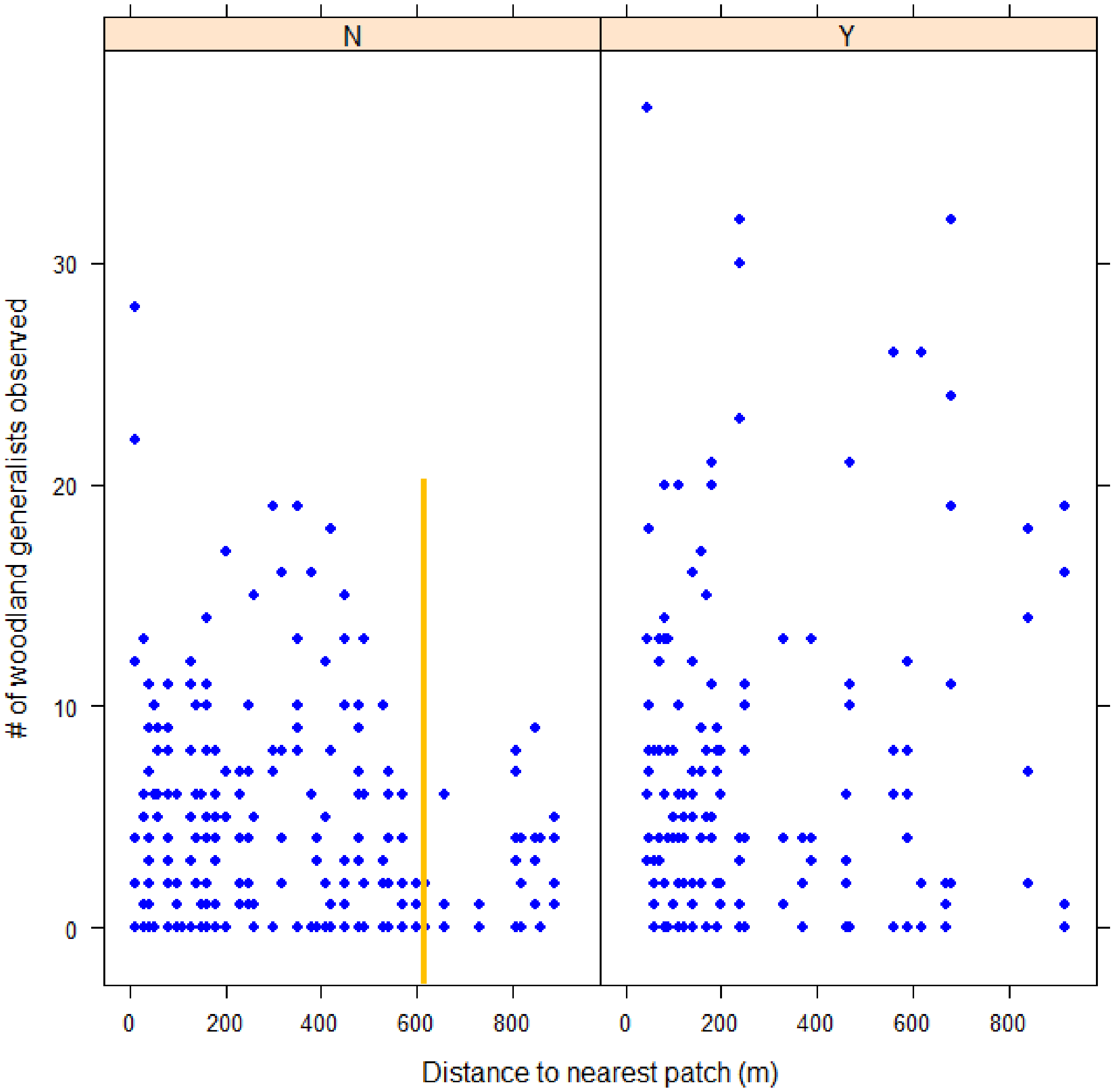

Figure 13. Abundance of woodland generalists as a function of both the distance to the nearest patch (x-axis) and whether the Barrett & Love spatial tool predicted the area was a functional connection based on gap distances or not (N/Y columns as labelled at the top). Abundances of zero represent the distances to the nearest patches around connectivity trees at which these species were not observed.

No patterns were seen for the open country species, but for the exotic invasive species, abundance was actually higher overall where there were insufficient scattered trees to provide connectivity according to the Barrett and Love spatial tool (Figure 14). Where connectivity was predicted to occur based on gap distances, abundances were lower at smaller distances from the nearest patch, only rising to high levels where patches were >650m away (equivalent of 1.3km inter-patch distance – see green line in figure).

While sample sizes for some of these combinations of distances and predicted connectivity are low, these results collectively suggest that woodland specialists may require both connectivity in terms of limited gap distances and inter-patch distances <1.1km to bring them out into the broader landscape. However, if sufficient scattered trees are present in inter-patch areas, nomadic foragers and woodland generalists may tolerate inter-patch distances up to at least 2.0km. However, providing both sufficient scattered trees and shorter inter-patch distances (<1.3km) could also reduce abundance of exotic invasive species.

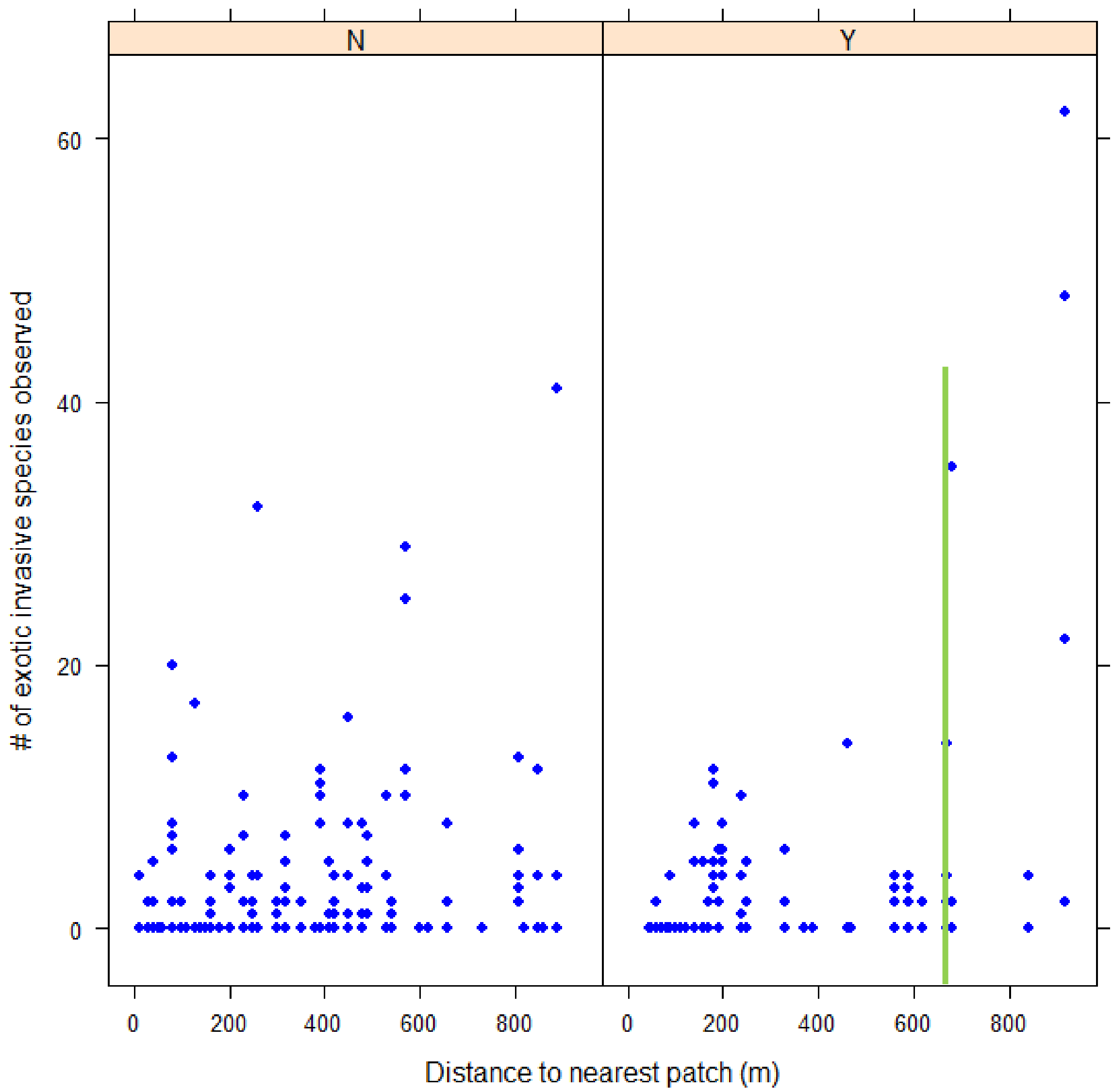

Figure 14. Abundance of exotic invasive species as a function of both the distance to the nearest patch (x-axis) and whether the Barrett & Love spatial tool predicted the area was a functional connection based on gap distances or not (N/Y columns as labelled at the top). Abundances of zero represent the distances to the nearest patches around connectivity trees at which these species were not observed.

Similarly, a set of figures from the analyses of movements in different directions highlights some potential thresholds in terms of gap distances between scattered trees as measured from aerial imagery, not just as modelled by Barrett and Love. Woodland specialists almost never moved into or out of connectivity trees in directions where gaps were >150m (Figure 15, see red line). Only one movement was recorded where the gap distance was greater, just over 200m.

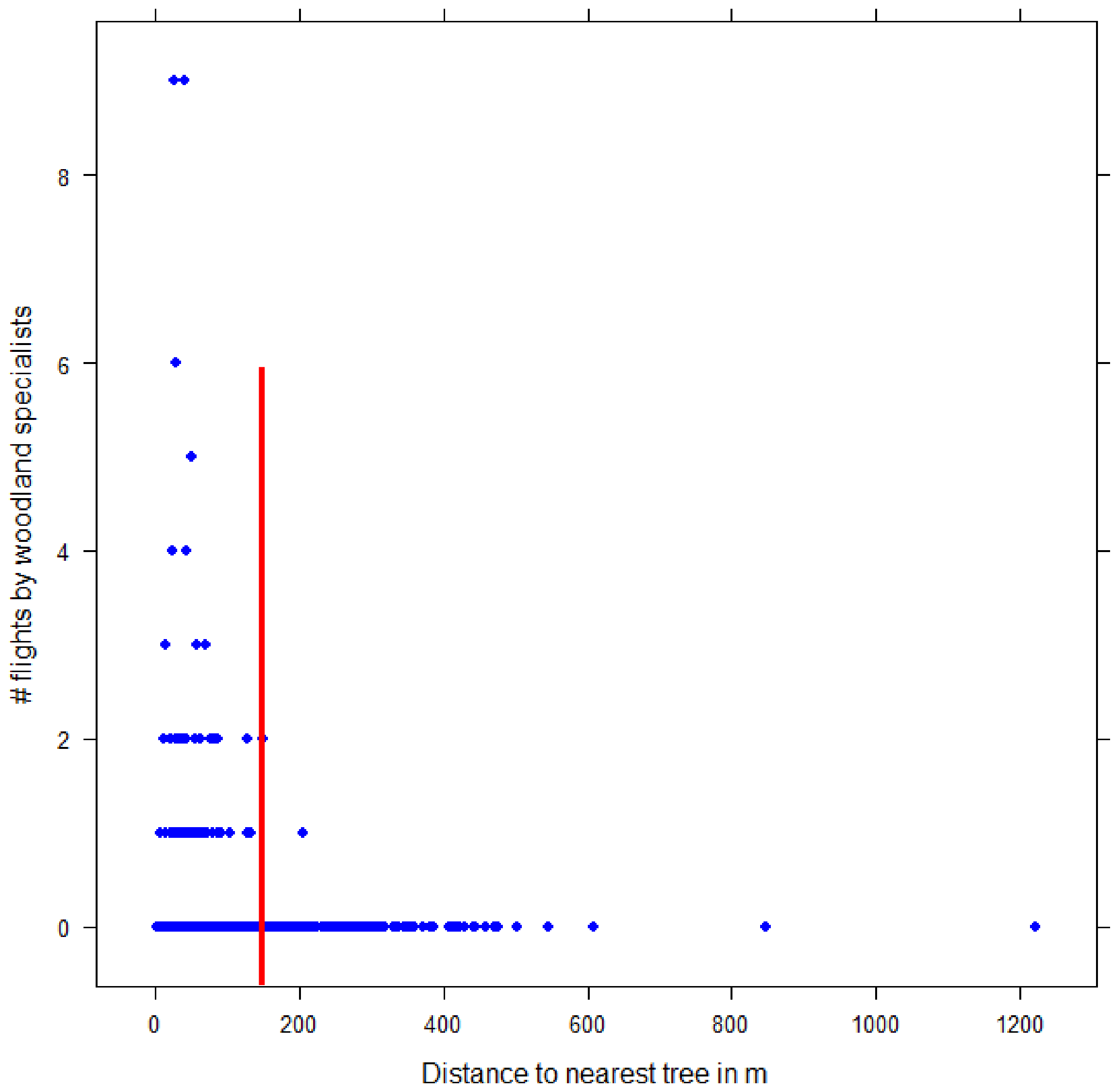

Figure 15. The number of flights made into or out of connectivity trees by woodland specialists as a function of the gap distance to the nearest tree in that direction. Records for zero flights indicate gap distances available but not crossed (i.e. other gap distances around connectivity trees where these species were observed).

A similar pattern but different threshold was observed for nomadic foragers, who almost never moved into or out of connectivity trees in directions where gaps were >400m (Figure 16, see red line). Only three movements were recorded where the gap distance was greater, ~550m. The pattern was present but not quite as strong for woodland generalists, who rarely moved into or out of connectivity trees in directions were gaps were >400m (see red line), and who almost never did this where gaps were >500m (Figure 17). Interestingly, woodland generalists were also markedly more abundant where gaps were <200m (see dashed red line). Finally, both open country species (Figure 18) and exotic invasive species (Figure 19) commonly moved where gap distances were 0-500m, but they more commonly made flights where there were larger gaps within this range than the other species groups. The apparent threshold for these groups at ~500m may thus be more indicative of available gaps in the landscape than a reluctance to cross larger gaps, particularly as there was a very small sample size of larger gaps in the landscape not used (i.e. only five zero values for larger gap distances).

