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Recreational trails are an important cause of fragmentation in endangered urban forests: a case-study from Australia

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Introduction

Recreational use of natural areas is increasing worldwide (Balmford et al., 2009; Monz et al., 2010; Newsome et al., 2013). In urban regions, remnant natural areas are important resources providing opportunities for people to engage with nature (Florgård, and Forsberg, 2006; Swanwick et al., 2003). Benefits of this include health, education and social connectedness with outdoor recreation largely viewed as a positive opportunity in areas otherwise lacking natural experiences (Lee and Maheswaran, 2011; Shafer et al., 2000; Takano et al., 2002). Recreational activities and the infrastructure provided for them, however, can also have negative environmental impacts where they are not effectively designed or managed. Despite rapid urbanisation globally, ecological research into the impacts of recreational activities and infrastructure in urban natural areas has lagged in comparison to similar research in protected and wilderness areas (Gaston, 2010).

Trails are among the most common forms of infrastructure provided for, or created by, visitors to many natural areas (Marion and Leung, 2001; Marion and Wimpey, 2007). In urban areas, recreational trails planned by management are often bordered by greenways of linear natural or semi-natural vegetation and thus have perceived benefits for community connectivity, varied recreational opportunities, alternative transportation, pollution reduction and environmental protection (Conine et al., 2004; Shafer et al., 2000). In this light, judiciously-planned urban trails can provide important benefits for local people and the local environment and extensive planning has been undertaken in such areas to maintain their sustainability (Conine et al., 2004; Gobster and Westphal, 2004). However, trails can become important environmental threats where their construction, maintenance and use are inadequately designed and managed causing a range of direct and indirect impacts on flora, fauna, soils and water (Cole, 2004; Liddle, 1997; Monz et al., 2013) as well as on the user experience itself (Lynn and Brown, 2003).

The environmental impacts of recreational trails have been comprehensively studied worldwide (Liddle, 1997; Monz et al., 2010). Some of the most well-documented impacts include reduced height and cover of vegetation and changes in composition as a result of trampling (Bernhardt-Römermann et al., 2011; Hill and Pickering, 2009; Pescott and Stewart, 2014; Zhang et al., 2012), changes in soil compaction and erosion (Farrell and Marion, 2002; Nepal and Nepal, 2004; Olive and Marion, 2009; Wilshire et al., 1978), increasing nutrient leaching (Godefroid and Koedam, 2004; Müllerová et al., 2011), changes to soil microbiology (Malmivaara-Lämsä et al., 2008), introduction of weed species and pathogens (Baret and Strasberg, 2005; Barros et al., 2013; Dickens et al., 2005; Hemp, 2008) and wildlife disturbance (Marzano and Dandy, 2012; Taylor and Knight, 2003). Other impacts however have received less attention in the literature, particularly large scale processes such as the extent to which trails may cause landscape fragmentation (Leung et al., 2011a; Pickering et al., 2012).

Fragmentation is a process by which once-contiguous areas of habitat are physically separated by human disturbance creating a network of isolated patches (Lindenmayer and Fischer, 2006). Tourism and recreation can contribute to this process through the clearance of vegetation for infrastructure such as resorts and hotels (Fenu et al., 2011; Peñas et al., 2011), as well as internal fragmentation of remaining vegetation by trail networks (Pickering et al., 2012). Trail networks are essentially complex linear arteries of disturbance with varying geometry that contribute to fragmentation by decreasing the total amount of undisturbed habitat in a given area (Geneletti, 2004; Leung et al., 2011a; Pickering et al., 2012). Moreover they can act as barriers to the movement of native organisms and conduits aiding the dispersal of invasive or feral ones (Benninger-Truax et al., 1992; Drayton and Primack, 1996). Trails also cause change at varying distances into adjacent vegetation, so-called edge effects, that alter abiotic factors such as light, wind and nutrient levels and hence, important facets of biodiversity such as community structure, function and composition (Pickering et al., 2012). In high use areas with extensive networks of trails, the combined area of trail tread and edge effect may even exceed that of undisturbed habitat (Barros et al., 2013). In urban areas where natural land is already limited by development, recreational trails may exacerbate this problem if their condition and spatial spread is not actively controlled and managed (Pickering et al., 2012). Although formal planned trails do often concentrate damage to limited areas (Marion and Leung, 2001), it is the proliferation of unauthorised, informal trails that is often more responsible for trail-based fragmentation (Leung et al., 2011a; Wimpey and Marion, 2011).

This research assesses how recreational trails can contribute to the fragmentation of an endangered remnant forest type in urban areas. Specifically, we assessed trail networks using geographic information systems (GIS) in 17 remnants of an endangered urban forest across 937 km^2 of some of the most highly developed lowland regions of Australia. The aims of the study were to: 1) assess the lineal extent and diversity of recreational trails in these remnants, 2) quantify the degree of trail-based fragmentation across remnants, 3) determine possible human and environmental factors influencing fragmentation in these remnants, and 4) explore possible relationships between these factors.

Methods

As a result of land clearing for agriculture and urbanisation along the east coast of Australia, many ecosystems are at high risk of extinction, and now consist of small isolated remnants of once much larger, contiguous ecosystems (Lindenmayer and Fischer, 2006). In the southeast of the state of Queensland, expansion and urban infilling around the two largest cities, Brisbane and the Gold Coast, have resulted in extensive clearing of coastal lowland habitats (Bradshaw, 2012; McAlpine et al., 2007; Wilson et al., 2002). Over 100 (64%) of the 156 regional ecosystems in southeast Queensland are threatened (Queensland Government, 2013). Many of these urban remnants are now popular destinations for recreational use (Queensland Government, 2007; Rossi et al., 2012) including the endangered Tall Open Blackbutt Forest ecosystem (Pickering et al., 2012).

This open dry forest is dominated by the tall hardwood *Eucalyptus pilularis* with a sparse shrubby mid-storey and under-storey of graminoids and forbs (Queensland Government, 2013). It is state-listed as ‘Endangered’ once covering over 10,000 ha prior to urbanization, but by 2006 only around 20% (2,024 ha) remained (State of Queensland, 2013). It is now restricted to a series of around 226 small (circ. 8 ha) scattered remnants within urban areas. Only 14 of these remnants are greater than 20 ha, some of which are protected under national park or conservation area status while the rest are very small with many having been sold to developers.

The forest provides habitat for a number of threatened fauna including the International Union for the Conservation of Nature (IUCN) Red-listed Green-thighed Frog (*Litoria brevipalmata*) and the Queensland state-listed Wallum Froglet (*Crinia tinnula*) and Glossy Black Cockatoo (*Calyptorhynchus lathami*). It also forms a popular destination for recreational use at least in part because most remnants are close to urban populations. The forest has a mixed terrain and generally open structure facilitating trail creation and many of the smaller remnants are unprotected.

