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Landscape management of the mahogany glider (*Petaurus gracilis*) across its distribution: subpopulations and corridor priorities

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Abstract. Key threatening processes to biodiversity include habitat loss and fragmentation, with populations restricted to small fragments of habitat being more prone to extinction. The mahogany glider (*Petaurus gracilis*) is endemic to sclerophyll woodland forests between Tully and Ingham in north Queensland and is one of Australia's most endangered arboreal mammals due to these processes. The aim of this study was to identify the degree of habitat fragmentation of the remaining remnant vegetation of the mahogany glider, identify subpopulations within its distribution and identify key wildlife corridors for restoration to facilitate the movement of this species within and between subpopulations. Ten glider subpopulations, spread over 998 habitat fragments, were identified, of which only five subpopulations may currently be considered to be viable. To assist in providing habitat connectivity between and within the subpopulations, 55 corridors were identified for restoration that had an average length of 8.25 km. The average number of gaps greater than 30 m was 3.4 per corridor, with the average length of these gaps being 523 m. This study confirmed a high degree of habitat fragmentation across the distribution of the mahogany glider and highlighted the need to strengthen the remaining subpopulations by restoring habitat connectivity between the remaining habitat fragments.

Additional keyword: restoration.

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Introduction

Habitat loss and fragmentation are key threatening processes to biodiversity (Fahrig 2003). Populations of wildlife restricted to small habitat fragments often have a reduced movement of individuals between adjacent populations due to their inability to traverse the area (i.e. the matrix) in between useable habitat (e.g. Prugh *et al*. 2008). As a result, these habitat fragments are prone to reduced gene flow between each other and across the landscape more broadly (Keyghobadi 2007). These small populations are therefore susceptible to localised decline and extinction due to inbreeding depression, loss of genetic diversity and the fixation of deleterious alleles (Lynch *et al*. 1995; Lande 1998; Frankham 2005; Charlesworth and Willis 2009).

Small populations are also susceptible to disease, catastrophes, and environmental and demographic stochasticity (Bennett 1990; Simberloff *et al*. 1992; Lindenmayer and Possingham 1994). Factors that influence the rates of extinction and colonisation can be classified as either intrinsic (including body size and population density) or extrinsic (including the area of the habitat fragments, the age of the fragments, and the degree of isolation of the fragments), which play a role in extinction probability (Crooks *et al*. 2001).

In order to reduce the issues associated with habitat loss and fragmentation, wildlife corridors have proven critically important in facilitating the movement of animals between fragments of habitat (Caryl *et al*. 2013). Studies on species related to the mahogany glider (*Petaurus gracilis*), including the sugar glider (*Petaurus breviceps*) and squirrel glider (*Petaurus norfolcensis*), have highlighted the importance of habitat connectivity in maintaining populations (Caryl *et al*. 2013; Goldingay *et al*.

2013*a*, 2013*b*; Malekian *et al*. 2015). For example, Goldingay *et al*. (2013*a*) explored the responses of squirrel gliders to habitat fragmentation and found that isolated local populations experienced a loss of genetic diversity and a significantly increased mean relatedness. They also concluded that there was likely to be a collapse of local populations in the future unless habitat connectivity was maintained or restored. Therefore, to promote gene flow across the landscape there is a need to design an effective reserve system with connecting wildlife corridors for species of concern (Hanski 1999; Lindenmayer and Fischer 2006; Gilbert-Norton *et al*. 2010; Shirk *et al*. 2010).

The mahogany glider is an endangered medium-sized arboreal marsupial glider that has a naturally limited distribution on coastal north Queensland, Australia (Fig. 1) (Jackson 2011). Despite the introduction of the *Queensland Vegetation Management Act 1999* to limit broadscale clearing of vegetation, including that within the distribution of the mahogany glider, significant conservation issues remain, resulting in this species being the focus of a draft national recovery plan (Jackson 2011; Jackson and Diggins, in press). Threats to this species include: (1) the historic and continuing loss of habitat that has resulted in a highly fragmented distribution with poor habitat connectivity between fragments (Jackson 1998, 1999; Parsons and Latch 2006; Jackson *et al*. 2011); (2) the increasing level of structural alteration of habitat towards closed forest due to the invasion of rainforest species or the thickening of the understorey by sclerophyllous species as a result of altered fire regimes (Jackson *et al*. 2011; Tng *et al*. 2012); (3) the degeneration of forest from weed invasion (unpub. data); and (4) wind damage by tropical cyclones, which are exacerbated by high forest edges to area ratios (Laurance and Curran 2008; Winter 2011) and the associated forest damage incurred from chainsaws and heavy machinery during clean-up operations.