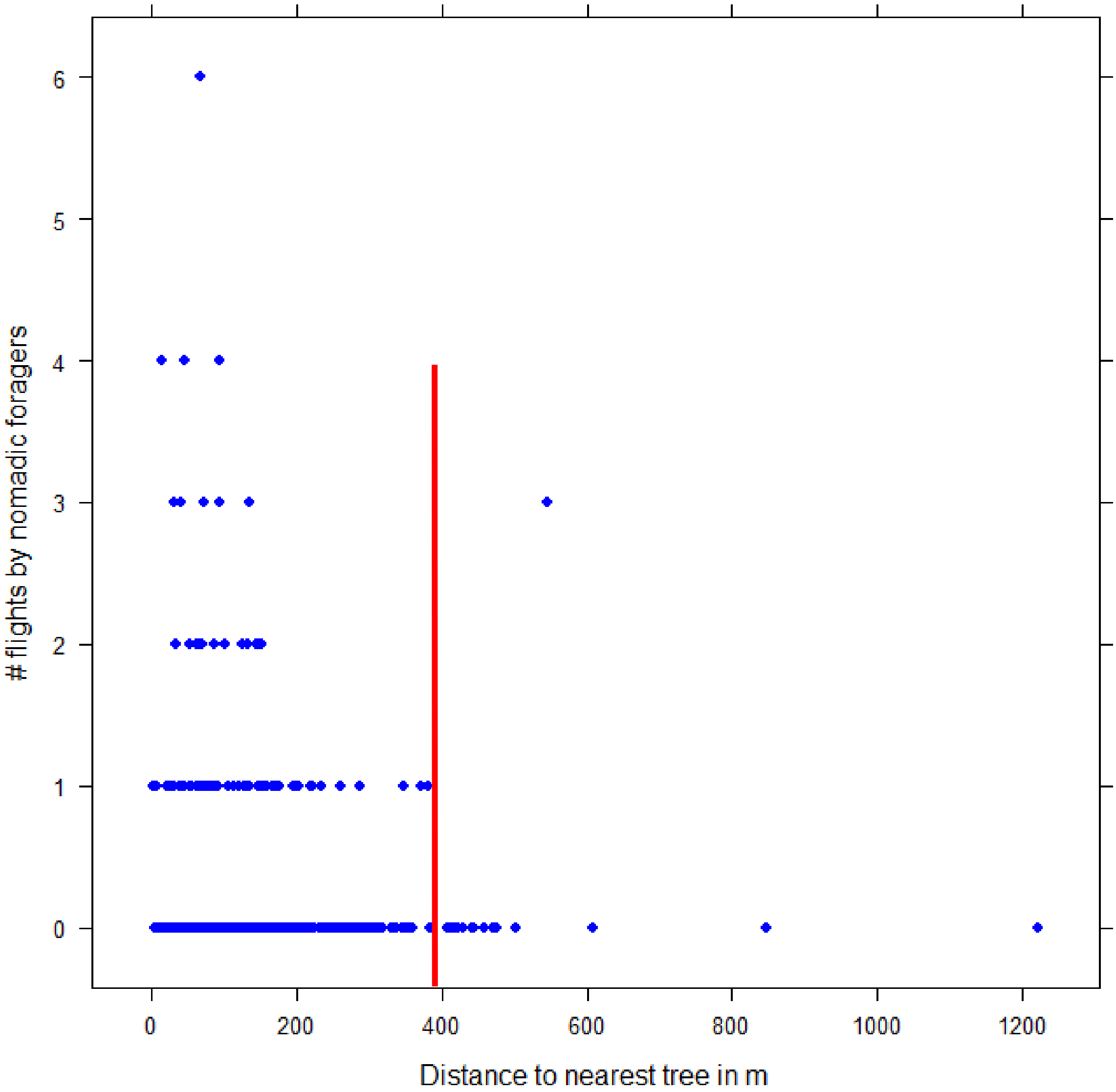

Figure 16. The number of flights made into or out of connectivity trees by nomadic foragers as a function of the gap distance to the nearest tree in that direction. Records for zero flights indicate gap distances available but not crossed (i.e. other gap distances around connectivity trees where these species were observed).

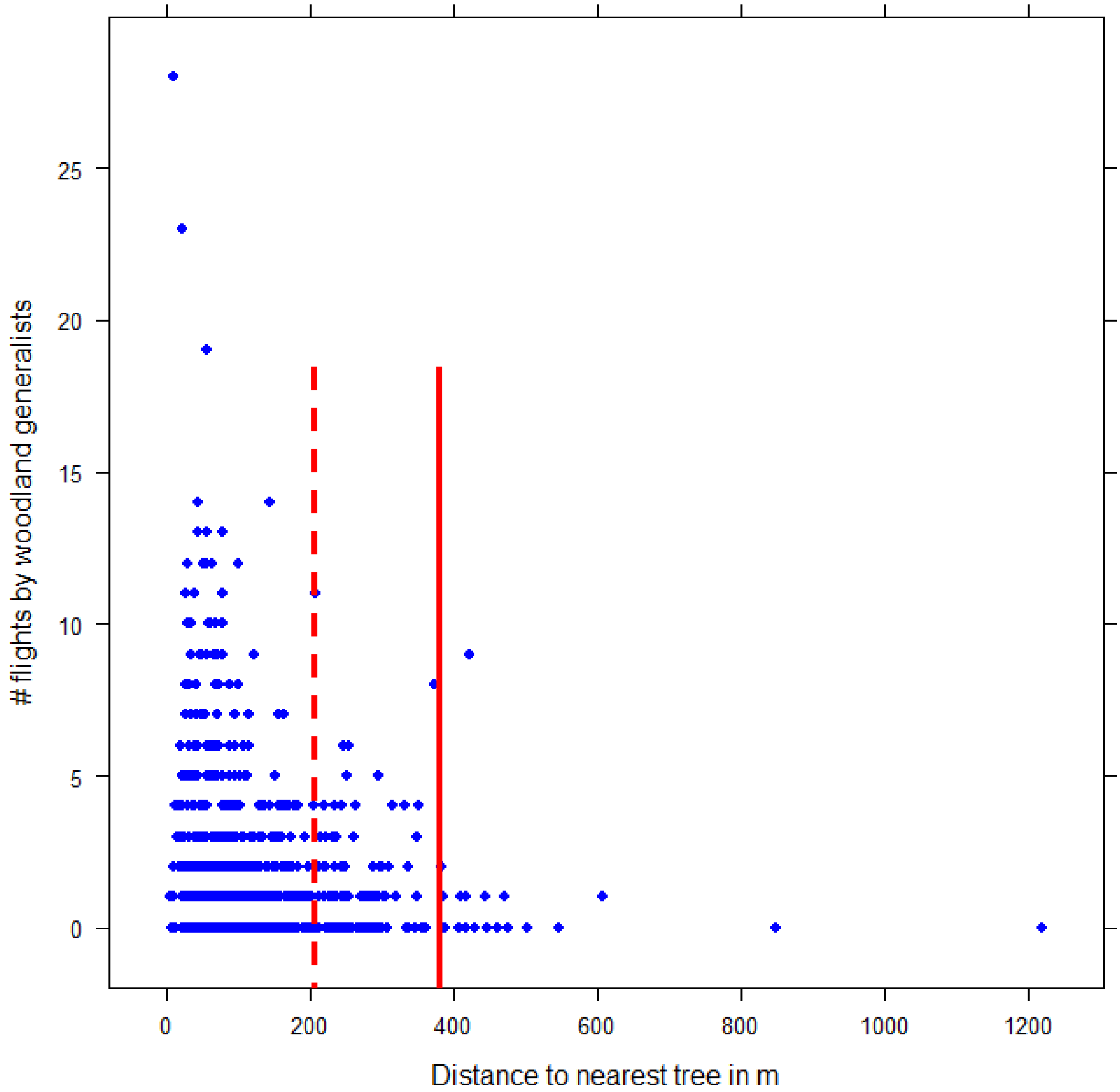

Figure 17. The number of flights made into or out of connectivity trees by woodland generalists as a function of the gap distance to the nearest tree in that direction. Records for zero flights indicate gap distances available but not crossed (i.e. other gap distances around connectivity trees where these species were observed).

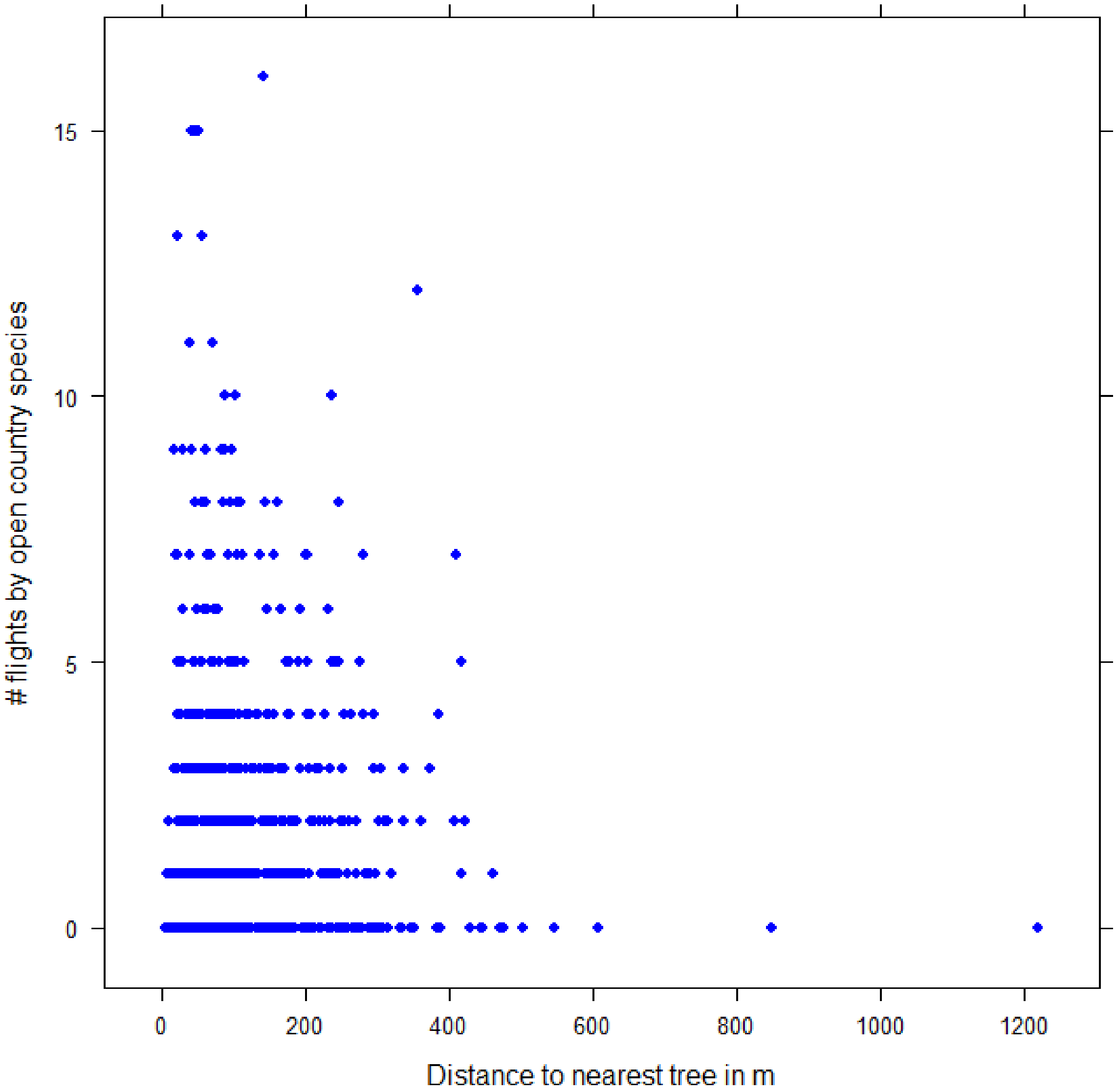

Figure 18. The number of flights made into or out of connectivity trees by open country species as a function of the gap distance to the nearest tree in that direction. Records for zero flights indicate gap distances available but not crossed (i.e. other gap distances around connectivity trees where these species were observed).

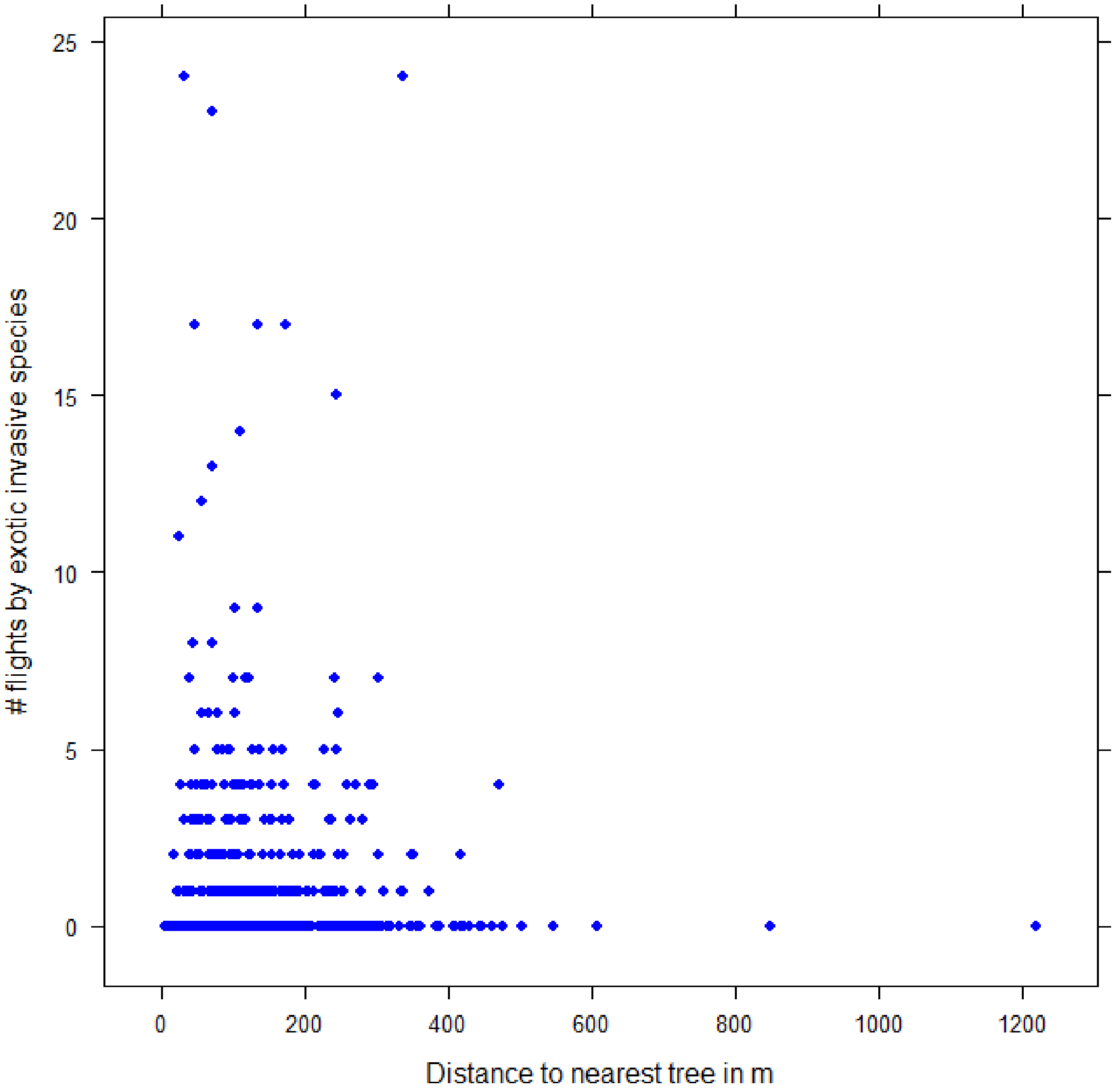

Figure 19. The number of flights made into or out of connectivity trees by exotic invasive species as a function of the gap distance to the nearest tree in that direction. Records for zero flights indicate gap distances available but not crossed (i.e. other gap distances around connectivity trees where these species were observed).