Study Region

The study took place within a 937 km^2 region between the Brisbane River and the New South Wales border in southeast Queensland where the majority of extant Tall Open Blackbutt Forest ecosystem remains (Figure 1). Soils in this region are characterised by coastal Palaeozoic sediments that have been strongly metamorphosed and interbedded with igneous strata (Queensland Government, 2013). The climate is sub-tropical with a mean annual temperature of 21.3°C and mean annual rainfall of just over 1,000 mm (Australian Bureau of Meteorology, 2013). Local topography is largely low-lying, under 100 m a.s.l., interspersed with sedimentary foothills that rise to igneous hinterland ranges in the west of about 1,000 m a.s.l. Within this region there are around 226 isolated remnants of Tall Open Blackbutt Forest covering 2,024 ha.

Sampling the lineal extent and diversity of recreational trails

First we identified all suitable remnants for sampling: e.g. all those that were > 5 ha and accessible to the public. Of the 226 remnants within the 937 km^2 region, only 31 fit these criteria based on data from the 'Vegetation Management Act (VMA) 2006 Remnant Regional Ecosystems of Queensland' and spatial data from the 'Land-use' and 'Land used for public recreation 2011' GIS layers (Queensland Government, 2013). When these 31 remnants were assessed during site visits in 2013, it was found that only 17 of them still fit the criteria with 13 having been transferred to private land and one clear-felled.

Between January and May 2013 the perimeters (and therefore areas) of the 17 Blackbutt forest remnants totalling 829 ha and all recreational trails within them were mapped. Remnants were geographically clustered in two districts: one to the north of the 937km^2 study region in the rural Redlands, and the other in the south around the highly urbanised city of the Gold Coast. Trail mapping was done using a Trimble Juno ST handheld GPS unit compatible with ArcPad Version 7.0, with a sampling interval of 1 m and a measurement accuracy of 1-10m. A trail was considered to be for recreational use where there were: 1) obvious signs indicating a visitor attraction (e.g. national park), 2) formal mapping by management or publication of trails on websites or blogs, 3) visible signs of recreational use (e.g. bike jumps, tyre marks), and/or 4) information on use provided by management staff. Trails were not mapped where: 1) they provided access to residences or other infrastructure, 2) they were formal highways cutting through forest remnants, 3) they were obviously animal-made, and/or 4) they appeared to be used primarily for access to forest land for dumping waste.

Recreational trails were mapped and divided into categories based on a visual survey method similar to those commonly used for condition class assessments of trails (Farrell and Marion, 2001; Walden-Schreiner and Leung, 2013). Categories were based on average width, formality and substrate; three important factors that can affect impacts (Cole, 2004; Marion and Leung, 2004). Widths of trail tread, defined as the most heavily trafficked area of the trail (Wimpey and Marion, 2010), were assessed to the nearest centimetre at the start of each new segment and categorised (1-5m wide) with 1m width allowing passage of 1 person (Pickering et al., 2012). Substrates were recorded as native (tempered bare soil or churned earth), mown grass, hardened with a loose edge (e.g. gravel and hard-core) or hardened with a hard edge (e.g. tarmac and concrete). Trails were also recorded as either formal or informal. Formal trails were those with visible maintenance, signage and/or accessed infrastructure and/or mapped by land-owners for public use. Informal trails were those that appeared to be both created and maintained by trail-users for recreation outside of the formally-managed trail system (Leung et al., 2002). The main type of recreational use per trail was also recorded based on visual observations and consultation with park managers. For multi-use trails, we recorded the main type of recreational use as the most popular activity based on ground observations and discussions with managers. Multi-use trails were rather common but a dominant use type was also apparent in most.

The overall loss of forest strata (litter, understorey, midstorey and trees) along trails was assessed using a stratified random sampling approach at 60 randomised points distributed amongst trail types in each surveyed remnant (n = 17) across the entire mapped trail network. All trail types based on width, formality and substrate were more broadly categorised into average widths for this analysis. As width of trail gap correlates directly with the loss of forest we broadly categorised trails [small (0-1 m), medium (1-3 m) and large (>4 m) trails] and applied 20 random points stratified within each using ET GeoWizards 10.2 in ArcMap Version 10.1. (Pickering et al., 2012).

To ensure that all trails were mapped, the field data was compared with aerial images from Google Earth, the 'land used for publication recreation 2011' GIS layers, online recreational blogs such as MTB Dirt (http://www.mtbdirt.com.au) and private land-cover maps. Forest perimeters in national park or conservation areas were not re-mapped unless they were known to have changed since the original 2006 remnant vegetation boundaries or if visual observations in the field indicated change.

Remnant forest perimeters and trail attributes were post-processed in ArcMap following guidelines from Leung and Louie (2008) and Moskal and Halabisky (2010) and to improve on any mapping errors from the GPS. The current and 2006 boundaries of the remnants were overlaid in contrasting colours. Noise from satellite readings was cut and split to avoid overlaps and miscalculations in distance measures. All trail sections belonging to a single category were then merged for calculating total length. The 'cleaned' remnant forests and trail layers were transformed from the default spheroid-based geographic coordinate system 'GCS_WGS_1984' used by the GPS to the 'GCS_Australian Geodetic Datum_1984' as the new geographic coordinate system and then to 'GDA_1994_MGA_Zone_56 Transverse Mercator' as the new local projected coordinate system. This allowed accurate measurement of the current area of each remnant, total trail length and total length of each trail type across the 17 remnants.

Quantifying trail-based fragmentation

Using ArcMap to assess the extent of internal fragmentation by trails within the 17 forest remnants, all trails were first buffered using their average width; data collected during trail mapping (Moskal and Halabisky, 2010). All trail buffers were merged across each trail category and erased from the remnant layer to accurately show the non-trailed remnant area only. Finally, the 'Explode Multipart Feature' tool was used to divide the remnant area into multiple 'patches' (Leung and Louie, 2008). Patches were thus distinct polgyons separated from other patches either entirely by trails and their area of edge effect, or by a conglomeration of trails and a remnant's actual edge/edges. The variation in the number and size of these patches per remnant was then used to determine the degree of trail-based fragmentation.

For each forest remnant, two specific measures of trail-based fragmentation were calculated; the Weighted Mean Patch Index (WMPI) and the Largest 5 Patches Index (L5PI) (Leung et al., 2011a). The former improves on work by McGarigal and Marks (1995) by accepting that trails have a dimension of their own and so their linear proliferation reduces the proportion of undisturbed habitat. Weighted Mean Patch Index adds a weighting related to the proliferation of trailed areas in a remnant so that it is not just based on remnant-size (Leung et al., 2011a) such that,

$$\mathrm{WMPI} = \mathrm{wf} * (\sum a_{ij}/n) * (1/10{,}000) \qquad (1)$$

where, wf (weighting factor) = $(\sum a_{ij}/A)$; a_{ij} = area (m^2) of patches ij; n = total number of patches; A = remnant area (m^2). Results are in hectares, with smaller values indicating higher fragmentation (range 0 - ∞).