Arboreal species such as the mahogany glider are sensitive to forest habitat fragmentation because of the limited time they spend on the ground (Jackson 2000*b*). Mahogany gliders can be restricted in their movement to areas where trees are not more widely spaced than the maximum glide distance, which reaches 60 m but averages 30 m per glide depending on the height of trees present (Jackson 2000*b*, 2000*c*). If gaps between habitat fragments are wider than this maximum glide distance, subpopulations are likely to become isolated (Jackson 2000*b*; Asari *et al*. 2010; Malekian *et al*. 2015). The mahogany glider is known to utilise wildlife corridors that link fragments, which highlights their importance in allowing the movement of gliders between habitat fragments.

A population viability analysis of the mahogany glider suggested that at least 800 individuals are needed to maintain a viable population or subpopulation. Using known densities such a population requires at least 8000 ha of suitable habitat (Jackson 1999, 2000*a*). Corridors are required to maximise movement between glider subpopulations that fall below this size threshold (Levins 1970; Bennett 1990; Hanski and Gilpin 1997; Gilbert-Norton *et al*. 2010). The movement of mahogany gliders throughout their range will promote gene flow between otherwise isolated populations (*sensu* Goldingay *et al*. 2013*a*; Soanes *et al*. 2018).

To better manage the conservation of the mahogany glider the size and location of remaining fragments of remnant vegetation across the distribution need to be identified to determine how many potentially viable glider subpopulations exist. There is also a need to identify priority corridors for restoration to facilitate movement throughout the landscape to assist in the conservation of the species. Therefore, the aims of this study were to identify: (1) the degree of fragmentation of the remaining remnant vegetation; (2) subpopulations throughout the mahogany glider's distribution; (3) key corridors requiring restoration to enable the movement of mahogany gliders between fragments of habitat; and (4) specific actions relevant to the design and management of corridors.

Materials and methods

Mapping of habitat fragments

The entire distribution of the mahogany glider was mapped during this study in order to understand the full extent of the habitat fragmentation, subpopulations and location where potential corridors (hereafter 'corridor') should be prioritised. The study area was located in North Queensland between Tully and south of Ingham. Within this distribution the known locations occur within a band that is 120 km north to south and 40 km east to west. The vegetation within this region includes a combination of wet sclerophyll and rain forest.

The fragments of habitat were defined as areas of continuous vegetation if they were within 100 m of each other. This distance was chosen as it was assumed to be large enough to isolate resident gliders from adjacent fragments of habitat because the longest known glide distance for the mahogany glider is ~60 m and they are not known to travel far along the ground (Jackson 2000*b*, 2000*c*). Gaps between fragments of habitat were buffered by 40 m (to make a 100-m gap) with overlapping polygons dissolved to form discrete fragment envelopes. The GIS program ESRI ArcGIS 10.2.1 for Desktop was used to identify which areas of habitat were continuous and that form discrete fragments. Areas of habitat within each discrete fragment envelope were considered to belong to that particular fragment and their area (in hectares) was included in the total fragment area calculation.

The fragments of habitat were mapped using the Queensland Herbarium State-wide preclearing and remnant regional ecosystem digitised mapping coverage, as described by Jackson *et al*. (2011). The approximate scale of this mapping was 1 : 50 000. All fragments of habitat within the known distribution of the mahogany glider were mapped using the data previously collected by Jackson *et al*. (2011). These data also included historical location records for mahogany gliders that had been captured or observed. The GIS program was used to calculate the area (in hectares) of mapped habitat (Jackson *et al*. 2011) using an Albers equal-area projection.