3 Radiotelemetry

3.1 Tracking Sites

The purpose of the radiotelemetry component of the study was to provide a very small sample size of tracked birds that had the potential to qualitatively confirm the results of the connectivity tree watches. If such confirmation could be achieved, it would strengthen our confidence that connectivity tree watches (still a novel approach) provide a reasonable indicator of actual movements through scattered trees and between patches. Thus, it was critical that radio-tracking efforts be focused in an area where a number of different inter-patch areas were simultaneously being studied using the connectivity tree watches.

Furthermore, to concentrate effort of trackers on the ground, it was important to select a central patch where birds that could potentially move through the wider landscape could be captured and fitted with radio transmitters, with a variety of inter-patch distances and scattered tree densities surrounding that core patch and in the broader landscape. We initially selected four potential areas within the regions where tree watches were being conducted, then ranked them according to the criteria above as well as ease of access, health and safety issues, etc. The result was that we selected Kama Nature Reserve as our core patch for attaching radio transmitters, and thus the landscape surrounding Kama as our study site for tracking landscape movements.

3.2 Tracking Data Collection

Kama Nature Reserve was systematically explored beginning in late October 2012 to identify candidate individuals for radio tracking – birds that might need to move outside Kama Nature Reserve itself for various purposes. Candidates included juveniles of resident species who might need to move outside Kama to disperse, adults of semi-nomadic foragers who might need to move outside Kama to find food sources, and adults of woodland generalist species who might simply utilise scattered trees in the wider landscape as part of their home ranges.

Once candidates were identified, we used targeted mist-netting to capture specific candidate individuals along flight paths they were observed using. The birds were banded with a numbered aluminium band and two plastic colour bands for individual identification by sight, then fitted with either 0.67g or 0.92g radio transmitters (model BD-2, Holohil Systems Ltd., Ontario, Canada). Transmitters were attached using a leg harness made of dissolving suture which was designed to drop off the bird after three or more months. Transmitter weight was chosen such that the transmitter weighed no more than 4% of the bird's body weight. Individuals were also marked with one aluminium leg band and two coloured plastic leg bands in unique combinations for individual identification by sight.

Birds were then tracked using a protocol similar to one that has been used successfully in the past to track dispersal movements and semi-nomadic foraging movements of Australian woodland birds (Doerr *et al.* 2011b). We tracked individuals until we could visually sight them and record their locations and behaviour. Each bird was located two or three times per day, between 7:30am and approximately 2pm – the hours when the vast majority of landscape movements occurred in previous studies (Doerr and Doerr 2005; 2007; Doerr *et al.* 2011b). However, we also checked the general direction and strength of each bird's signal more frequently than that, which allowed us to be opportunistic and locate individuals that were not in their normal core areas. As a result, we were able to record additional locations when an individual was in a new or unexpected place in the landscape to gain a more detailed understanding of actual flight paths. Radio transmitters were attached in mid-November 2012 and birds were tracked every day through mid-December 2012.

3.3 Tracking Summary Statistics

The radiotelemetry was intended to be a small, supplementary component of the study as available resources meant there would be too few individuals tracked to provide sufficient data for formal statistical analysis. However, the intent was to calculate summary statistics that could be compared with results from the connectivity tree watch analyses. Thus, where birds moved outside of Kama Nature Reserve, we estimated both the inter-patch distances they crossed as well as the gap distances between scattered trees along their known or likely flight paths. We also noted gap distances in areas where birds were loitering at the patch edge and were motivated to leave the patch but failed to do so.

3.4 Tracking Results

3.4.1 BIRDS TRACKED

Nine birds were fitted with radio transmitters in Kama Nature Reserve (Figure 20):

- One juvenile rufous whistler (*Pachycephala rufiventris*), likely a female – a potential disperser of a woodland/forest specialist species
- One juvenile female white-throated treecreeper (*Cormobates leucophaea*) – a potential disperser of a woodland/forest specialist species
- Three white-plumed honeyeaters (*Lichenostomus penicillatus*) – semi-nomadic foragers
- Two black-faced cuckoo-shrikes (*Coracina novaehollandiae*) – woodland generalists
- Two noisy miners (*Manorina melanocephala*) – woodland generalists

A total of 433 locations were collected during radio tracking and eight of the nine birds were followed for the duration of the tracking period. The ninth bird, the juvenile rufous whistler, moved out of the study landscape (see below) and thus was only tracked for a short period.

Figure 20. Attaching a radio transmitter to a rufous whistler (left) and banding a black-faced cuckoo-shrike prior to radio transmitter attachment (right).

3.4.2 GENERAL MOVEMENT PATTERNS

Of the nine birds tracked, only two made movements outside Kama Nature Reserve – the juvenile rufous whistler and an adult female black-faced cuckoo-shrike. All other birds maintained discrete home ranges within the bounds of the reserve (see Appendix C for their location details).

On 17 November, the juvenile rufous whistler left Kama via the south-south-east corner and travelled south to the Molonglo River (Figure 21). From there, she spent two days apparently following the river west and north-west to its intersection with the Murrumbidgee River. She crossed the Murrumbidgee and spent six days in Woodstock Nature Reserve, seven kilometres away from Kama. On the seventh day, we could not detect her signal, suggesting either her radio transmitter battery was dead earlier than expected or she continued to move, probably many kilometres away given the prior detectability of her radio signal (i.e., she had been detectable at least 6km away from the highest points in the landscape).

On 21 November, a black-faced cuckoo-shrike also left Kama via the south-south-east corner to make a foray to the Molonglo River, returning to Kama within less than half an hour (Figure 22). This bird was probably a female based on the presence of a brood patch and subsequent incubating behaviour, though both sexes care for the young in this species. She forayed again to the Molonglo River on 22 November and 24 November following slightly different paths. Interestingly, she then began full-time incubation on a nest on 25 November. Given the timing of her forays to the river and the fact that other black-faced cuckoo-shrikes were observed at the river, at least once in an agitated state following her foray, it seems highly possible that these forays were for the purpose of obtaining extra-pair copulations prior to laying eggs (laying of eggs usually occurs every 1-2 days in Australian woodland birds).

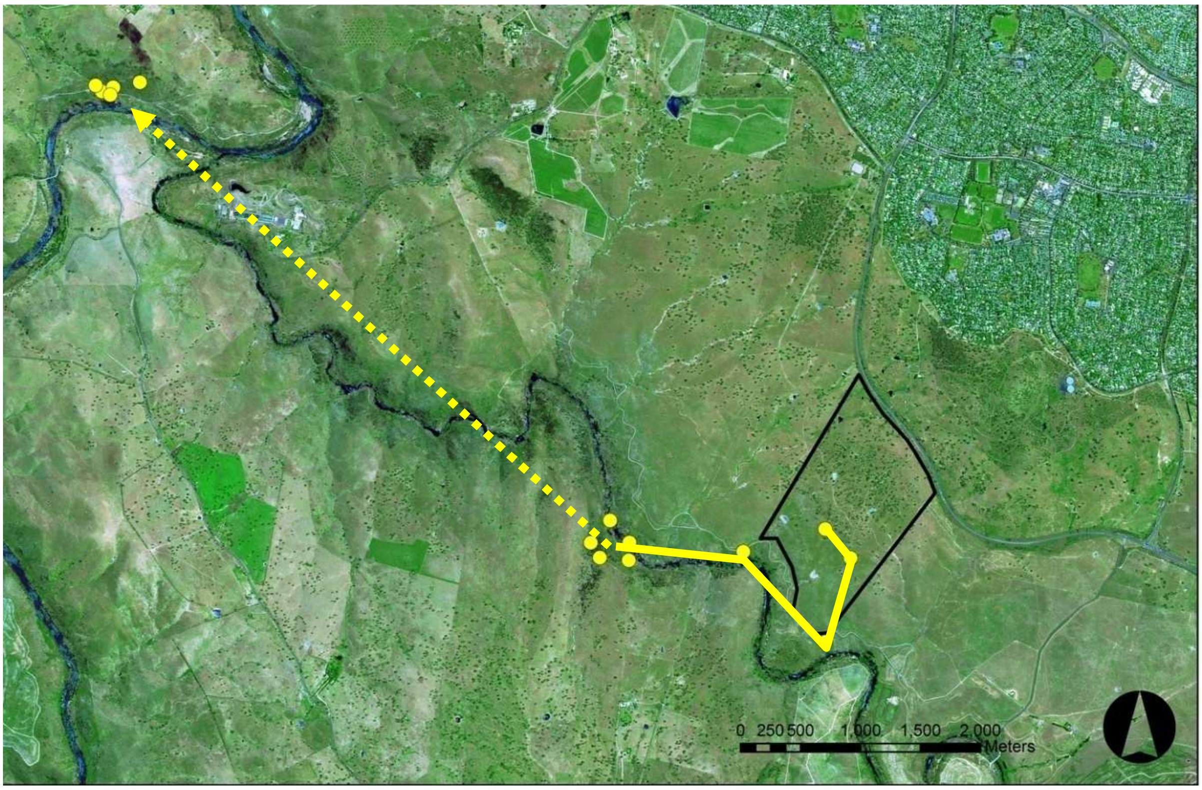

Figure 21. Radio locations of juvenile rufous whistler, with approximate movement path in yellow and boundary of Kama Nature Reserve in black. The solid yellow line is the more certain part of the path, while the dashed line was a very rapid movement over a long distance so we are less certain of the path (though it is reasonable to believe she followed the Molonglo River as all actual locations were in the riverside vegetation).

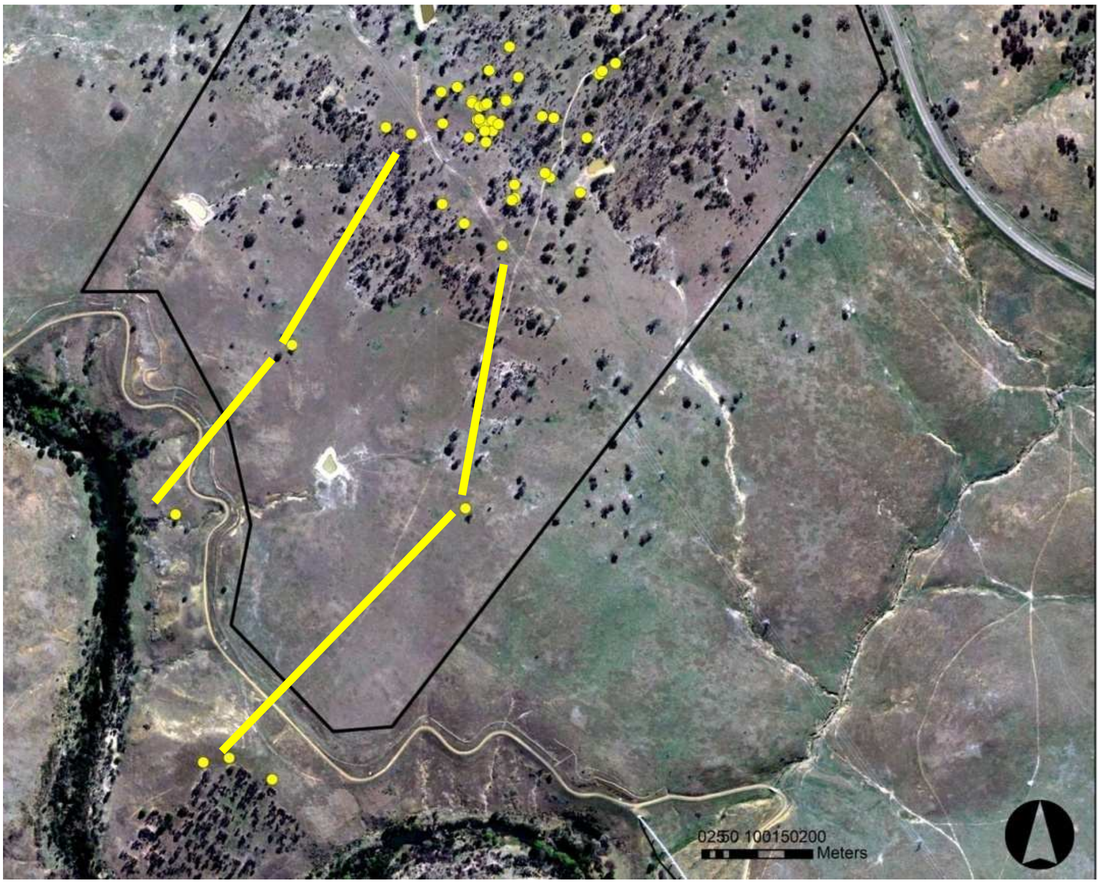

Figure 22. Radio locations of adult black-faced cuckoo-shrike, with approximate movement pathways for forays in yellow and boundary of Kama Nature Reserve in black.

3.4.3 MOVEMENTS RELATED TO GAP & INTER-PATCH DISTANCES AND PATCH SIZES

All movements that we observed into the wider landscape surrounding Kama Nature Reserve were to the south of the reserve, with birds moving through the inter-patch area between Kama and the Molonglo River. One and probably two of these movements occurred through inter-patch Ka1 and a third movement likely occurred through inter-patch Kb1 as well (Figure 23). Both of these inter-patch areas were included in the connectivity tree watch component of the study.