The L5PI differs to WMPI in that it sums the area of the largest five patches to evaluate the proportion of the fragmented remnant occupied by relatively large, more undisturbed patches, and not just assuming fragmentation occurs similarly across all remnants. This method improves that of McGarigal and Marks (1995) by averaging the size of the largest five patches rather than using the largest single patch and risking over-sensitivity to changes in its area. The formula is,

$$L5PI = \sum \max_5 / A * 100\% \qquad [2]$$

where, $\max_5$ = largest 5 patches within remnant x, A = area (m^2) of remnant area. Results are in percentages with smaller values showing higher degrees of fragmentation. Both indices have been used in previous studies of fragmentation by recreational trails (Leung et al., 2011b; Moskal and Halabisky, 2010). We also used a third, more general measure, median patch size to compare its efficiency against WMPI and L5PI in analysing fragmentation.

To compare whether values for WMPI, L5PI and median patch size differed significantly between northern (Redlands) and southern (Gold Coast) districts (possibly relating to different levels of urbanisation) we used a simple One-way Analysis of Variance (ANOVA) in SPSS Version 21. Values for all three measures were log-transformed to satisfy normality and the assumptions of the ANOVA model.

The total loss of forest along trails across the 17 remnants was calculated using ArcMap. The total area without litter, understorey, midstorey and tree vegetation was calculated by buffering the previously-ascribed small, medium and large trail categories by the mean distance to each of these four forest strata (calculated using the 60 randomised points), dissolving any overlapping buffers (Pickering et al., 2012). This buffer was then erased from each of the respective forest polygons and overall loss of each strata calculated for the total 17 remnants. This essentially showed an average loss of forest due to trail edge effects which when combined with the loss of forest to the trail itself, provides a figure for total combined loss.

Possible causes of fragmentation

To assess factors that could be contributing to the creation of trail networks and hence fragmentation, we identified 10 possible predictors (Appendix A). These were selected based on a systematic review of academic literature on trail impacts, field assessments and discussions with park management staff. The literature review used 153 references retrieved from Google Scholar using the search terms ‘'Touris*', 'Fragment*', 'Trampl*', 'Bik*', 'Walk*', 'Disturb*', 'Hik*', 'Infrastructure', 'Climb*', 'Edge Effect*', 'Trail*', 'Network' in multiple combinations. The 10 chosen predictors included 7 scale variables: 1) local population density within 10 km of forest edge, 2) density of road/rail networks within 1 km of forest edge, 3) density of water bodies within forests, 4) total number of entry points, 5) percentage of trail network composed of native substrate, 6) percentage of forest on flat ground (< 5% rise), and 7) average altitude. Added to this were 3 categorical variables: 1) compatibility of surrounding land-use matrix, 2) status of forest, and 3) main trail-use (Appendix A).

All scale variables were entered into a Multivariate Ordinary Least Squares (OLS) global regression analysis using ArcMap 10.1 and assessed against the two indices of fragmentation (WMPI and L5PI) as dependent variables in separate models. Such spatial regressions help elucidate influential factors on spatial ecological patterns and highlight cases of autocorrelation amongst variables (Lichstein et al., 2002). To satisfy the assumptions of this type of analysis, variance inflation factors were maintained below 7 to avoid multicollinearity and variable redundancy (where multiple variables are correlated). The Koenker’s studentized Breusch-Pagan p-value (to check for variance in relationships across global study area) and Jarque-Bera p-value (to check for model bias and non-normally distributed residuals) both had to be non-significant (p >0.05). To check for spatial autocorrelation amongst WMPI and L5PI values across the 17 patches, a Global Moran’s I test using the residuals of each separate model was performed. For categorical variables, a main effects multivariate ANOVA was used to detect significant effects on the same two indices of fragmentation using SPSS Version 21. Values for both indices were log-transformed to satisfy normality and thus the assumptions of the ANOVA model.

Correlations amongst factors

We tested whether there was correlation between fixed factors including the size of forest remnants, total length of trails per remnant and any significant independent factors from the OLS, as well as dependent variables including the area lost to trails and the fragmentation indices. This was to determine whether there were underlying patterns between variables that could not be explained by the OLS model, especially those relating to the spatial attributes of each remnant. To do so, we eliminated one outlying remnant (at least 3 times greater in size than other remnants) and then performed a Pearson correlation on log-transformed data for all factors to determine correlations. We used a curve estimation function to determine the nature of the relationship between correlated factors using SPSS Version 21.

Results

What is the extent and diversity of trails in this endangered forest?

The current status of 17 remnants of Tall Open Blackbutt Forest, consisting of a total of 829 ha and ranging in size from 3 to 437 ha, was assessed. The area of forest within seven remnants had declined since original mapping was done in 2006, some by as much as 77% largely due to land clearance by developers (Table 1). This process has led to an overall reduction of 69.3 ha (7.7%) over seven years from a total of 898 ha in 2006.

There was a total of 46.1 km of recreational trails within the remaining 829 ha of forest consisting of 14 different trail types (Table 2). Over 57% (26.5 km) were informal trails where the trail surface consisted of either tempered/churned earth or trampled/mown grass (Figure 2). All the formal trails (43%; 19.6 km) were hardened and included hard solid-edged (concrete and tarmac) and hard loose-edged trails (gravel) (Figure 2).

The trails were used for a range of activities, with biking (23.1 km; 50%) and hiking (20.6 km; 45%) trails the most common, while there were fewer dirt-biking (1.4 km; 3%), visitor parking and entry (468 m; 1%) and 4x4 trails (186 m; 0.4%) (Table 3). The trails used for motorised sports such as 4x4-driving and dirt-bikes tended to be wider than others averaging 3.9 m in width (range 2.6-7.1 m). The trails used for biking and hiking were considerably narrower averaging 2.3 m in width (range 0.8-3.4 m).

How much have trails contributed to the loss of forest?

By combining average widths and lengths of each trail type, we found a total of 18 ha (2.2%) of the 829 ha of forest had been cleared for recreational trails (Table 3). Based on the data from 60 points measuring the distance from the edge of the trails to different structural components of the forest, the network also caused the additional loss of 0.8 ha of the litter strata, 5.7 ha of understorey, 17.8 ha of mid-storey and 29.2 ha of the tree strata, with wider trails causing the greatest loss. Combining the direct loss of vegetation from the trail tread itself with the loss of adjacent vegetative strata, a total of 47.2 ha (5.7%) of forest has been directly affected by trail-based fragmentation.