Mapping of glider subpopulations

In this study a glider subpopulation was defined as a group of animals that live within remnant vegetation fragments that were connected by vegetated corridors or separated by gaps of less than 100 m (Jackson *et al*. 2011). Divisions between subpopulations were assigned where there were gaps greater than 100 m as a result of land clearance for agriculture and roads, or natural barriers including rocky slopes, rivers and elevations

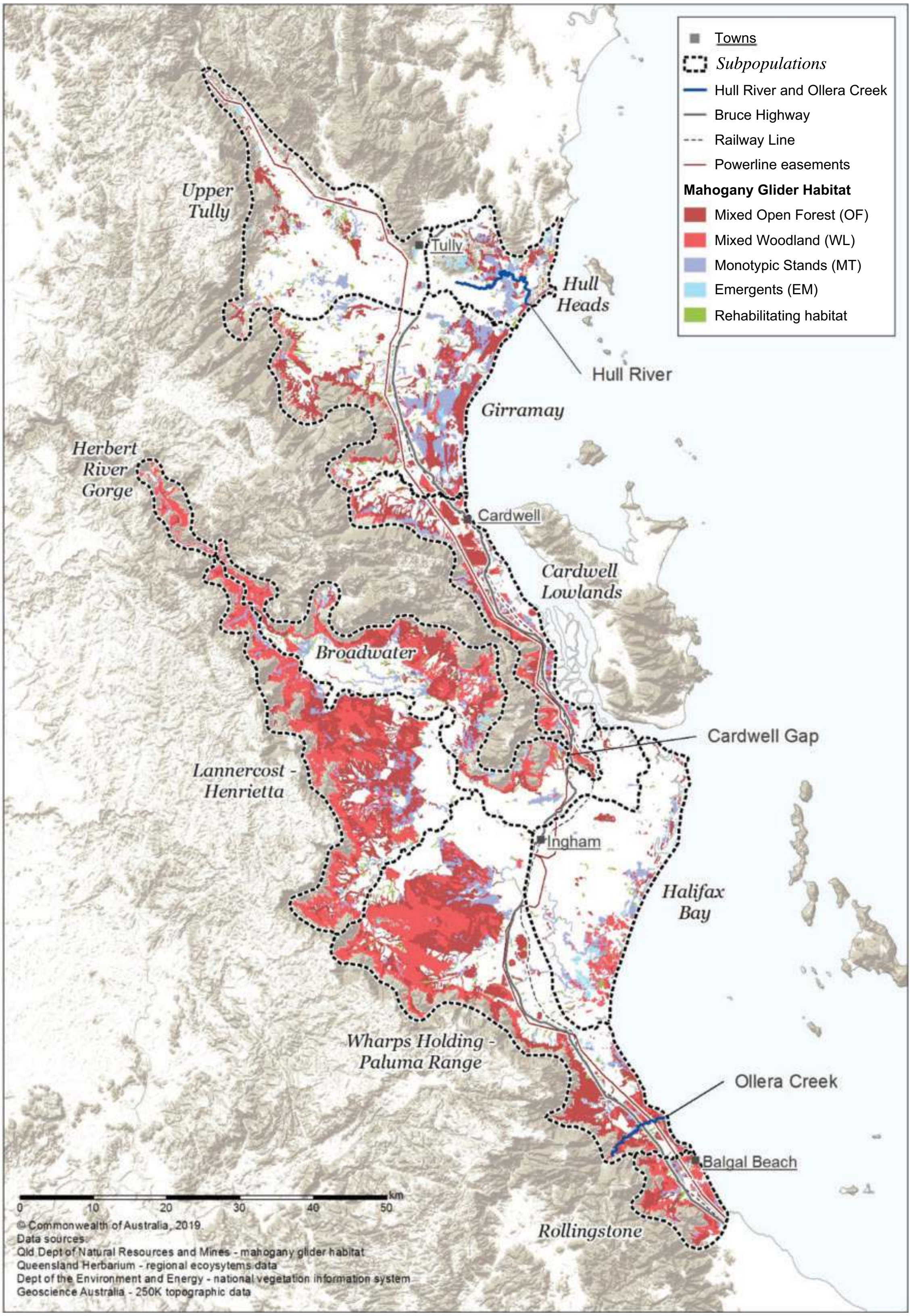

Fig. 1. Location of the different subpopulations of the mahogany glider within its known distribution. The topography is also shown to indicate how the subpopulations link together.