The inter-patch distances crossed varied from 540m to 950m depending on the direction and angle of the likely movement path – values under the recommended maximum inter-patch distance of 1.1km. Patch sizes on either end of the inter-patch area were both larger than the recommended minimum of 10ha. However, the gap distances crossed were much larger than the suggested maximum of 100m. The distance between scattered trees within likely crossing areas averaged 321m (±a standard deviation of 261m). Where known gaps were crossed (i.e. where the start and end points of flights were sufficiently known – for the black-faced cuckoo-shrike), these were as large as 602m and 756m.

It is also worth noting that the juvenile female white-throated treecreeper did in fact leave her natal territory and appear to attempt to disperse (as we would have expected her to at this time of year). But her natal territory was the only territory of white-throated treecreepers in Kama Nature Reserve, so the reserve did not contain any mates for her. After leaving her natal territory, she set up her own home range at the southern edge of Kama (Figure 24), where she encountered the same spacing of scattered trees that the whistler and the cuckoo-shrike moved through to get to the river. Yet she never left the patch to move into or through these scattered trees. This behaviour was surprising as females are the dispersive sex in this species and males establish the territories. However, such behaviour might be expected if the larger gaps between scattered trees were too large for this species and inhibited inter-patch movement.

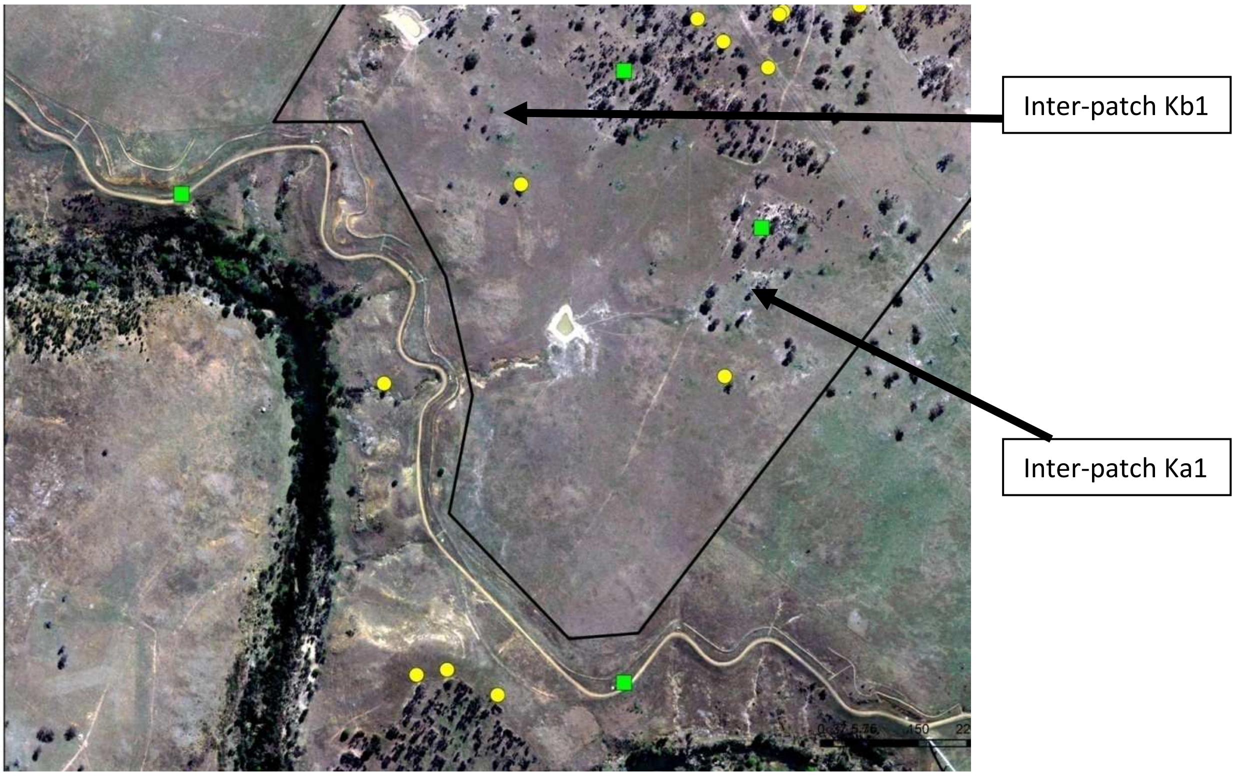

Figure 23. Locations where the juvenile rufous whistler (green squares) and the adult black-faced cuckoo-shrike (yellow circles) were found to the south of the Kama Nature Reserve woodland patch. All of these locations were part of movements to the Molonglo River.

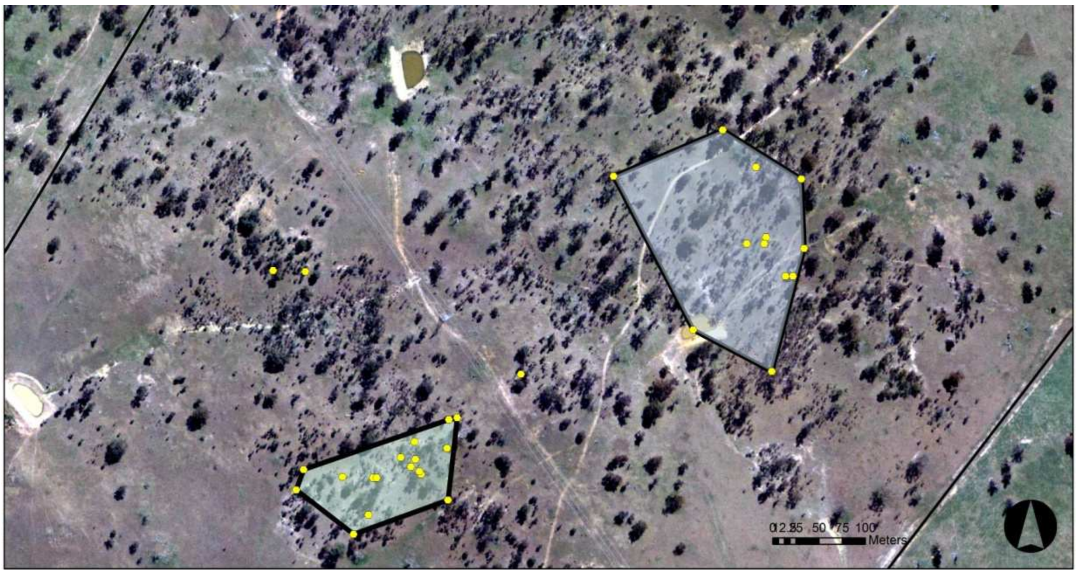

Figure 24. Two home ranges used by the juvenile female white-throated treecreeper – her natal territory shared with her parents and siblings (light blue shading on the right side of the figure), and the solo home range she established at the edge of the Kama Nature Reserve woodland patch (light green shading on the left side of the figure) which is unusual behaviour for this species.

4 Discussion of Tree Watches & Tracking Results

4.1 Overall Conclusions

Across all the final statistical models for the data from connectivity tree watches, we found that some measure of gap distances among scattered trees in inter-patch areas (either as measured by us or as modelled in the Barrett and Love spatial tool) was the factor that most consistently predicted abundance and number of movements at connectivity trees. Gap distance as measured by us was a factor that predicted number of movements in particular directions for all five of our species groups. For the abundance analyses where the unit of analysis was a tree rather than direction and thus multiple gap distances were associated with each unit of analysis, we used the Barrett and Love spatial tool to predict whether or not functional connections existed in the tree's inter-patch area, and that categorical variable was associated with abundance at each connectivity tree for all our species groups except exotic invasive species.

Some measure of distances between patches (either inter-patch distance, distance to near patch or distance to far patch) was also important in many of our models, often as an interaction with gap distances. For example, woodland specialists were more abundant where the Barrett and Love spatial tool predicted that functional connectivity existed, but only where the distance to the nearest patch was <550m (equivalent of 1.1km inter-patch distance; Figure 11). This is an important result because it suggests these two parameters work in concert and thus should be planned that way in landscape restoration initiatives.

Patch sizes were rarely an important factor in these models. This does not mean that patch size is unimportant for sustaining viable populations in fragmented landscapes, but rather that patch size may not have much influence on movement between patches – one component of viability. Instead, patch size may still be critically important (presumably along with condition) for providing habitat for species to live in, and thus a significant contributor to birth and death rates – other components of viability.

Interestingly, some aspects of landscape structure that were beneficial for native species were also associated with lower abundances or numbers of flights of exotic species. In particular, exotic invasive species were most abundant where inter-patch distances were larger than those preferred by woodland specialists (Figure 14 compared to Figure 11). This suggests we may be able to help minimise the influence of exotic species in our landscapes simply by managing landscape structure for natives.

The results also suggest that the landscape structure needs of woodland specialists, nomadic foragers, woodland generalists, and open country species are generally nested, in that order. For example, while gap distances were important to all these species groups, the majority of movements occurred where gap distances were <150m for woodland specialists (Figure 15), <400m for nomadic foragers (Figure 16), and <500m for woodland generalists (Figure 17). Open country species may still be limited to gaps <500m but were more likely to move where gaps were larger up to this potential threshold (Figure 18). Thus, by managing and restoring connections for woodland specialists, we should also be providing connections for nomadic foragers and habitat for woodland generalists and open country species. In fact, the woodland generalists were most abundant where gaps distances were <200m, very similar to the gap distances required by woodland specialists for movement. Thus, maintaining scattered trees at a certain density in the landscape could simultaneously improve prospects for the at-risk movement-limited species while helping to keep the common species common.

However, it is worth noting that the results from the connectivity tree watches did not entirely align with the results from the radiotracking component of the study. While the radiotracking data were very limited, the birds that were directly observed leaving Kama Nature Reserve definitely crossed gaps larger than would have been predicted from the tree watch results. This was particularly true for the juvenile rufous whistler, which was classified as a woodland specialist species and thus would have been predicted to cross gaps >150m only very rarely, let alone gaps >300m (the average distance between scattered trees in the area this bird used to move south to the river). Of course, the juvenile white-throated treecreeper was also classified as a woodland specialist species and had the opportunity to but did not cross these larger gaps. This partial incongruity in results may arise simply because the tracking data were so limited and we happened to observe relatively unusual events. But it may also arise because the radio tracked birds were known to be moving through the landscape, while observations during the tree watches included birds living there as well as moving through and we had no way to distinguish these two groups. Thus, the tree watch data may have mostly captured landscape structure requirements for species to live in, not move through (see 4.2 Limits to the Approach below). This is certainly true for the woodland generalists and open country species given the numbers observed in the scattered trees, but it may be that our observations of specialists in the tree watches were also resident individuals. Thus, it is possible that woodland specialists (and maybe nomadic foragers too) can cross larger gap distances during inter-patch movements than revealed by our connectivity tree watch data.

Two final conclusions worth mentioning relate to the methods we used. First, the analyses of movements in different directions produced broadly similar results to the analyses of abundance. This suggests that abundance could be successfully used for longer-term monitoring, where simpler methods will be easier to apply consistently over time using different observers. Second, the analyses (of movement in different directions in particular) yielded far richer results and conclusions than we anticipated. While it is still unclear how much this approach was able to capture actual dispersal movements of woodland specialists (one of the primary goals), it gave very rich information about how different species groups use variegation in our landscapes, particularly highlighting potential thresholds in gap distances (and thus tree densities) that could help identify where scattered trees are currently providing the most important range of functions in our landscapes. Thus, while the analyses in particular were complex, the approach was an extremely worthwhile one.

4.2 Limits to the Approach

As noted briefly above, observations at connectivity trees could not distinguish between individuals resident in and around the trees versus those purely using the trees for inter-patch movements. We had hoped that by conducting a relatively large number of hours of observation within each inter-patch area (7.5 hours), we would have a reasonable chance of observing some true inter-patch movements. We also assumed that woodland specialists (and nomadic foragers to a lesser extent) would be unlikely to be living in these inter-patch areas and thus observations of these species groups would mostly constitute inter-patch movements and would be much rarer than observations of the other species groups. Indeed, woodland specialists and nomadic foragers were rarely observed compared to the other species groups. However, the nature of some of the results suggests that we were still possibly observing resident rather than transient individuals much of the time. For example, woodland specialists were more abundant where the Barrett and Love spatial tool predicted that functional connectivity existed, but only where a patch was also close by (Figure 11). These individuals may have been practicing ‘habitat supplementation’, using moderately dense areas of scattered trees at the edges of patches to augment habitat within the patch, rather than actually using the scattered trees to move to another patch.

As a result, many of our conclusions may actually predict the landscape structure that species groups require for living in a part of the landscape, rather than just moving through it. We anticipated this would be true for woodland generalists and open country species, but it may also be true for the woodland specialists, which is also the species group that appeared to have the most stringent landscape requirements (e.g., shortest gap distances). Thus, our results could suggest overly conservative approaches to the restoration and management of landscape structure.

An additional limit to the approach used in this study involves the number of different aspects of landscape structure we needed to examine and the challenges in that case of trying to create a balanced research design. Despite our attempts to identify study sites with variation in gap distances, inter-patch distances and patch sizes, we could not identify sites with all possible combinations of those variables. The problem is both that an extremely large sample size would be needed to do that and that some of these variables tend to be naturally correlated. So in this case, larger patches tended to be in areas that were more connected. It is possible that the limited number of sites with large patches that weren't connected limited our ability to detect patch size effects.

4.3 Adjustments to the 100m Gap Rule

Based on the above results and conclusions, we could recommend the following change to the 100m Gap Rule:

Gaps within a connection (i.e., between scattered trees or breaking up a linear link) should be no more than **150m** but many should still be shorter (Figure 15). However, if the targets of management are nomadic foragers and/or more common and generalist species (rather than the strict woodland specialists), then gaps could be up to 400m (Figure 16 and Figure 17).

It is also possible that even a 150m Gap Rule is conservative, based on habitat residency rather than movement requirements. However, the previous 100m Rule was based in part on research that measured gaps during known inter-patch movements, not just during residency, and the predictions from the Barrett and Love spatial tool that incorporated a 100m gap distance were significant in a number of our models of abundance. Nonetheless, this parameter deserves further study particularly as it was the most important parameter in our models and thus may be the most critical to manage and restore in connectivity initiatives.

4.4 Adjustments to the 1.1km Inter-patch Rule

Based on the above results and conclusions, we recommend no change to the 1.1km Inter-patch Rule, except:

Be flexible with its application, aiming for inter-patch distances between ~ 1.0 and 1.3km.

Inter-patch distances in this range were associated with abundance and movements of woodland specialists in particular (Figure 11), but they also minimised the abundance of exotic invasive species (Figure 14). However, if the targets of management are nomadic foragers and/or more common and generalist species (rather than the strict woodland specialists), and exotic species aren't a concern either because of the location or because they are managed in other ways, then inter-patch distances could be up to 2km (Figure 12 and Figure 13).