Based on their contribution to the loss of forest from their tread and edge effect, particular types of trails such as 4x4 trails and dirt-bike trails caused more severe localised damage (Figure 2b) but as these trails were relatively uncommon their impact on forest loss was small overall (0.3 ha lost overall). At the local scale however, these trails caused more severe damage, affecting > 5% of smaller remnants. Generally, hiking and biking trails caused most forest loss because they accounted for over 95% of the total lineal extent of all trails with some remnants losing as much as 16% of forest due to this use (Figure 3).

How much have trails contributed to forest fragmentation?

When quantifying fragmentation using the WMPI and L5PI indices, we found that the most fragmented remnants were in the highly urbanised southern district (Gold Coast). Around 97% of the trails in these seven remnants were informal biking and hiking trails whereas for the northern district in the more rural Redlands area, only 39% of trails were informal and they were mostly for biking (Table 3). There were differences in the average fragmentation measures between the north and south, but none significant. The average WMPI in the south was 2.53 compared to 15.27 for the north ($F = 3.711$, $p = 0.073$), while for L5PI it was 87.46 in the south compared to 93.9 in the north ($F = 0.945$, $p = 0.346$). The remnants in the southern district also had a much lower median patch size of 2.28 ha, while for the northern remnants it was 13.97 ha ($F = 1.369$, $p = 0.260$) (Table 3). Remnants themselves were on average much smaller in the south (9.8 ± 8.2 ha) than the north (75.9 ± 133.5 ha). As part of their small size, southern remnants had high average trail densities at 126.4 ± 92.7 m ha^{-1} compared to 46.4 ± 33.1 m ha^{-1} in the north. This disparity is also partly due to higher proportions of trails per unit area across all remnants in the south, whereas in the north the range of total trail lengths was much greater (27.3 km vs. 6.5 km for the southern district) with only a few large remnants containing most of the trails.

The two indices WMPI and L5PI provide different information about fragmentation in the remnants. The two most fragmented remnants were in the south according to the WMPI index (Musgrave Park, 0.35 and Coombabah Wetlands, 0.36). However, according to the L5PI index, the largest five sub-patches of each of these remnants comprised over 87% and 93% of total forest areas, respectively. A third remnant (Griffith University) in the south, however, had both a low WMPI (0.49) and L5PI (49%) meaning that this remnant was the most fragmented based on both indices likely a result of the rather uniform degree of fragmentation across the whole remnant and that all patches created were similarly small.

What are the factors influencing fragmentation in remnants?

When we assessed factors that may contribute to trail-based fragmentation using Ordinary Least Square regressions, the only significant passing model and predictor of fragmentation was the number of entry points per remnant and this was only significant using L5PI. Using this index, we found that fragmentation increased with the number of entry points and subsequently lowered the L5PI value (Adjusted $R^2 = 0.67$, $p = <0.001$, $JB = 0.49$, $AIC = 161.68$, *Koenke*r = 0.74; *Moran's I z-value* = -0.97, $p = 0.33$). A multivariate ANOVA on categorical variables found that none of these factors significantly affected the level of fragmentation either across remnants for both WMPI and L5PI indices ($p > 0.05$).

Are there correlations amongst factors?

Some of the factors we assessed were correlated with each other. For example, the size of remnants, as expected, was correlated with WMPI ($p = 0.003$), but not the length of trails ($p = 0.143$), the total area lost to trails ($p = 0.056$) or the number of entry points ($p = 0.646$).

For the trails themselves, the total length was positively correlated with the number of entry points (linear relationship, $R^2 = 0.51$, $p = 0.001$). For the two fragmentation indices, the total length of trails, the number of entry points and the area lost to trails were all negatively correlated with L5PI (cubic relationships, $R^2 = 0.86$, $p = <0.001$; $R^2 = 0.79$, $p = <0.001$; $R^2 = 0.50$, $p = 0.025$). The area of the remnant and median patch size were positively correlated with WMPI (cubic relationships, $R^2 = 0.77$, $p = <0.001$; $R^2 = 0.63$, $p = 0.004$). We also found that the WMPI and L5PI indices were not correlated with each other and hence appear to explain different aspects of fragmentation well ($p = 0.316$).

Discussions

What is the extent and diversity of trails in this endangered forest?

We found that the majority of trails across the 17 remnants of endangered Tall Open Blackbutt Forest were informal, especially in the highly urbanised south of the study region. Informal trails are particularly problematic as they tend to be poorly planned and managed and hence can traverse sensitive habitats including areas occupied by rare species and ecosystems with limited tolerance to disturbance (Marion and Leung, 2011; Newsome and Davies, 2009). They can also facilitate the use of these areas for a range of illegal activities such as poaching and dumping (Baret and Strasberg, 2005; Matlack, 1993). The lack of trail-design and regulation often leads to proliferation of trails deep into forest interiors. This means entire forests can be exposed to an accumulation of complex geometrical networks of trail edge effects (Pickering et al., 2012). Depending on the nature of the trail and level of disturbance from the activities themselves, edge effects of forest clearing such as increased wind-blow, UV and weed dispersal may occur up to 50 m into adjacent vegetation (Harper and MacDonald, 2002; Harper et al., 2005) thus causing secondary biotic effects on structural, compositional and functional components (Harper et al., 2005; Leung et al., 2011b; Moxham and Turner, 2011; Stenhouse, 2004). For remnant forests, this can have particularly severe effects as many remnants are small (< 150 m wide), and therefore, the quality of the total area may be compromised as trails continue to dissect what is already essentially a habitat ‘island’ (Matlack, 1993; Drayton and Primack, 1996).

As found in other studies (Pickering et al., 2010a; Rossi et al., 2012; Wing and Shelby, 1999), mountain biking and hiking were the most common activities on trails accounting for over

95% of the total length of trails in the 17 remnants. On the trail itself, these activities can cause contrasting levels of environmental damage. Some studies have found that plant height, cover and soil erosion are less impacted under hiking and biking compared to other activities such as horse-riding (Pickering et al., 2010b), however others have found they can be as equally severe (Wilson and Seney, 1994). Across the 17 remnants, the hiking and biking trails tended to be on relatively flat ground and rather narrow, so their edge effects per unit area were small. However, because they are widespread and penetrate most of the remnants, they caused the greatest cumulative forest loss overall. This diluted effect across the whole landscape may be more damaging than the severe, but localised degradation caused by wide trails created and used for motorised activities. As such, the per unit area edge effect of trails may be surprisingly different to their overall contribution to forest loss. This area requires further research.