Table 1. The areas of primary and secondary subpopulations and associated fragments of habitat within the distribution of the mahogany glider
Fragments within 100 m of each other are considered to be 'continuous'. The 'Maximum' column refers to the largest fragment of habitat in that subpopulation. The 'Fragment sizes' column shows the number of fragments in each size class. Range limit are areas of suitable habitat on the drier margins of the known distribution where the glider has not yet been found

Subpopulation	Population type	Area (ha)	No. of glider records	No. of fragments	Maximum area (m)	Fragment sizes (ha) <1–20	21–100	>100	>8000	Total edge (m)	Ratio edge/area
Girramay	Primary	18 326	51	168	13 738	155	11	1	1	1 599 672	87
Cardwell Lowlands	Primary	11 386	60	50	11 084	44	5	0	1	1 064 807	94
Broadwater	Primary	15 495	20	121	14 791	113	6	1	1	1 475 430	95
Lannercost–Henrietta	Primary	28 846	29	60	28 566	57	2	0	1	1 712 546	59
Wharps Holding–Paluma Range	Primary	33 430	163	125	32 831	115	9	0	1	1 975 615	59
Upper Tully	Secondary	3369	0	222	489	200	13	9	0	645 914	192
Hull Heads	Secondary	4162	1	76	2648	60	13	3	0	522 981	126
Halifax Bay	Secondary	5030	2	159	2611	140	15	4	0	800 018	159
Herbert River Gorge	Range limit	1253	0	7	1188	4	2	1	0	148 368	118
Rollingstone	Range limit	5412	0	10	5397	9	0	1	0	370 111	68
Average		12 671	33	100	11 334	90	8	2	1	1 031 546	106
Total		126 708	326	998	113 343	897	76	20	5	10 315 463	

above 120 m: gliders have only rarely been recorded above this elevation (Jackson *et al*. 2011).

A primary subpopulation was considered to be one that had an estimated minimum viable population of at least 800 individuals occupying an area of at least 8000 ha based on a previously conducted population viability analysis and known density estimates of this species (Jackson 1999, 2000*a*). Primary subpopulations also contained preferred habitat utilised by the mahogany glider as mapped by Jackson *et al*. (2011), and confirmed by the number of glider sightings. Secondary subpopulations were those that occupied an area of less than 8000 ha and therefore were thus considered to be unviable without the establishment of corridors to connect them to larger fragments of habitat.

Mapping of corridors

The location of potential corridors for restoration were subjectively identified using maps of the entire preclearing and current distribution of the mahogany glider (Jackson *et al*. 2011). Efforts were made to visit each corridor in the field (depending on land tenure and access permitted by the owner) to determine the condition of each priority corridor, including the number of gaps greater than 30 m in length (i.e. the average glide distance), the summed gap length, and the dominant tree species. Where on-ground access was not possible these attributes were determined using remote-sensing satellite imagery.

Each corridor was subjectively prioritised for restoration using a combination of factors including: (1) the length of the corridor; (2) the quality of the habitat within the corridors, with better corridors having dominant tree species utilised by the glider and the absence of rainforest (Jackson 2000*d*, 2001; Jackson *et al*. 2011); (3) whether they were linked to a primary or secondary subpopulation; and (4) the number of other corridors connecting the same subpopulation. Corridors were classified according to the urgency with which they needed to be restored based on the factors referred to above. Corridors recognised as 'High' priority should be targeted for commencement of restoration within 2–5 years, those marked as 'Medium' within 5–9 years, those as 'Low within 9–12 years.

Results

Habitat fragments and subpopulations

In total, 998 fragments of habitat were identified within the current known distribution of the mahogany glider. Of these, 897 (90%) fragments were smaller than 20 ha. A further 76 (7.5%) fragments were 21–100 ha. Only 25 (2.5%) fragments were larger than 100 ha. The latter were relatively evenly distributed among the different glider subpopulations, each of which ranged over one and nine large fragments (larger than 100 ha) (Table 1). Only five fragments were larger than 8000 ha. The number of fragments within primary subpopulations ranged from 50 to 168 and for secondary subpopulations, 7 to 222. The maximum area of individual fragments of habitats ranged from 11 084 to 32 831 ha for the primary subpopulations and 489 to 5397 ha for the secondary subpopulations (Table 1). The size of the various subpopulations was reflected in the number of mahogany glider records. There were 20–163 glider reports for each of the primary subpopulations but fewer than two for each of the secondary subpopulations.