4.5 Adjustments to the 10ha Patch Size Rule

Based on the above results and conclusions, we do not have sufficient information to recommend adjustments to the 10ha Patch Size Rule. From our analyses, it seems that patch size may not be particularly important for facilitating connectivity per se, but may still be important for providing habitat in the landscape. Indeed, this is the reason why it was originally included in The 100m/1.1km/10ha Rule.

Intermediate patch sizes were occasionally important in our models, which corresponds to patches roughly between 10 and 100ha. This may be because smaller patches simply don't have or produce enough individuals to detect movement out of them, and because larger patches (in our data, ~300ha and ~900ha) are large enough that individuals may not have to move outside the patches very often to access the resources they need (e.g., territories and mates for woodland specialists, foraging resources for nomadic foragers). Thus, it is possible that while 10ha might be a minimum patch size to support resident psub-opulations of woodland specialists, connectivity restoration should be focused in areas where patch sizes are between 10 and 100ha as this is where movement between patches may be most necessary. This idea requires further investigation, but it potentially suggests that while 10ha could still be a minimum, larger patches should be encouraged.

4.6 Final Conclusions – Connectivity Restoration in the ACT

Based on this study, we revise the CSIRO Functional Connectivity Model used by the ACT Government as depicted in Figure 25, increasing the gap distance threshold to 150m and suggesting a more flexible inter-patch distance threshold of 1.0 to 1.3km. In addition, while we did not actually test whether scattered tree connections were better than linear corridors, we suggest that they may often be the preferred option because we found that they can provide substantial habitat for woodland generalist species given the recommended spacing between scattered trees. Linear connections are much less likely to provide woodland habitat and will tend to do so over a much smaller total area than scattered tree connections. Thus, maintaining scattered tree connections with the spacing described in Figure 25 will tend to produce more of a landscape mosaic rather than a strict patch/matrix structure, with greater heterogeneity of habitat types and thus the ability to support a greater range of species.

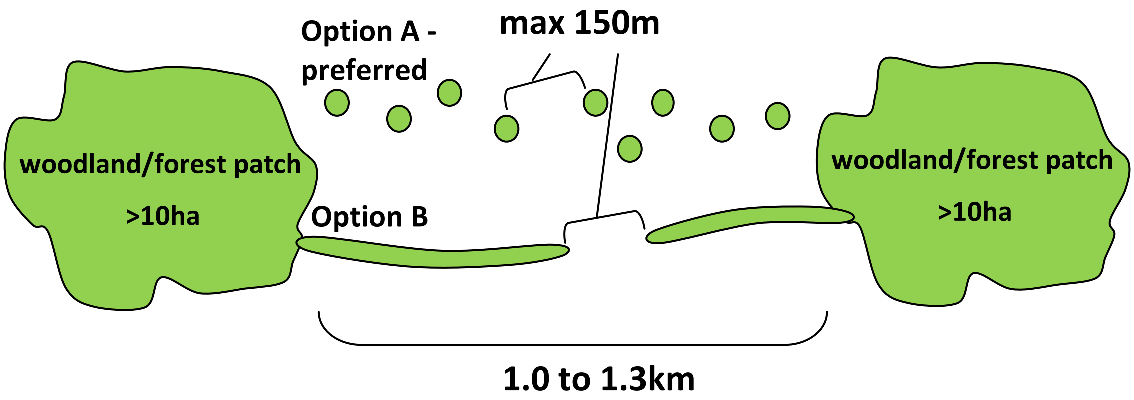

Figure 25. Revised CSIRO Functional Connectivity Model.

As this work was intended to provide a 'space for time substitution' to monitor the ACT Government's work to manage and restore landscape connectivity, our final conclusions relate to what our results tell us about the effectiveness of the program of work and the validity of the model upon which it is based. Our results suggest than any work based on the original CSIRO Functional Connectivity Model and the Barrett and Love (2012) spatial model based on those parameters will tend to be effective and provide benefits for birds in the landscape. If anything, that approach may be slightly too conservative, and additional opportunities to manage and restore connections may arise if the revised CSIRO Functional Connectivity Model is applied instead. However, we would not suggest that the Barrett and Love (2012) model needs to be re-run as a result. Barrett and Love provided a local links layer that showed where gaps were <195m as well as a layer that showed where gaps were <100m. In reality, there are only small differences between those layers and it is possible to use the two of them to make an informed judgement about where the additional management and restoration opportunities may exist. Thus, what really requires slight revision is the precise application of the Barrett and Love model to decisions about on-ground works, rather than the model itself.

5 Monitoring Framework

To develop a long-term approach to monitoring, it may be helpful to compare a range of potential methods and options with a reasonable understanding of the relative advantages and disadvantages of each. As it is often expensive and time-consuming to observe species movements (as opposed to species presence, for example), monitoring approaches that have the potential to be implemented may need to be based on fairly approximate indicators of movement. Such approaches can be used effectively as long as the risks and disadvantages are well understood and can be occasionally paired with more detailed investigations that can help validate or refine the more approximate indicators. Thus, we decided to develop a framework that articulates the range of options, relationships between them, relative confidence that they truly measure the outcomes desired, and tractability of implementation. The intention was that such a framework could be used to inform choices about monitoring options over long time frames, ensuring that primary options achieve an acceptable balance between accuracy, tractability, and a clear relationship to outcomes desired, while secondary options can be chosen when opportunities arise that will most effectively complement the primary approaches.

5.1 Monitoring Workshop

Our intention to develop a monitoring framework coincided with funding from the New South Wales Environmental Trust to the Slopes to Summit partnership of the Great Eastern Ranges Initiative (GER) to run a workshop to help inform monitoring of connectivity improvements in the GER. Given that we (CSIRO, through V. Doerr and E. Doerr) are members of the Slopes to Summit partnership, it seemed sensible to combine these efforts and use the workshop to produce a monitoring framework, built by a much wider range of experts than we would have had access to in this project alone. The connectivity monitoring workshop was jointly run by David Watson, from Charles Sturt University (CSU), and Veronica Doerr, and was held on 8 May 2013.

We deliberately invited participants who have recent hands-on experience measuring and observing species movements to inform connectivity management and restoration, not just those who have theorised or written conceptual papers about connectivity. We also deliberately invited participants who use a range of different methods (genetic, behavioural, general ecological) and who specialise in different taxonomic groups (plants, mammals, birds, reptiles, invertebrates). We looked for opportunities to combine these multiple perspectives and skills in individual participants, to ensure the number of participants was relatively small to facilitate deeper discussion. Invitees who were able to participate on the day were (in alphabetical order): Sam Banks (ANU), Veronica Doerr (CSIRO), Don Driscoll (ANU), Paul Sunnucks (Monash U.), Rodney van der Ree (U. of Melbourne), David Watson (CSU). Additional invitees who were unable to participate were Andrew Bennett (Deakin U.), Sean Fitzgibbon (U. of Queensland), and Andrew Young (CSIRO), though we attempted to harness some of their ideas through more informal communications.

The workshop was specifically focused on monitoring improvements in connectivity as one component of the larger aims of landscape-scale restoration initiatives. It was acknowledged that a range of monitoring approaches already exist that are appropriate and tractable for monitoring improvements in other landscape-scale restoration goals such as improvements in native vegetation extent, patch sizes, and vegetation condition. We structured the workshop to focus on four sequential discussion points: 1) the ultimate outcomes desired from connectivity improvements, 2) what success would look like in terms of the more detailed movement processes and at what scales, 3) a range of options for how to measure different movement processes at different scales, and 4) how to structure such information to make it most useful to practitioners. The desired outcome was a draft framework, or way of expressing the relationships between outcomes, movement processes, and measures of movement.

The workshop deliberately brought together scientific experts to utilise their depth of knowledge about measuring species movements. Yet it also needed to be informed by the desires and constraints of practitioners – people who administer improvements to connectivity and are in charge of monitoring the outcomes of their programs. To incorporate that information into the structure, tone, and outputs of the workshop, we sought specific input from a few key practitioners, including ACT ESDD and the Australian Government's Department of Sustainability, Environment, Water, Populations and Communities (SEWPaC). Advice was collected during semi-structured conversations, focusing in particular on practitioner aspirations when it comes to monitoring but also logistical, financial, and administrative/policy constraints to implementing monitoring approaches. Workshop participants were briefed on these aspirations and constraints both before and during the workshop, and they were used to guide the conversations such that practical and implementable approaches to monitoring remained at the forefront. In addition, Sam Niedra and Gary Howling of the Great Eastern Ranges Initiative were present as observers at the workshop and provided some additional commentary and guidance on practitioner perspectives.

The workshop produced a likely structure for how participants thought monitoring methods should be presented/synthesised to facilitate decision-making about which to pursue. This structure was based on a range of movement processes, spatial scales over which on-ground activities occur, applicability to different species, and ease/cost of implementation. The current draft of the framework is presented below. The complete production of the framework is on-going, with workshop participants now drafting the more conceptual paper and brief version of the framework that we hope will have international applicability and be published in an international scientific journal. We anticipate then developing an Australia-specific version with more detail on guidance on more specific methods and species groups. Given the timeline for the Flyways and Byways project, we will need to develop our own more specific version based on the information below for the ACT Government approach to monitoring connectivity, as we will need it sooner than it will be available from this workshop group.

5.2 Draft Framework

The Connectivity Monitoring Framework involves two components and thus two decision-making steps. The first component, the Connectivity Outcomes Hierarchy, elucidates the logical relationships between actions to improve connectivity and the ultimate outcomes desired (Figure 26). The intention is to show that this is not a direct relationship. Actions are designed to influence movement, but movement is only one contributor among many to the highest level outcomes desired, like maintaining or improving population persistence and species richness at the landscape scale. As a result, there are multiple levels at which monitoring connectivity restoration could be targeted, from relatively simple assessment of inputs (the amount of action undertaken) to monitoring of the highest level outcomes despite their complex influences. At each level, there are trade-offs to be made in terms of tractability, ability to assess achievement relative to the ultimate goals, and ability to evaluate whether current actions are working to achieve those goals (i.e., to adaptively manage). Thus, the first decision-making step using this framework is to decide at which of these levels (or combination of levels) a practitioner wishes to target monitoring efforts. The Connectivity Outcomes Hierarchy and associated table of Monitoring Levels (Figure 26 and Table 11) is designed to assist with that decision by making the levels and their trade-offs clearer.

For example, monitoring inputs (like numbers of hectares of connections managed or restored) is the easiest option but it is very far removed from the ultimate outcomes desired. Thus, a choice to monitor inputs alone involves the implicit assumption that all the links in the Connectivity Outcomes Hierarchy really do flow from the actions taken. Because no consequences of those inputs/actions are being assessed, adaptive management is not possible. At the other end of the spectrum, monitoring the ultimate

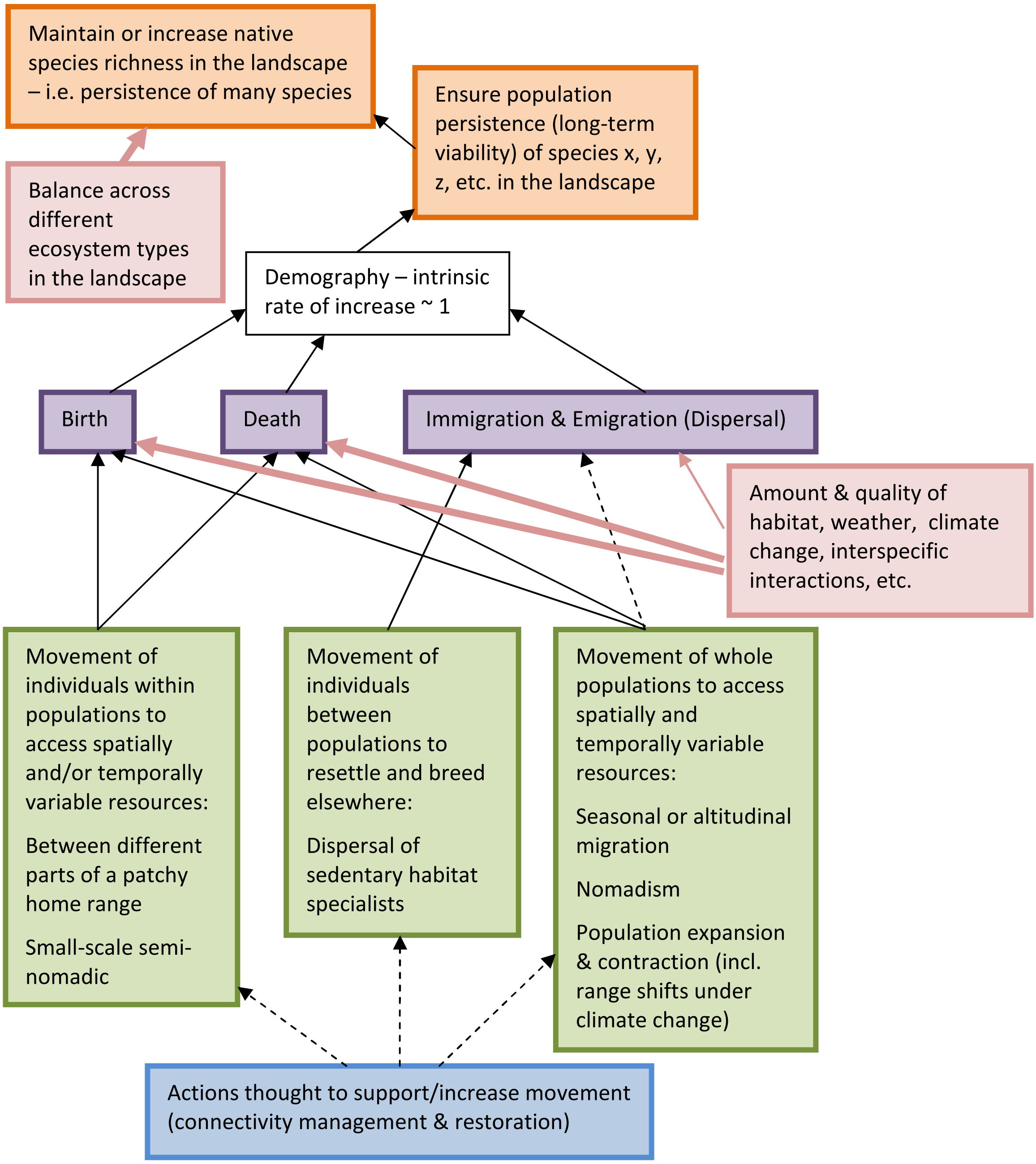

Figure 26. The Connectivity Outcomes Hierarchy – the first decision point in the monitoring framework. Actions to improve connectivity are inputs (blue box at the bottom). These inputs are related to the ultimate outcomes desired (orange boxes at the top) through outputs such as increases in movement types (green boxes), and components of the outcomes desired – individual components of demography (purple boxes). Pink boxes show substantial other influences on these factors that are not related to landscape connectivity. Monitoring could be targeted at inputs (blue), outputs (green), components of outcomes (purple) or ultimate outcomes (orange), with the basic explanation of monitoring at these levels and inherent trade-offs detailed in Table 11