Despite accounting for < 5% of the total length of trails, the trails created by heavy, motorised recreation such as 4x4-driving and dirt-biking were much wider. This is likely to be a direct result of the fast, heavy mass-load of these activities and often repetitious accelerating and braking behaviour of users (Buckley, 2004; Liddle, 1997). As found in this study, the trails themselves tend to be formed as runs up and down steep hills (Wilshire et al., 1978). Such poorly designed, unsurfaced trails can result in large-scale soil erosion sometimes exceeding 1 metric tonne m^{-2} (Wilshire et al., 1978). This soil loss is generally seen as permanent with recovery/restoration difficult to implement (Olive and Marion, 2009). Eroded substrate can also pollute water-courses (Hammitt and Cole, 1998) and compromise visitor safety and experience (Marion and Leung, 2001). The repeated use of motorised activities also disturbs local wildlife (Buckley, 2004) and the wide geometry of these trails means that they can form similar barriers to the movement of animals across the trail as that caused by highways and roads (Goosem, 2007) particularly for macro-invertebrates, amphibians and small mammals (Baur and Baur, 1990; Gaines et al., 2003; Wilshire et al., 1978).

More work is needed to address the biological effects of different trail types based on activity. Such a quantification of associated impacts will allow managers to make decisions on whether an extensive but narrower network of trails (hiking and biking) is of greater ecological concern than small but more highly degraded areas such as those created for dirt-bike and 4x4 trails.

What are the degrees and causes of forest loss and fragmentation across the remnants?

We found that 5.7% of the forests had been directly lost or damaged by trails. This means that the level of forest loss caused by trails approaches that caused by external fragmentation for urban development.

To date, the majority of fragmentation research worldwide has concentrated on external, progressive clearance of vegetation as a result of development, agriculture and resource extraction (Bayne and Hobson, 1998; Gehring and Swihart, 2003; Harper and MacDonald, 2002; Moxham and Turner, 2011). In this study, however, we found recreational trails forming complex internal networks within forest remnants can cumulatively affect nearly as much area (5.7%) as these better-recognised sources of fragmentation (7.7%) although the time-frame and intensity at which these two processes operate is different. Despite these caveats, it is important to emphasise that although the process itself may not be rapid blanket clearing and thus biological effects may not be as severe, the arterial spread of multiple cleared areas for trails may still have a strong capacity to cause forest loss and ultimately result in long-term degradation of remnants across large areas. Many ecosystem responses may have a lagged temporal effect such as alterations to above-below ground nutrient cycling (Kissling et al., 2009) and plant dispersal (Broadhurst and Young, 2007) and may change as a function of visitor use patterns. Trail-based fragmentation therefore may play an important role in the persistence of these forests as functional ecosystems (Pickering et al., 2012).

Because forest remnants in the southern district of the study area had the most informal trails, the highest density of trails per unit area and the smallest size of remnants, these forests were the most fragmented, although not significantly different to the north (only marginally non-significant for WMPI). When we compare indices of fragmentation found here with those for heavily-visited national parks in the USA, we find the severity of fragmentation is of the same order of magnitude (Leung et al., 2011b; Manning et al., 2005; Moskal and Halabisky, 2010). For example, the degree of fragmentation of alpine meadows in Yosemite National Park, California was greater than in our study for only 15% of meadows; despite an annual park visitation to Yosemite of over 3.7 million people (Leung et al., 2011b). It is likely that these most fragmented remnants experience the greatest impacts in terms of biological structure, composition and function.

GIS-based spatial regression models did not detect many predictors of trail-based fragmentation which may be due to the reduced statistical power in this study (resulting from only 17 replicate remnants). The only significant predictor was the number of entry points which resulted in increasing fragmentation using the L5PI index. The number of entry points was also positively correlated with the total length of trails. It is likely that entry points were significant using L5PI due to its more accurate reflection of change to the largest patches created by trails, instead of relying on the mean as in WMPI. Access points are both a cause and product of trail-based fragmentation with studies showing that increased trail densities are positively correlated with increasing numbers of access points (Priskin, 2003). Increased visitor access also directly correlates with increased damage to vegetation (Farris et al., 2013). Visitor access is therefore an important factor to monitor, especially in areas with high visitor loads and easily-accessible terrain such as open urban forests.

On the other hand, we found no correlation between the size of forest remnants and the length of trails, although there were relationships present with the actual degree of fragmentation such that more trails and entry points caused a decline in the size of the largest five patches while a larger initial remnant size buffered trail fragmentation with less severe effect on the mean size of patches. This indicates that, although the resulting fragmentation is related strongly to the size of these remnants and the amount and density of trails, the actual process driving the creation of trails themselves between remnants may be rather idiosyncratic. In other words, larger remnants are no more likely to be initially disturbed by trails than smaller ones and that there are likely strong and variable socio-demographic influences on trail-based fragmentation even within a single landscape.

We also corroborated previous work (Leung et al., 2011a) that the two fragmentation indices, WMPI and L5PI, explain different aspects of the fragmentation and are useful metrics for related research when compared to other indices such as median patch size. These indices have the benefit that they are not over-sensitive to changes in the number of trails and patches if the actual extent of the effect is similar (Leung et al., 2011a). These indices could therefore be integrated into a ranking instrument to confidently monitor fragmentation over time (Leung et al., 2011a).

The remnants in the southern area of the study were in proximity to over twice the population found around the more rural northern remnants and nearly 3-times the density of roads and other hard infrastructure (State of Queensland, 2013). Despite not finding any effects of these urbanisation factors on trail-based fragmentation in this study or differences in fragmentation between more and less urbanised districts, we postulate that they may still be strong causal factors because they largely govern the amount of, and availability of access, for visitors (Stenhouse, 2004). Urbanisation is an important factor contributing to the creation of trails, especially informal ones which have a greater capacity to fragment (Ballantyne and

Pickering, 2012; Matlack, 1993; Newsome and Davies, 2009; Pickering et al., 2010a). Additional research with a greater number of replicates (remnants) across an urbanisation gradient may have greater statistical power, and hence, would provide clearer understanding of the range of factors that may influence trail-based fragmentation in an urban context.