Habitat connectivity within and between subpopulations

Throughout the distribution of the mahogany glider a total of 55 corridors were identified (Fig. 2, Table S1 available as Supplementary Material at the journal's website). The glider subpopulations with the greatest need to increase habitat connectivity to adjacent subpopulations include those at Girramay with 16 corridors (one shared with the Cardwell Lowlands subpopulation), Cardwell Lowlands with 7 corridors (one shared with that at Girramay), Broadwater with 5 corridors, Lannercost-Henrietta with 4 corridors (one shared with that at Wharps Holding–Paluma Range), and Wharps Holding–Paluma Range with 17 corridors (including 1 shared with that at

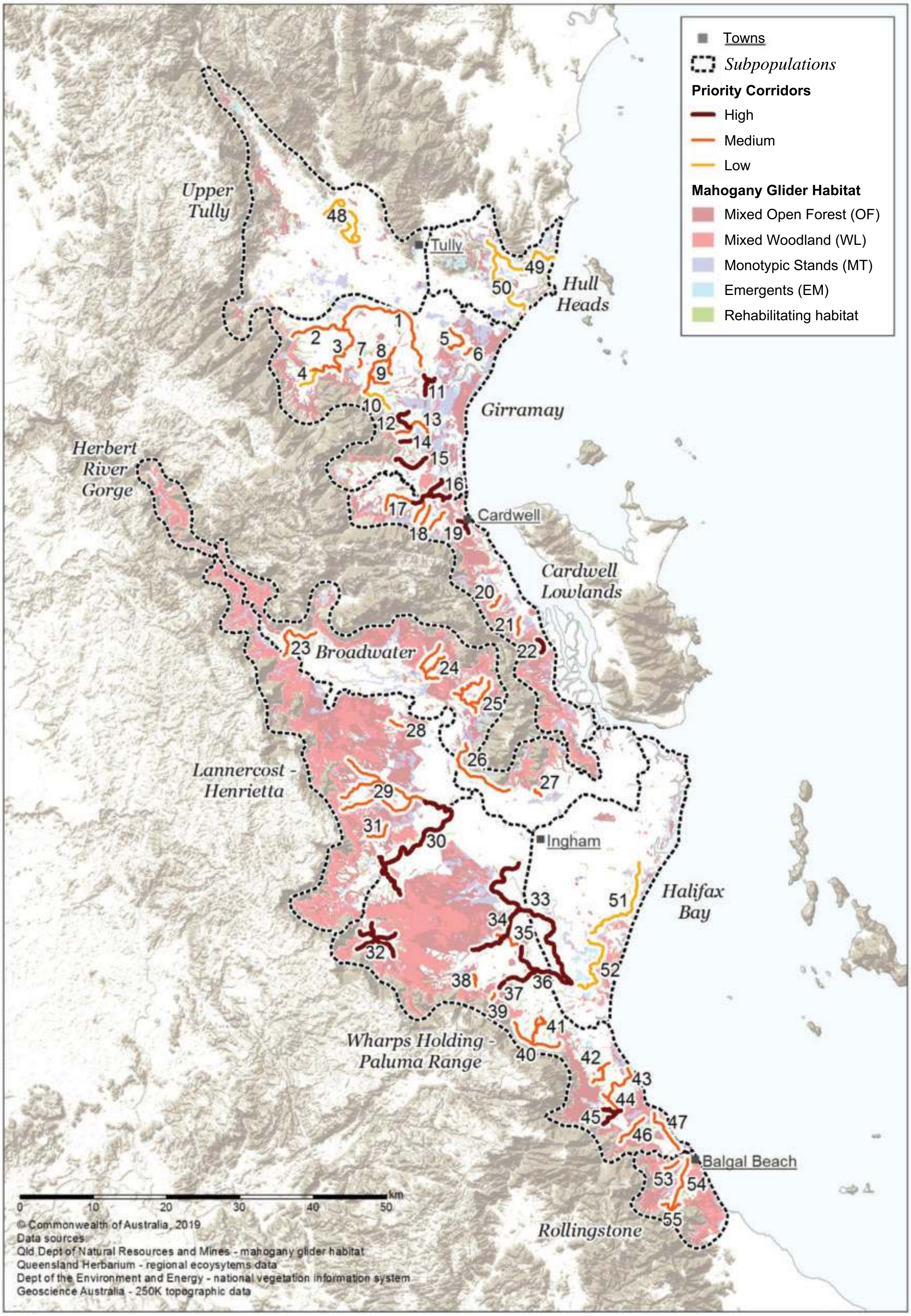

Fig. 2. Location of the 55 numbered corridors located within and between the subpopulations. The topography is also shown to indicate how the subpopulations link together.

Lannercost-Henrietta and 2 shared with that at Halifax Bay). On the periphery of the distribution the Upper Tully subpopulation had 1 corridor, Hull Heads had 2 corridors, Halifax Bay had 2 corridors and Rollingstone had 3 corridors.

Condition of corridors

Of the 55 corridors, 36 were accessed on-ground to determine various attributes, including tree species composition (unpublished data) and total length, gaps >30m, and combined gap lengths (Supplementary Material Table S1). The average length of the corridors was 8.25 km. The condition of the corridors was assessed by the average number of gaps >30 m, which was calculated to be 3.4, and the total length of the gaps of each corridor, which was calculated to be 523 m (Supplementary Material Table S1). All corridors were at least partly in existence but incomplete so require formal protection and enhancement by removing gaps across their length. Of the corridors identified, 14 were high priority, 34 medium priority, and 7 low priority.

Discussion

Glider subpopulations and corridors

The current study aimed to identify the degree of habitat fragmentation of the remaining remnant vegetation occupied by the mahogany glider and to identify subpopulations within its distribution. It also aimed to identify key corridors for restoration to facilitate the movement of this species between subpopulations. The results confirmed a high degree of habitat fragmentation, with a total of 998 fragments, of which only five were larger than 8000 ha, the threshold used to define a viable subpopulation of the mahogany glider. In total, 55 corridors were identified that could maximise the movement of gliders within and between these subpopulations. The restoration of connectivity in the identified corridors is an important component in the conservation of this endangered species that is currently the subject of a draft national recovery