Table 11. Monitoring Levels in the Connectivity Outcomes Hierarchy, and their trade-offs in terms of tractability of data collection and analysis repeatedly over time, relationship to the ultimate outcomes desired, and ability to use the monitoring results for adaptive management (i.e., to compare actions and determine which are more effective)

Level	Description of Monitoring	Tractability	Relationship to Ultimate Outcomes	Ability to Adaptively Manage
Inputs	Recording the number/area and type of actions to improve connectivity	High	Low	Low
Outputs	Measuring changes in the amount of movement for each type of movement that actions are designed to support	Variable, depending on how directly movement is assessed	Moderate to low	High
Components of Outcomes	Measuring changes in the one or two components of demography most likely to be influenced by the movement type that actions were designed to support (e.g., measuring changes in birth, death, immigration & emigration rates)	Moderate to low	Moderate	Moderate
Ultimate Outcomes	Measuring changes in landscape-level species richness or population viability (often with a model like a population viability analysis) of individual species	Moderately high for richness, low for population viability	High	Low

outcomes themselves may be the best way to say whether there is real ecological improvement in an area where connectivity is being managed and restored. While the data may be moderately tractable to collect for some parameters (like richness, which can be obtained purely through survey-type data), these outcomes may only eventuate over long time scales. In addition, they are inherently achieved at the scale of the landscape, not the scale of individual actions, and are influenced by a large number of factors other than potential improvements in connectivity and movement. Thus, there is virtually no ability to use this level of monitoring to compare the consequences of different types of connectivity management/restoration actions and adaptively manage these actions over time. Neither of these options is wrong or bad – they just serve different purposes. So practitioners need to decide what the purpose of their monitoring program is to choose an appropriate level (or multiple levels) of the hierarchy.

The second decision-making step involves choosing what basic data collection method to employ for the level(s) of monitoring chosen. While these options are relatively straightforward and few in number for Inputs, Components of Outcomes, and Ultimate Outcomes (main options mentioned in Table 11), there is a plethora of potential ways to assess movement (Outputs), either directly or via its immediate population consequences. This is because movement is traditionally the most challenging aspect of population dynamics to study and researchers have thus devised multiple ways of trying to assess it as accurately and cost-effectively as possible. However, this variety of potential methods can make it difficult for practitioners to decide what method to choose. This is also the level of monitoring which may be the most critical, as it is the only level that assesses the immediate consequences of individual actions, and thus can truly be used to inform adaptive management. Thus, the second part of our Connectivity Monitoring Framework involves a tool to help practitioners decide what method to use if there is a desire to monitor at the level of Outputs.

This second part of the Framework recognises that the monitoring method chosen will likely depend on four factors: the type of movement that connectivity management/restoration actions are intended to support, the scale at which information is desired, the tractability (cost and ease of implementation) of the method, and the species (or taxonomic groups) the method is suitable for. Table 12 is thus a list of potential methods organised according to the first three of these factors, with some additional notes about species provided below.

In this table, there are three types of movement which correspond to the three types shown in Figure 26. There are three nested scales at which information might be desired. At the smallest scale, the consequences of individual actions (e.g., connections restored or managed) might be important to understand, particularly for adaptive management in which multiple types of actions might be compared to determine which are most effective. The intermediate scale is the local landscape or priority area within a larger landscape-scale initiative. This is the scale at which funding for on-ground works is often awarded and must be reported on, and multiple individual actions would be nested within these local landscapes. Finally, the largest scale is that of the entire landscape-scale initiative, which usually involves multiple priority areas with multiple on-ground actions within them. The basic techniques that might be used to monitor changes in movement (Outputs) are then listed for each combination of movement type and scale of monitoring. Methods are listed in order of relative tractability. Note that this order sometimes changes from cell to cell in the table because methods are differentially affected by scale and movement type. For example, quantifying presence in connection sounds highly tractable, but is less so as the type of movement becomes rarer and thus many more hours of observation might be required to have a chance of observing individuals using the connection. Similarly, the tractability of capture-mark-recapture (CMR) techniques is much lower at larger scales because the area over which recapture attempts must be made increases dramatically.

Table 12. Choices for methods to monitor changes in movement (Outputs) depending on the type of species movements actions are intended to support, the scale at which monitoring information is desired, and the tractability of implementing each method in these contexts

Type of Movement/Scale of Monitoring	**Individual connections or patches being connected (scale at which actions undertaken)**	**Cluster of patches and connections (local landscape, sub-initiative or single priority area – scale at which funding often awarded)**	**Multiple clusters of patches and connections (Whole-of-initiative, state or continental scale)**
Individuals within populations (home-range & semi-nomadic movements)	• Presence in connection • Increased richness or abundance in connection • Directional movement in connection • Increase in species turnover in patches being connected • Increase in abundance in patches being connected at a time when resources available • Traditional capture/mark/recapture • Tracking (radio or GPS)	• Increase in variance in composition across multiple sites within the priority area • Aggregation of other observational methods at the scale of individual connections (e.g., presence in connection) • Increase in body condition • Tracking (GPS or satellite) • Tracking (radio) • Traditional capture/mark/recapture	• Monitor inputs at this scale that monitoring work from other scales suggests are successful • Aggregate data from other scales of monitoring • Model possible outcomes based on inputs (using some sort of spatial pattern analysis)
Individuals between populations (dispersal)	• Occupancy of previously unoccupied patch being connected • Equalisation of sex ratios in patch being connected (for species with sex-biased dispersal) • Presence in connection • Increased richness or abundance in connection • Directional movement in connection • Traditional capture/mark/recapture • Increase in population stability in patch being connected • Tracking (radio or GPS) • Indirect genetic measures (e.g., decrease in pairwise genetic	• Aggregation of observational methods at the scale of individual connections (e.g., presence in connection) • Increase in population stability at the priority area scale • Indirect genetic measures (e.g., decrease in genetic structure within priority area) • Tracking (GPS or satellite) • Tracking (radio) • Direct genetic measures (e.g., parentage/assignment tests studied at priority area scale) • Traditional capture/mark/recapture	• Monitor inputs at this scale that monitoring work from other scales suggests are successful • Aggregate data from other scales of monitoring • Model possible outcomes based on inputs (using some sort of spatial pattern analysis) • Indirect genetic measures (e.g., population structure) • Satellite tracking (animals only)

	differences) • Direct genetic measures (e.g., parentage/assignment tests)		
Whole populations (migration, nomadism, range shifts)	• Temporal variation in occupancy of patches being connected • Presence in connection • Increased richness or abundance in connection • Directional movement in connection • Traditional capture/mark/recapture • Tracking (radio or GPS)	• Temporal variation in occupancy of the priority area • Aggregation of other observational methods at the scale of individual connections (e.g., presence in connection) • Increase in survival rate during or at end of movement period (if movement known/thought to occur through the local landscape) • Tracking (GPS or satellite) • Tracking (radio) • Traditional capture/mark/recapture	• Monitor inputs at this scale that monitoring work from other scales suggests are successful • Aggregate data from other scales of monitoring • Model possible outcomes based on inputs (using some sort of spatial pattern analysis) • Change in isotope signatures (if movement from an area with a unique signature is supported more than from other areas • Increase in apparent survival rate during movement period (if movement known/thought to occur through the initiative area) • Tracking (mostly satellite – animals only)

Species (or taxonomic groups) interact with all these factors – the movement types are applicable to different species, the scale at which species engage in those movements will influence the scale of monitoring for which data from that species should be used, and the tractability of methods will often vary among species. For example, plants don't move around a home range, some species migrate entirely within a local landscape while others migrate at whole-of-initiative scales or larger, and CMR is straightforward to implement with birds but can be very challenging with plant seeds and pollen. However, we cannot produce a general framework that includes species because these will differ from region to region. Thus, we include some general notes in Table 12 about species, but suggest that practitioners could develop an overlapping table of species within their region that engage in each of the movement types at each of the scales and use that in concert with Table 12 (see next section on using this framework).

5.3 Use of Framework for Long-term Monitoring

We recognise the framework is still reasonably complex. We plan to continue developing this framework with colleagues from our monitoring workshop to refine both content and presentation to do our best to synthesise fairly complicated concepts and myriad options into something practical and useful for practitioners. It will never take the place of careful and considered decision-making, but should be able to inform that process in a logical way. At the moment, this is how we suggest it might best be used:

1) Consider what is most important to achieve from your monitoring program (assessing ultimate outcomes? reporting? using adaptive management to revise actions over time?) and use the Connectivity Outcomes Hierarchy to decide at which level(s) you wish to focus your monitoring.
2) Choose your basic methodology within each level. If you have chosen to monitor at the Outputs level:
    a) Develop a table of species (or broader taxonomic groups) that live in your region that exhibit each type of movement at each scale of monitoring (i.e., a table with the same row and column headings as Table 12). Consider only those species/groups that are abundant enough to be easily studied and able to be captured and/or genetically sampled. Note that some cells of the table may not be filled – for example, there may be no species that need to move within a single patchy home range at the scale of an entire landscape-scale conservation initiative.
    b) Decide which cells of Table 12 and your species table are most important to you. These decisions could be based on a focus on species, movement types, scales of monitoring, or a balance between these.
    c) Within your top priority cell, choose your top monitoring method(s) based on tractability given your financial and logistical constraints, and ability to apply those methods using the species that are available to you.
    d) Examine whether that method also appears (potentially associated with the same or similar species/groups) in other cells that are important to you, in which case slight modifications to the approach could give you broader information.
    e) Make a decision about a method (or methods) to use based on both which will best address your top priority given your constraints as well as which may allow you to address multiple priorities at once, in a cost-effective way. You may also wish to consider whether/how the method overlaps with any other monitoring or data collection you do in the same area for other purposes.
3) For each monitoring method you have chosen to use, develop a written monitoring protocol that incorporates solid experimental design. This means it should:
    a) Involve data collection in areas where connectivity management/restoration is not happening as well as where it is happening, to serve as controls for other causes of change
    b) Consider the sample size of actions/priority areas/initiatives (depending on the scale of monitoring) that would be required to statistically analyse the data as opposed to just qualitatively evaluate it
    c) Explain how data should be collected, stored and analysed in sufficient detail so that someone who wasn't involved in its development could still implement the protocol in a consistent way

    d) Plan how frequently and over what total time frame data will be collected, as well as who will do the work
4) Seek out opportunities to value-add to your chosen monitoring approach in a targeted way. Students and professional researchers may be able to do shorter term projects that:
    a) Address a different level of the outcomes hierarchy or better define/confirm the links in the hierarchy to strengthen confidence that ultimate outcomes are being achieved through the actions you are implementing
    b) Give you much more information within a priority cell in Table 12 by using methods that are less tractable for practitioners to implement but give richer data (as tractability and accuracy are usually negatively correlated)
    c) Give you much more information within a priority cell in Table 12 by working with a species or taxonomic group that is less tractable for practitioners to collect data on
    d) Use richer/more accurate information within a priority cell in Table 12 to test whether the simpler method you are applying is generally yielding the same conclusions, to confirm your approach is adequate

5.4 The Future of Landscape-scale Conservation

There is no doubt that we still have much to learn about how fragmented landscapes function and can be designed to support long-term species persistence. We believe the tests of the CSIRO Functional Connectivity Model presented in this report provide an even stronger basis for its use in planning connectivity management and restoration, particularly in south eastern Australia. However, the connectivity outcomes hierarchy reminds us that connectivity is only one part of functioning landscapes, and what may matter the most to long-term outcomes is how multiple factors interact in one landscape to shape sustainable balances between birth, death, immigration and emigration. Thus, monitoring and further research should play critical roles in continuing to shape landscape-scale conservation by revealing the long-term consequences of managing for movement and how those may depend on integrated management of both core habitats and connections.

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Appendix A: Locations of all connectivity tree watches

Table 13. Names of regions and inter-patch areas where connectivity tree watches were performed, number of the figure depicting the inter-patch area (see figures below the table), and UTM coordinates (in datum WGS84, zone 55H) for the location of each of the three connectivity trees in each inter-patch area.