Recommendations

Due to the high conservation value of many urban remnant forests (Godefroid and Koedam, 2003; Tratalos et al., 2007) and their importance in maintaining local ecosystem services (Niemalä et al., 2010; Tratalos et al., 2007), we emphasise the need for more sustainable planning and recreational use of these areas. Poorly-designed and regulated, dense informal networks of trails with numerous access points are primarily responsible for the trail-based fragmentation we found. We propose that managing poorly-designed trail networks to reduce forest loss and fragmentation should be the focus of a collaborative effort between conservation and recreation stakeholders. The first step should be to remove, or at least prevent the growth of, the most intrusive trail types such as used by informal motorised recreation, and to encourage the relocation of these activities to less sensitive, formalised areas (Newsome and Davies, 2009; Pickering et al., 2010a). Secondly, for areas traversed primarily by dense networks of hiking and biking trails, prevention of further segments developing should be prioritised using educational means such as stakeholder talks, signage, trail bordering and hardening (International Mountain Biking Association, 2009; Marion and Wimpey, 2007). In areas with the highest degrees of fragmentation and numerous entry points, decisions should be made on how to centralise visitor flow and which entries and trails to close. This will require additional stake-holder decision making and ranking of the most popular trail routes as well as the most sensitive ones. Negotiations on how to best stratify the network to maintain visitor satisfaction whilst limiting fragmentation could be carried out using survey data and experimental trials.

Our study emphasises that recreational trails can cause extensive internal fragmentation of endangered urban forest remnants. To our knowledge, this is the first study to apply a GIS-based approach to investigating the extent and possible causes of this process across multiple remnants at a landscape scale. We hope it will stimulate further investigation into how trail-based fragmentation may affect the structure, composition and function of ecosystems, especially those that are already threatened.

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Table Captions

Table 1: Characteristics of the 17 remnants of Tall Open Blackbutt Forest surveyed for recreational trails in southeast Queensland, Australia. CA = Conservation Area, NP = National Park. Highlighted cells signify those remnants that have been reduced in area by external fragmentation. Average altitude from GPS reading, total area (ha) in 2006 from 2006 Remnant Regional Ecosystems of Queensland GIS shapefiles.

Table 2: Trail characteristics surveyed for recreational trails in 17 remnants of Tall Open Blackbutt Forest surveyed in southeast Queensland, Australia. Total number of trail types is 14 with most being native/earth and hard solid-edged trails. Widths of 1-5 person indicate roughly 1-5m. Missing values indicate zeroes.

Table 3: Trail and fragmentation data for the 17 remnants of Tall Open Blackbutt Forest surveyed for recreational trails in southeast Queensland, Australia. Missing values indicate zeroes. CA = Conservation Area, NP = National Park, Inf. = Informal. Highlighted cells signify those remnants most strongly impacted by trail-based fragmentation in this study.

Table 1: Characteristics of the 17 remnants of Tall Open Blackbutt Forest surveyed for recreational trails in southeast Queensland, Australia. CA = Conservation Area, NP = National Park. Highlighted cells signify those remnants that have been reduced in area by external fragmentation. Average altitude from GPS reading, total area (ha) in 2006 from 2006 Remnant Regional Ecosystems of Queensland GIS shapefiles.

Name	Location	GPS detail (S,E)	Average altitude (m asl)	Protected	Recreation authorised	Total area (ha) 2006	Total area (ha) 2013
Bayview CA (1)	Northern	-27.643998,153.277424	38.9	Yes	Yes	437.1	437.1
Bayview CA (2)	Northern	-27.649814,153.253735	21.9	Yes	Yes	52.9	52.9
Venman Bushlands NP (1)	Northern	-27.629589,153.201852	88.3	Yes	Yes	19.4	19.4
Venman Bushlands NP (2)	Northern	-27.632255,153.204382	95.5	Yes	Yes	14.8	14.8
Venman Bushlands NP (3)	Northern	-27.629627,153.198803	83.1	Yes	Yes	3.9	3.9
Venman Bushlands NP (4)	Northern	-27.633961,153.196614	94.2	Yes	Yes	41.8	41.8
Venman Bushlands NP (5)	Northern	-27.636281,153.189319	113.9	Yes	Yes	32.7	32.7
Sanctuary Drive	Northern	-27.630197,153.249915	48.9	No	No	178.2	143.4
Mount Cotton Village	Northern	-27.642592,153.248327	42.9	No	No	31.4	10.6
Lakeside Drive	Northern	-27.646697,153.250773	19.8	No	No	9.9	2.9
Griffith University	Southern	-27.967797,153.378622	26.8	No	No	32.7	27.9
Coombabah Wetlands	Southern	-27.932465,153.366988	9.1	Yes	Yes	8.9	7.4
Currumbin Chase	Southern	-28.144168,153.481014	41.2	No	No	4.5	4.5
Old Coach Road (1)	Southern	-28.117411,153.413895	44.7	No	No	10.5	10.5
Old Coach Road (2)	Southern	-28.119795,153.415397	43.5	No	No	4.6	4.6
Musgrave Park	Southern	-27.957069,153.391196	12.3	No	No	5.0	4.8
Geoff Wolter Drive	Southern	-27.968403,153.367855	26.7	No	No	9.2	9.2
Total						897.5	828.4

Table 2: Trail characteristics surveyed for recreational trails in 17 remnants of Tall Open Blackbutt Forest surveyed in southeast Queensland, Australia. Total number of trail types is 14 with most being native/earth and hard solid-edged trails. Widths of 1-5 person indicate roughly 1-5m. Missing values indicate zeroes.

Width	Substrate Group (m)			
	Native/Earth (Informal)	Hard Solid Edge (Formal)	Hard Loose Edge (Formal)	Grass (Informal)
1 person	18,569	74		
2 person	7,251	1,469	274	463
3 person	5,039	225	10,426	211
4 person	592	21	787	
5 person	663			
# trail types	5	4	3	2

Table 3: Trail and fragmentation data for the 17 remnants of Tall Open Blackbutt Forest surveyed for recreational trails in southeast Queensland, Australia. Missing values indicate zeroes. CA = Conservation Area, NP = National Park, Inf. = Informal. Highlighted cells signify those remnants most strongly impacted by trail-based fragmentation in this study.