plan (Jackson and Diggins, in press). It has been argued that low-quality corridors could act as sinks (i.e. populations maintained by immigration) and lead to a high mortality rate that decreases the size of the subpopulation (Henein and Merriam 1990; Soulé and Gilpin 1991). In contrast, other research on metapopulation theory that assessed source–sink dynamics has proposed that an increased exchange of individuals between source patches and sinks is important as they may provide a stabilising effect, thus promoting population viability (Holt 1997). Therefore, a limited number of seemingly insignificant small but high-quality habitat patches could play an important role and should be taken into consideration (Foppen *et al*. 2000). Despite potential concerns mahogany gliders are highly mobile, travelling 590–3430 m (mean 1506 m) per night, and will utilise corridors if they include suitable plant species as gliders are known to reside in corridors for varying lengths of time if there is adequate food and shelter (Jackson 1998, 2000*b*, 2001; Asari *et al*. 2010). They are also known to regularly cross artificial breaks in habitat by gliding, including the Bruce Highway, minor roads and electricity transmission easements, which can exceed 40 m (Jackson 1998, 2000*b*; Asari *et al*. 2010).

Artificial wildlife crossing structures such as wooden poles and rope bridges have been successful in facilitating the movement of arboreal marsupials, including the sugar glider, squirrel glider and yellow-bellied glider (*Petaurus australis*) across large gaps including major roads (Ball and Goldingay 2008; van der Ree *et al*. 2010; Goldingay *et al*. 2011, 2013*b*, 2019; Taylor and Goldingay 2012, 2013; Soanes *et al*. 2013, 2015, 2018). A study on squirrel gliders along a 70-km section of the Hume Freeway in Victoria, Australia, monitored the use of canopy bridges and glider poles and suggested that it takes time for gliders to adequately habituate to crossing structures, so they should be monitored for at least two years (Soanes *et al*. 2013). An associated genetic study by Soanes *et al*. (2018) along the same stretch of freeway found that gene flow was restored within five years by installing crossing structures across barriers such as freeways. Glide poles have been erected for the mahogany glider to glide across powerline easements, the Cardwell Gap overpass where widening of the highway has occurred, and several other smaller road crossings where vegetation does not currently exist. Preliminary observations show that mahogany gliders use these poles, but further studies are needed to assess their effectiveness in enabling movement. Therefore, in some instances, gliding poles or rope bridges may act as an important component in facilitating habitat connectivity for the mahogany glider.