Region	Inter-patch	Figure	Tree 1	Tree 2	Tree 3
Kama	Ka1	Figure 27	684213 6094761	684474 6094899	684429 6095153
Kama	Kb1	Figure 27	683620 6095105	683835 6095260	683981 6095317
Kama	Kc1	Figure 27	683422 6097619	683089 6097492	683093 6097665
Kama	Kc2	Figure 27	682693 6097451	682409 6097383	682379 6097534
Kama	Kd1	Figure 27	681292 6097724	681029 6097698	681071 6097444
Kama	Ke1	Figure 27	683879 6097544	683713 6097386	683566 6096970
Kama	Ke2	Figure 27	683149 6096925	682832 6096539	682494 6096434
Kama	Kf1	Figure 27	682389 6092720	682302 6092895	682368 6093133
Kama	Kf2	Figure 27	682313 6093996	682533 6094083	682586 6094334
Kama	Kg1	Figure 27	686127 6095732	686367 6095657	686809 6095546
Stromlo	Sb1	Figure 28	680614 6089854	680748 6090094	680849 6090108
Stromlo	Sc1	Figure 28	680671 6091202	680750 6091217	680886 6091060
Stromlo	Sd1	Figure 28	681252 6090311	681186 6090300	681137 6090339
Stromlo	Se1	Figure 28	682067 6092339	682031 6092477	682189 6092473
Gooroo	Ga1	Figure 29	697176 6104968	697240 6104922	697200 6104856
Gooroo	Gb1	Figure 29	697689 6104962	697758 6105056	697962 6104939
Gooroo	Gc1	Figure 29	698470 6105264	698455 6105214	698371 6105148
Gooroo	Gd1	Figure 29	698086 6104800	698097 6104584	697962 6104439
Gooroo	Ge1	Figure 29	697831 6102795	697798 6102612	697824 6102422
Gooroo	Ge2	Figure 29	698311 6102986	698179 6102718	698221 6102553
Majura	Mb1	Figure 26	698364 6095792	698478 6096208	698569 6096399
Majura	Mc1	Figure 26	699185 6100046	699035 6100243	699164 6100386
Majura	Mc2	Figure 26	699138 6100157	699224 6100837	699110 6100856
NSW	Na1	Figure 31	700782 6107210	700796 6107019	701085 6107321
NSW	Nb1	Figure 31	701728 6108322	701699 6108534	701331 6108802

NSW	Nd1	Figure 31	702099 6108634	702141 6108708	702176 6108611
NSW	Ne1	Figure 31	701584 6105954	701852 6105980	701713 6106301
NSW	Ne2	Figure 31	701974 6106581	701783 6106567	701925 6106642
NSW	Nf1	Figure 31	702222 6108051	702234 6107929	702180 6107913
NSW	Nh1	Figure 31	701573 6107858	701046 6107664	700897 6107734
NSW	Ni1	Figure 31	701813 6105479	701952 6105416	702223 6105475

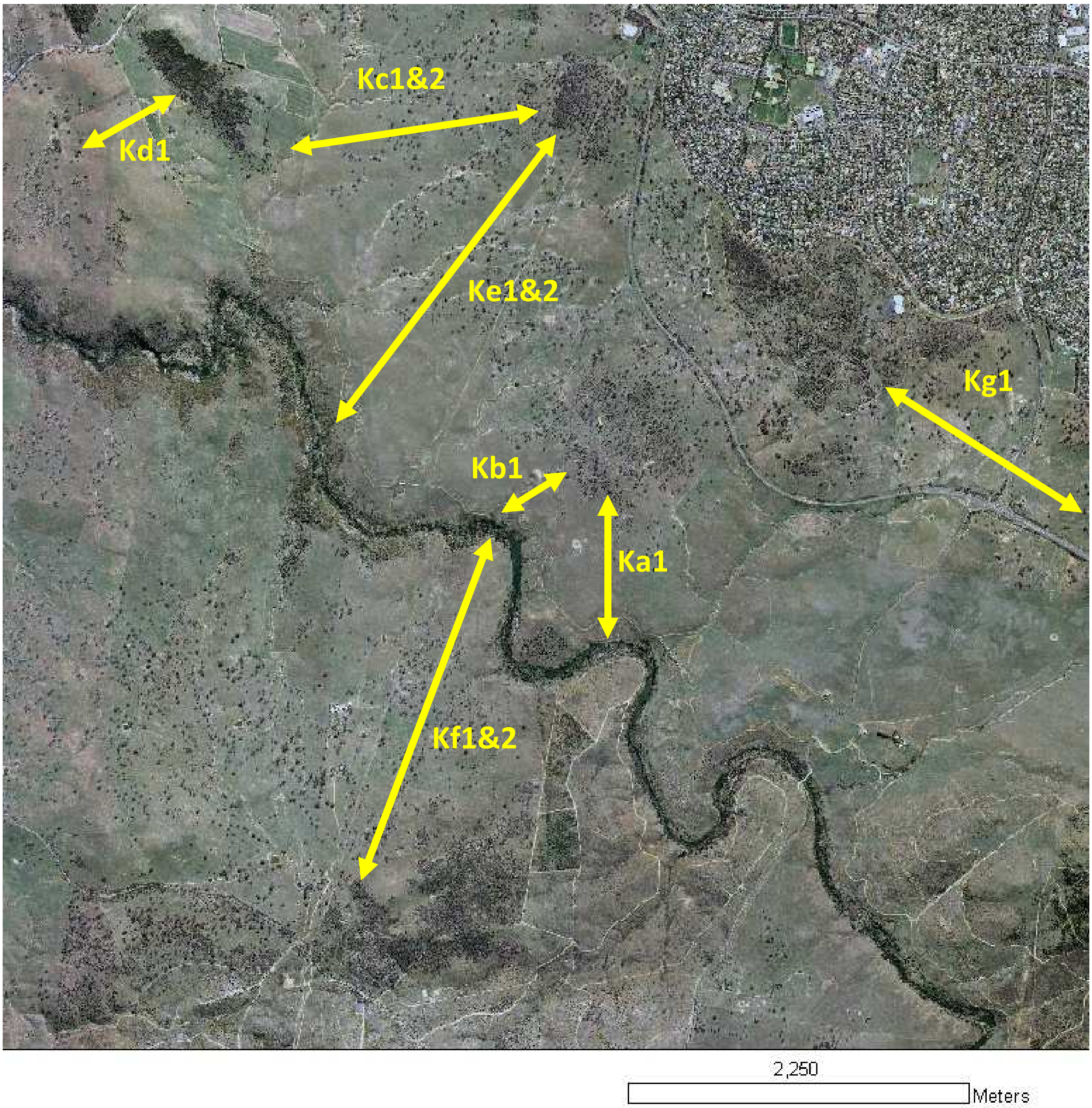


Figure 27. Kama Region, with inter-patch areas (sites) marked. Three trees were selected for connectivity tree watches within each inter-patch area

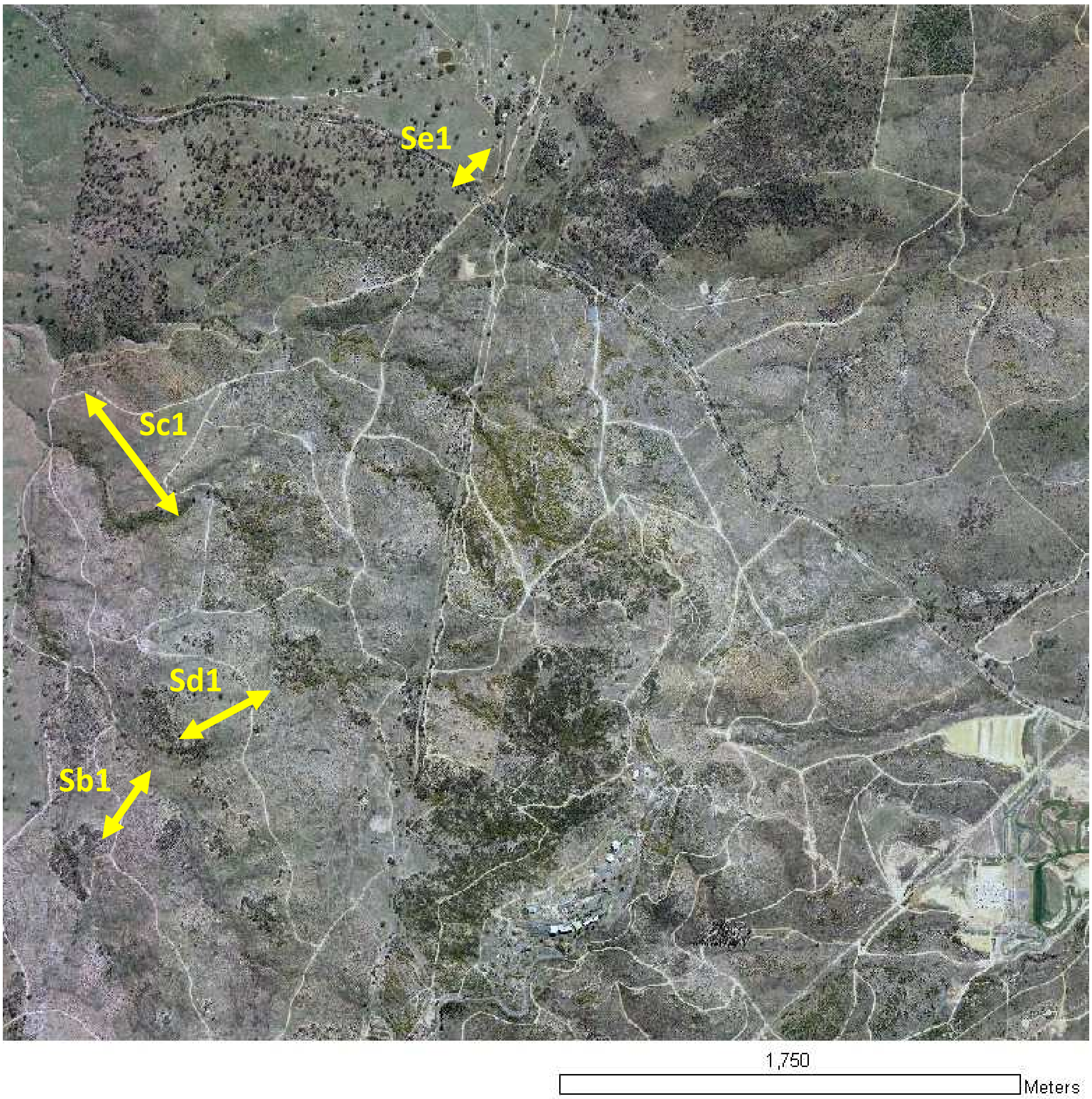


Figure 28. Stromlo Region, with inter-patch areas (sites) marked. Three trees were selected for connectivity tree watches within each inter-patch area

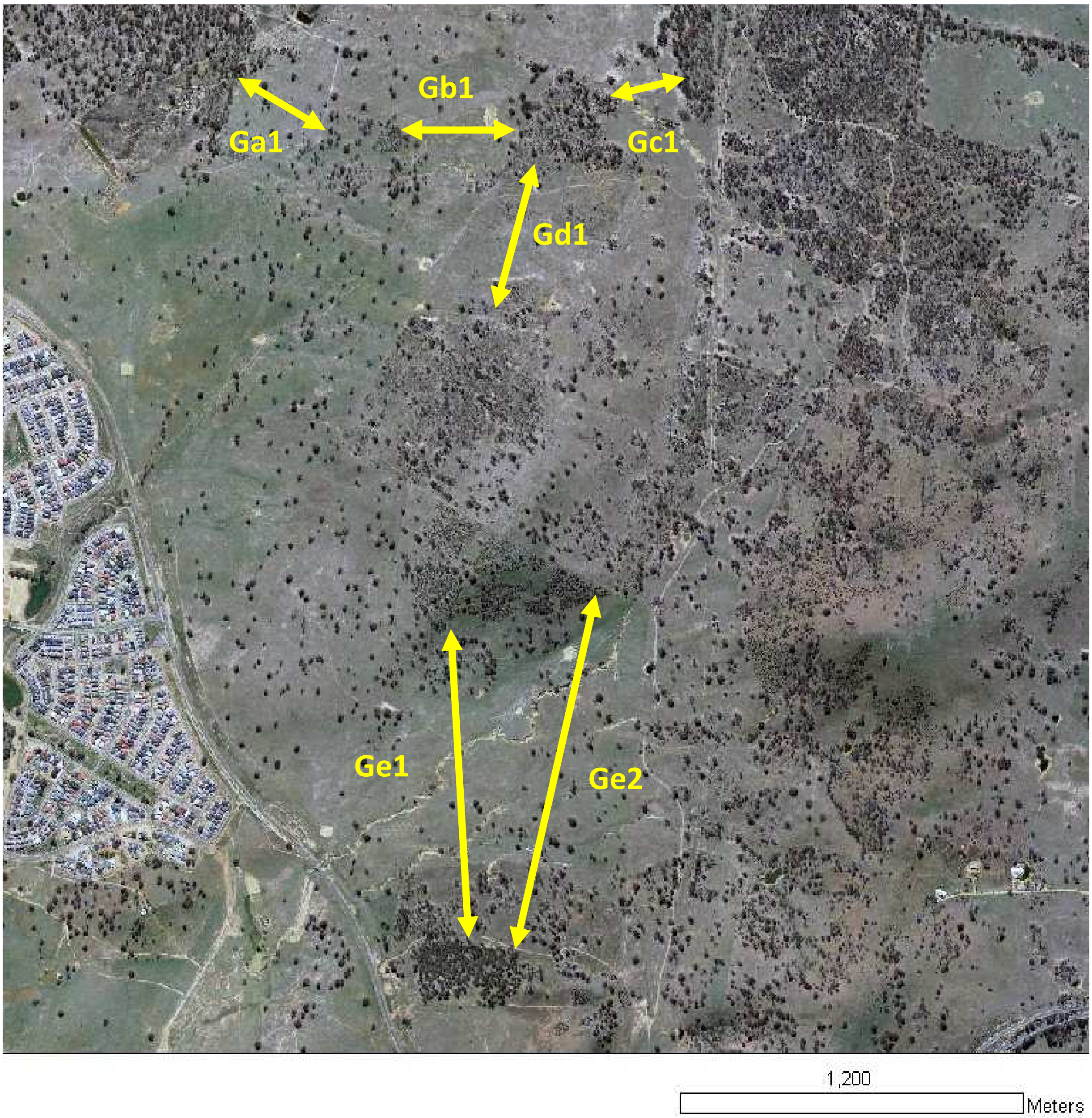
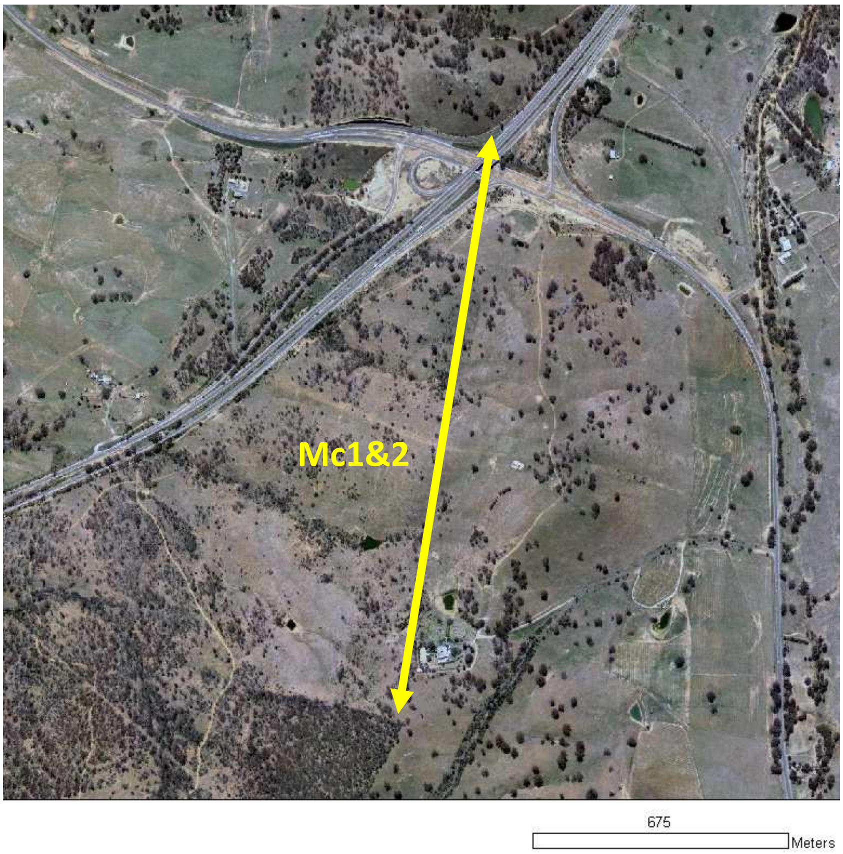