Name	Length of trails (m)							Density of trails (m ha $^{-1}$)	Total area lost to trail tread (ha)	Median patch size (ha)	WMPI	L5PI
	Total	Formal	Inf.	% Inf.	Walking	Biking	Motor					
Northern District (Redlands)												
Bayview CA (1)	27,358	11,779	15,579	57	9,243	16,744	1,371	62.59	10.90	0.58	6.60	68.24
Bayview CA (2)	136		136	100	136			2.57	0.08	53.00	52.85	99.84
Venman Bushlands NP (1)	1,842	1,631	211	11	1,842			94.91	0.74	0.05	1.20	83.84
Venman Bushlands NP (2)	910	910			123		787	61.63	0.48	0.02	1.15	96.07
Venman Bushlands NP (3)	137	85	52	38	137			34.84	0.04	0.24	1.29	98.87
Venman Bushlands NP (4)	2,002	1,582	420	21	2,002			47.87	1.04	5.15	7.95	97.52
Venman Bushlands NP (5)	1,461	1,461			1,461			44.72	0.80	7.66	7.78	95.57
Sanctuary Drive	426	225	201	47	426			2.97	0.22	71.59	71.48	99.85
Mount Cotton Village	990	850	140	14	990			93.59	0.24	0.02	1.01	97.59
Lakeside Drive	52		52	100	52			17.99	0.01	1.43	1.43	99.64
Southern District (Gold Coast)												
Griffith University	6,603	240	6,363	96	254	6,349		237.1	1.79	0.13	0.49	49.09
Coombabah Wetlands	871	707	164	19	871			117.60	0.33	0.003	0.36	93.91
Currumbin Chase	104		104	100	104			23.18	0.02	4.50	4.45	99.54
Old Coach Road (1)	191		191	100	191			18.12	0.08	10.5	10.37	99.27
Old Coach Road (2)	414		414	100	228		186	90.21	0.24	0.21	0.69	94.58
Musgrave Park	1,192		1,192	100	1,192			248.96	0.48	0.04	0.35	87.39
Geoff Wolter Drive	1,374	58	1,316	96	1,374			149.57	0.56	0.61	1.01	88.43
Total	46,063	19,528	26,535		20,626	23,093	2,344		18.05			

Appendices Captions

Appendix A: Outline of the 10 predictor variables used in a global regression to analyse their effects on trail-based fragmentation across 17 Tall Open Blackbutt forest remnants in south-east Queensland.

Appendix A: Outline of the 10 predictor variables used in a global regression to analyse their effects on trail-based fragmentation across 17 Tall Open Blackbutt forest remnants in south-east Queensland.

Variable	Spatial Data Used	Source of Spatial Data	Methods
Scale			
Local population density within 10 km of forest edge (Human)	Queensland Statistical Area 2 (SA2) region boundaries shapefile; population estimates for SA2 regions	Australian Bureau of Statistics 2011 National Census Data	The total population and area (km^2) of each SA2 region was calculated using the 'Calculate Geometry' tool. Population density (number of persons per km^2 per SA2) was calculated using the 'Field Calculator' tool storing values as attributes in a new field. Finally, mean local population density per patch was calculated by averaging all population density values for all SA2 zones within 10 km of the patch edge which were selected using a 10 km ring buffer based on Euclidean distance ('Buffer' tool).
Density of road/rail networks within 1 km of forest edge (Human)	Physical road/rail networks shapefiles	Queensland Government Information Service	To analyse the average density of road and rail networks within 1km of each patch edge, a 1000 m buffer was applied to each patch using the 'Buffer (Analysis)' tool. Then, using the 'Select layer by location' tool, all sections of road and rail that were contained within the 1000 m buffer were selected. A raster dataset was then created using the 'Line Density' tool to determine the density of roads within these buffers. This method calculates the density of line features (roads) within the neighbourhood of all raster cells contained within a given polygon (1000 m buffer). Essentially a circular search radius of 1m is drawn around the centre of each raster cell and all lines that are within it are summed and divided by the area's circle such that:Density = (L1 + L2 + L3… Li) / (area of circle) where Li is the calculated length of line within the circle radius of 1 m around cells of a

			size shorter than the width or height of the output extent, divided by 250. Then, to calculate the average density of roads/rail within 1000 m buffer of each patch, the 'Zonal Statistics' tool was used based on values produced from the line density raster above per buffer zone. Values were recorded as metres per square kilometre. See: ArcGIS 9.2 Desktop help – density calculations – line density calculations http://webhelp.esri.com/argisdesktop/9.2/index.cfm?TopicName=Density%20calculations.
Density of water bodies within forests (Biophysical)	Vegetation management watercourse map (1:25000) - version 1.2 shapefile	Queensland Government Information Service	To assess the average density of water bodies within each patch, all intersecting and contained water courses within each patch were selected using 'Select layer by location' in Vegetation management watercourse map (1:100000 and 1:250000) version 1.2. A raster was then created using 'Line Density' to determine density of watercourses within each patch, based on above formulae. Finally 'Zonal Statistics' were used to calculate average density per patch in metres per square kilometre based on raster cell values.
Total number of entry points (Human)	17 mapped forests	This study	The number of entry points was totalled per patch. An entry point was defined as any fixed point where a recreational trail intercepted an external edge, except those formed solely by a natural change in vegetation.
% trail network with native substrate (Human)	17 mapped forests	This study	The percentage of total trail network within each patch that was composed of native substrate was calculated by selecting all mapped native trails and using 'Sum'.
Percentage of forest on flat ground (< 5% rise)	1 second SRTM derived 3-second smoothed Digital Elevation Model (DEM) raster	Australian Government Free Data Downloads	Slope was calculated from the DEM raster using the 'Slope' tool in ArcMap with degree of measurement in percent rise and Z-factor set at 1 displayed using nearest-neighbour pyramid sampling. Percent rise is calculated thus: 100 * rise / run, where rise is difference in vertical distance over a set horizontal distance (run). 100 m^2 fishnet was created over the slope raster using the 'Create Fishnet' tool. Then the 'Extract values to points' tool was used with interpolation of values at point locations to assign cell values of the raster

			layers to the centroid points of each fishnet cell. All resulting sampled data points within patches were selected and exported to an Excel database, where % of patch with < 5% rise was calculated as a mean.
Average altitude (Biophysical)	1 second SRTM derived 3-second smoothed Digital Elevation Model (DEM) raster	Australian Government Free Data Downloads	A 100 m^2 fishnet was created over the DEM raster using the ‘Create Fishnet’ tool. Then the ‘Extract values to points’ tool was used with interpolation of values at point locations to assign cell values of the raster layers to the centroid points of each fishnet cell. All resulting sampled data points within patches were selected and exported to an Excel database, where average altitude per patch was calculated as a mean. The ‘Fishnet’ tool in ArcGIS is useful as it applies a stratified grid over the study area compartmentalising different parts of the forest and allowing for stratification of raster layers in order to analyse them statistically across each forest patch. It has been used in landscape-scale forest research in the past. See: Ashutosh, S. (2012). Monitoring forests: a new paradigm of remote sensing and GIS-based change detection. *Journal of Geographic Information Systems*, 4, 470-478. AND Roush, W., Munroe, J.S., and Fagre, D.B. (2007). Development of a spatial analysis method using ground-based repeat photography to detect changes in the alpine treeline ecotone. Glacier National Park, Montana, USA. *Arctic, Antarctic and Alpine Research* 39(2), 297-308.
Categorical			
Compatibility of surrounding land-use matrix (Human)	Vegetation Management Act (VMA) 2006 Remnant Regional Ecosystems of Queensland;	Queensland Government Information Service	The compatibility of surrounding land-use matrix was visually calculated using a compatibility rating from 1-6 similar to that of Stenhouse (2004). The assessment was based on information obtained from the on-ground surveys combined with map consultation. Surrounding land parcels were included only if within 100 m abutting the forest edge. The ratings were: 1: other patches with at least 75% native vegetation

	land-use 1999; land used for public recreation 2011 shapefiles		2: other patches with between 50-75% native vegetation 3: other patches with <50% native vegetation mixed with rural development 4: arable land and/or residential/parkland with mosaic vegetation 5: residential estates with <10% vegetation 6: hardened urban surfaces with industrial and transport infrastructure
Status of forest (Human)	Land-use 1999; land used for public recreation 2011 shapefiles	Queensland Government Information Service	Status of each forest patch was recorded as national park, conservation area, community or government reserve, freehold land or residential.
Main Trail-use (Human)	17 mapped forests	This study	Main trail use was noted based on observations made during on-ground surveillance or from discussions with local researchers and land managers.