Plant species composition of corridors

Where corridors need to be restored, natural regeneration should be encouraged by excluding domestic livestock, and controlling competitive grasses, until the trees are large enough to withstand fires and cattle pressure. Tree planting should reflect the preclearing ecosystem mapped for the area (Jackson *et al*. 2011). Tree species recommended for planting includes those of the genera *Eucalyptus*, *Corymbia, Melaleuca* and *Acacia* (Jackson 1998; Supplementary Material Table S2). It is important to plant multiple individuals of each species to allow for a potentially high failure of establishment.

Corridor management

An active program of fire management is required to ensure the long-term usage of corridors by the mahogany glider, due to issues such as rainforest expansion, sclerophyll thickening and weed invasion (Jackson 1998; Jackson *et al*. 2011). Corridors often have high numbers of rainforest pioneers or introduced grasses and vines that can decrease the effectiveness of the corridor over time by impeding the growth of sclerophyll trees (e. g. Panetta and Hopkins 1991; Jackson *et al*. 2011). Rainforest expansion occurs along creek lines from the inside out, leaving only emergent food trees such as *Corymbia intermedia*, *Eucalyptus pellita*, *Eucalyptus tereticornis* and *Melaleuca leucadendra*, and a long-term transition to rainforest ensues (e.g. Ash 1988; Unwin 1989; Harrington and Sanderson 1994). Rainforest species are not typically utilised for shelter by this species, with only *C. torelliana* and *Melicope elleryana* known to be utilised for food (Van Dyck 1993; Jackson 2001). Sclerophyll thickening can also reduce corridor utility for the glider, and some native species, in particular *Acacia flavescens*, can grow in high densities along creek lines and the edges of corridors leading to decreased utilisation by the mahogany glider and increased usage by the sugar glider (Jackson 2000*d*).

Conclusion

The current study confirms the high degree of habitat fragmentation across the distribution of the mahogany glider and that only five subpopulations appear to be viable. It also emphasises the need to strengthen the remaining subpopulations by restoring and maintaining a network of corridors to maximise the habitat connectivity between habitat fragments. The results of this study also provide a framework for components of the draft mahogany glider recovery plan (Jackson and Diggins, in press) and highlights the need for the strategic expansion of mahogany glider habitat within its known distribution by restoring priority corridors that have been identified.

Specific management actions for the mahogany glider associated with the restoration of corridors identified in this study include: (1) planting appropriate tree species along identified wildlife corridors to close gaps greater than 30 m in length; (2) installing artificial wildlife crossing structures such as wooden poles and rope bridges to assist animals to cross gaps where plantings are not possible or where it will take many years for trees to mature; (3) monitoring the effectiveness of vegetation corridors and artificial wildlife crossing structures (using camera traps) in allowing gliders to move between habitat fragments; (4) undertaking a broad genetic study that provides data on current gene flow throughout the distribution; (5) monitoring populations in several large and small habitat fragments; (6) implementing appropriate fire regimes to manage the habitat to reduce rainforest expansion and sclerophyll thickening; (7) undertaking further research to maximise the effectiveness of the use of fire; (8) replanting habitat on land that has been destroyed from stochastic events such as tropical cyclones; (9) undertaking an active program of weed management along corridors and within fragments of habitat; (10) promoting the use of only high-tensile plain wire (i.e. without any barbs) for fencing if no cattle are present (if cattle are present consider avoiding barbed wire on the top two or three strands of the fence as this will reduce the risk of entanglement: van der Ree 1999); and (11) removing livestock from corridors to reduce the introduction and impact of weeds and allow better growth of the vegetation.

Conflicts of interest

The authors declare no conflicts of interest.

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