Figure 29. Goorooyarroo Region, with inter-patch areas (sites) marked. Three trees were selected for connectivity tree watches within each inter-patch area



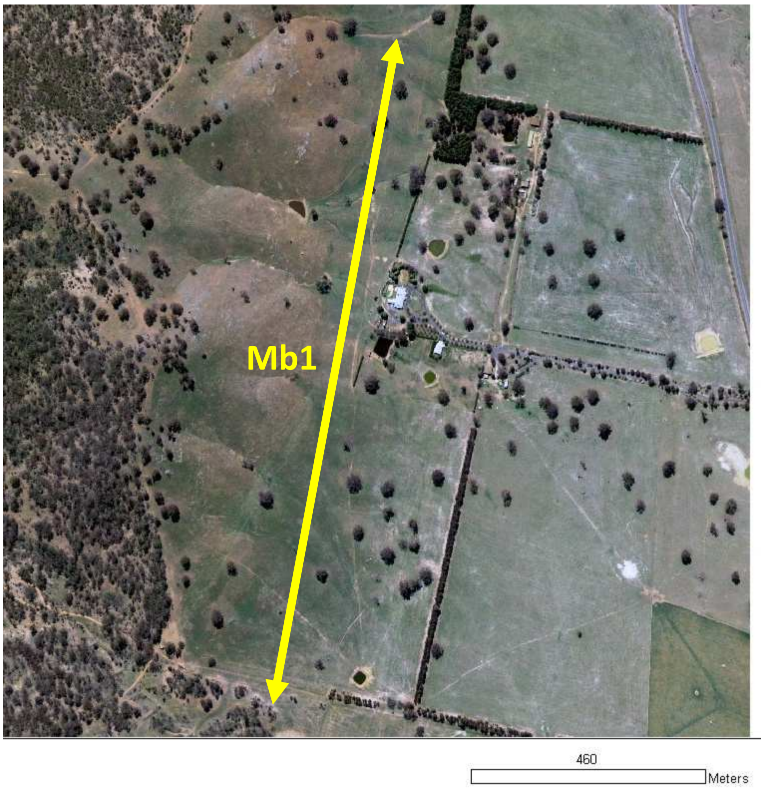


Figure 30. Majura Region, with inter-patch areas (sites) marked. Sites c (between Mt Majura and Goorooyarroo Nature Reserves) and b (between Mt Majura and Mt Ainslie Nature Reserves) are shown in separate images as there is a significant distance between them.

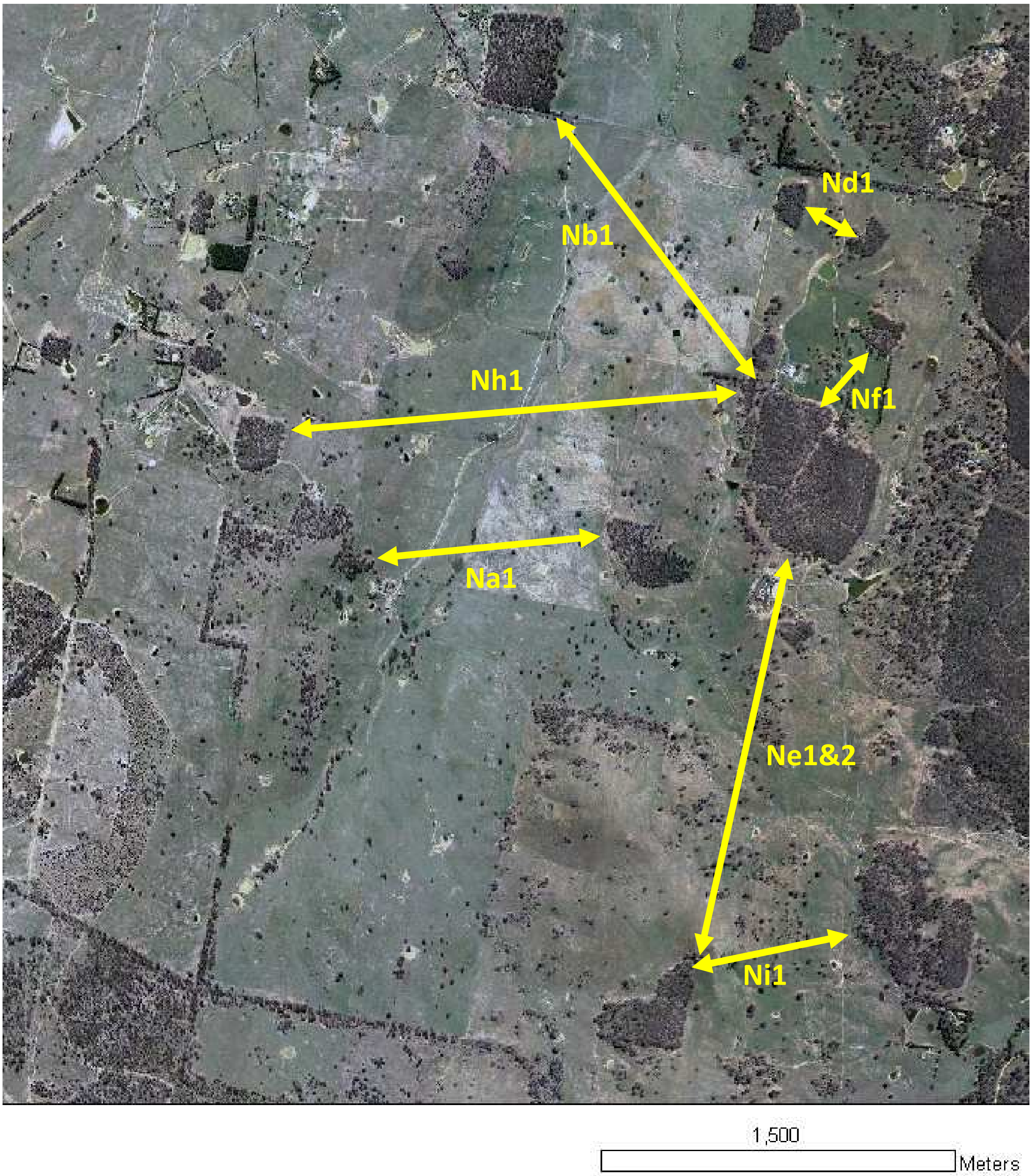


Figure 31. New South Wales Region (Greater Goorooyarroo), with inter-patch areas (sites) marked. Three trees were selected for connectivity tree watches within each inter-patch area

Appendix B: Species observed in connectivity tree watches & classification of functional groups

Table 14. Common names of species observed during connectivity tree watches (in alphabetical order, with partial identification categories last), the number recorded across all watches, and the functional species group to which each species was assigned (OC= open country species, NF = nomadic forager, WG = woodland/forest generalist, WS = woodland/forest specialist, EI = exotic invasive species)

Species	Total # Recorded	Species Group
Australasian Pipit	4	OC
Australian Hobby	2	OC
Australian King-Parrot	2	NF
Australian Magpie	206	OC
Australian Raven	83	OC
Australian Wood Duck	113	OC
Black-faced Cuckoo-shrike	116	WG
Black-shouldered Kite	3	OC
Brown Falcon	12	OC
Brown Goshawk	11	OC
Brown Thornbill	6	WS
Brown-headed Honeyeater	9	NF
Buff-rumped Thornbill	55	WS
Common Blackbird	41	EI
Common Myna	10	EI
Common Starling	1127	EI
Crested Pigeon	14	OC
Crimson Rosella	622	WG
Diamond Firetail	2	WG
Dusky Woodswallow	11	OC
Eastern Grey Kangaroo	3	OC
Eastern Rosella	602	WG
European Goldfinch	9	EI
Galah	416	OC
Grey Butcherbird	6	WG
Grey Currawong	7	WG

Grey Fantail	71	WS
Grey Shrike-thrush	1	WS
House Sparow	2	EI
Jacky Winter	2	WG
Laughing Kookaburra	10	WG
Little Corella	12	OC
Little Raven	18	OC
Magpie-Lark	19	OC
Masked Lapwing	2	OC
Mistletoebird	18	NF
Nankeen Kestrel	25	OC
Noisy Friarbird	20	NF
Noisy Miner	228	WG
Olive-backed Oriole	1	NF
Pacific Black Duck	12	OC
Pallid Cuckoo	2	WG
Pied Currawong	8	WG
Red Wattlebird	36	NF
Red-rumped Parrot	255	OC
Rufous Fantail	1	WS
Rufous Songlark	59	WG
Rufous Whistler	10	WS
Silvereye	29	WG
Southern Whiteface	2	OC
Speckled Warbler	6	WS
Spotted Pardalote	2	WS
Straw-necked Ibis	10	OC
Striated Pardalote	253	WG
Sulphur-crested Cockatoo	450	OC
Superb Fairy-wren	49	WG
Superb Parrot	247	OC
Tree Martin	343	OC
Varied Sittella	22	WS
Wedge-tailed Eagle	4	OC
Weebill	4	WG

Welcome Swallow	114	OC
Western Gerygone	2	WS
White-browed Woodswallow	23	OC
White-faced Heron	13	OC
White-necked Heron	6	OC
White-plumed Honeyeater	37	NF
White-throated Gerygone	2	WS
White-throated Treecreeper	6	WS
White-winged Triller	56	WG
Willie Wagtail	72	OC
Yellow Thornbill	7	WS
Yellow-faced Honeyeater	26	NF
Yellow-rumped Thornbill	250	WG
Unknown large honeyeater	1	NF
Unknown thornbill	13	WG
Unknown small honeyeater	4	NF
Unknown small woodland bird	62	WG
Unknown	10	OC

Appendix C: Radiotelemetry results for birds that remained within the Kama NR woodland patch

We used the locations of birds who remained within Kama to define their home ranges, using Minimum Convex Polygons (MCPs). As all the white-plumed honeyeaters we tracked used the same areas and appeared to interact, we defined one MCP for them collectively. Similarly, both noisy miners we tracked were part of the same social group (only one group of this species resides within Kama) so we defined one MCP for those two birds. The black-faced cuckoo-shrikes did not appear to maintain separate territories, though they did not interact often and were only rarely found in each other's normal areas. For simplicity of presentation, we also defined one MCP for these two birds. Finally, we defined two MCPs for the juvenile female white-throated treecreeper we tracked because she set up a solo home range partway through the tracking period outside her parents' territory (see main text). Collectively, these MCPs paint an interesting picture of how different bird species used the Kama Nature Reserve woodland patch.

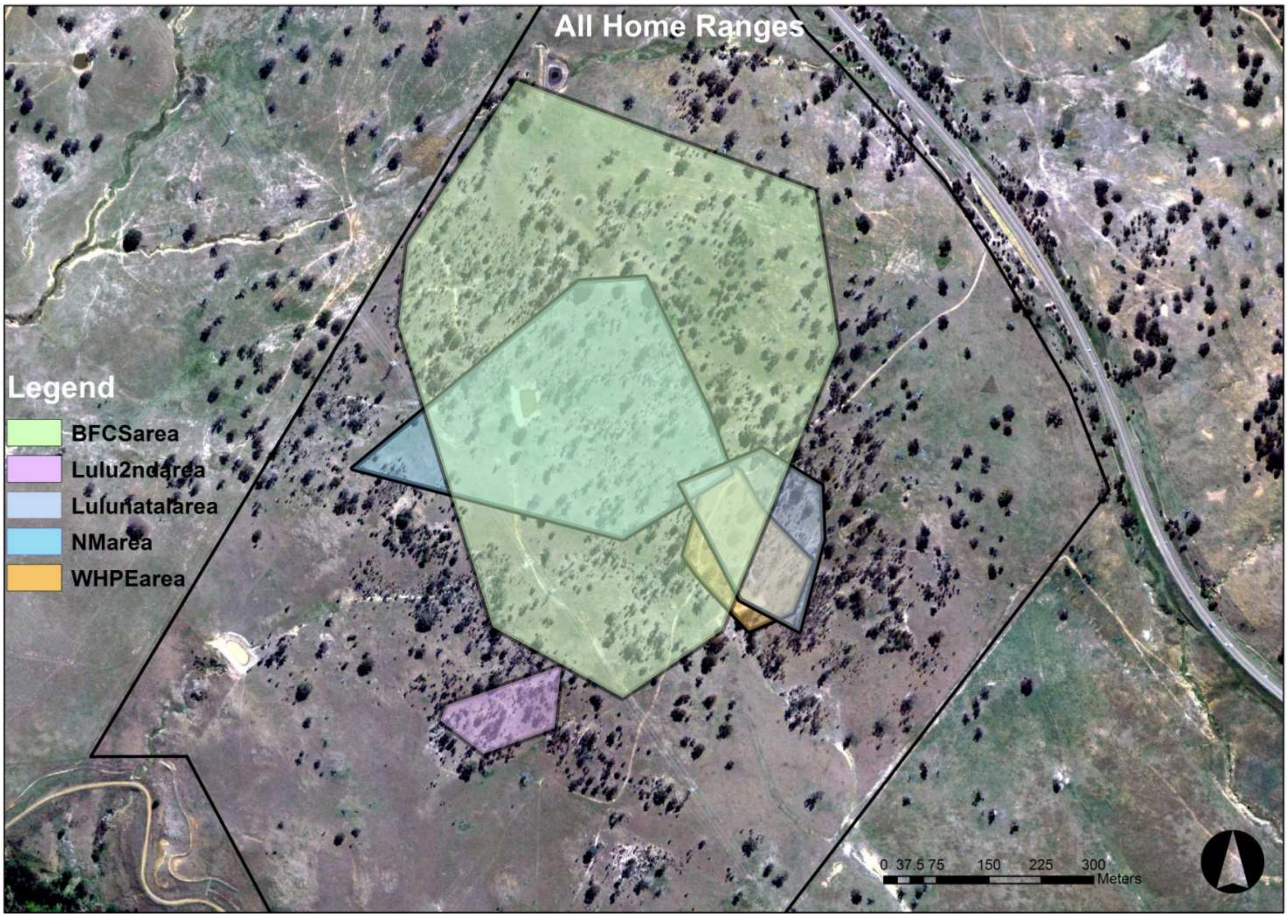


Figure 32. Minimum convex polygons showing the home ranges of birds we tracked who remained within Kama Nature Reserve. BFCSarea = collective home range of the black-faced cuckoo-shrikes, Lulu2ndarea = solo home range established by the juvenile female white-throated treecreeper, Lulunatalarea = natal territory of the juvenile white-throated treecreeper, NMarea = home range of the noisy miners, WHPEarea = collective home range of the white-plumed honeyeaters

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