LIST OF FIGURES

Figure 1: The location of 17 Tall Open Blackbutt forest remnants surveyed for recreational trails in south-east Queensland, Australia. Contour lines from the Australian Government Geoscience Australia Topography Contours 1:250,000 scale SG56-15 package and sub-set map of Australia from the Australian Government Geoscience Australia - National Dynamic Land Cover Dataset data package. Map created in ArcMap Version 10.1.

Figure 2: Examples of common trails that comprised 46.1km of trail across the 17 Tall Open Blackbutt forest remnants surveyed: (a) a hard-surfaced, loose-edged trail composed mainly of local gravel and hard-core substrates, (b) extreme trail widening caused by motorised recreation using straight, downhill runs, (c) segment of hard-surfaced, solid-edge trail made of concrete and (d) common narrow informal trail fragmenting a small patch of forest.

Figure 3: Examples of the most fragmented remnants of Tall Open Blackbutt forest from the south around the Gold Coast: (a) in this 27.8ha remnant > 6.4% of forest has been replaced by trails, resulting in extensive fragmentation (Weighted Mean Patch Index of 0.48 and Largest 5 Patches Index of 49.1), (b) a smaller 4.7ha remnant that has lost > 9.9% of forest to trails, and is highly fragmented (had the lowest Weighted Mean Patch Index of 0.35 and Largest 5 Patches Index of 87.4). Both remnants have multiple entry points facilitating access (black dots). Map created in ArcMap Version 10.1.

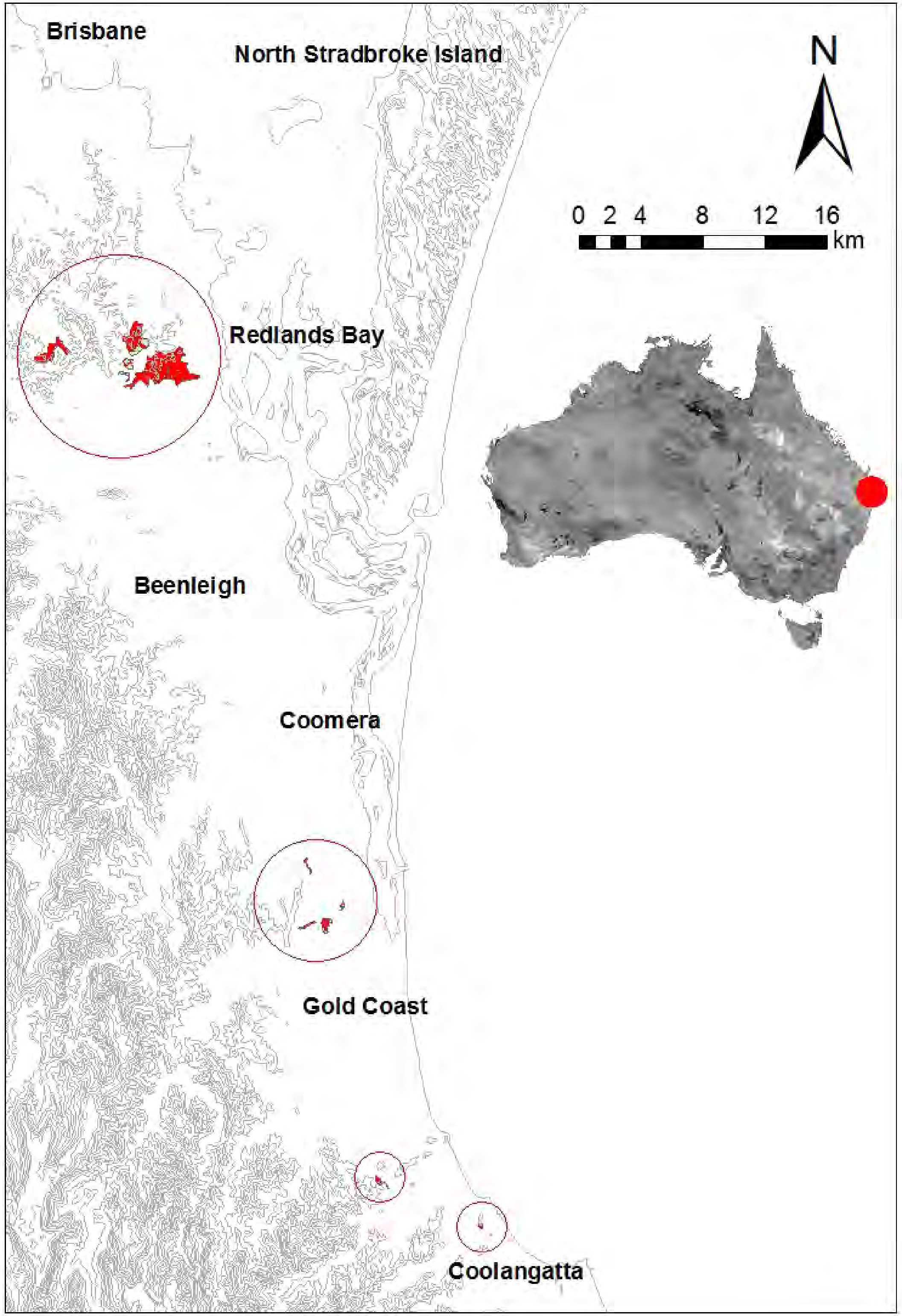

Figure 1: The location of 17 Tall Open Blackbutt forest remnants (circled) in the 937km ^{2} study region surveyed for recreational trails in south-east Queensland, Australia. The total remnant area existing in this region is 2,015 ha with 829 ha being surveyed for trails. Contour lines from the Australian Government Geoscience Australia Topography Contours 1:250,000 scale SG56-15 package and sub-set map of Australia from the Australian Government Geoscience Australia - National Dynamic Land Cover Dataset data package. Map created in ArcMap Version 10.1.

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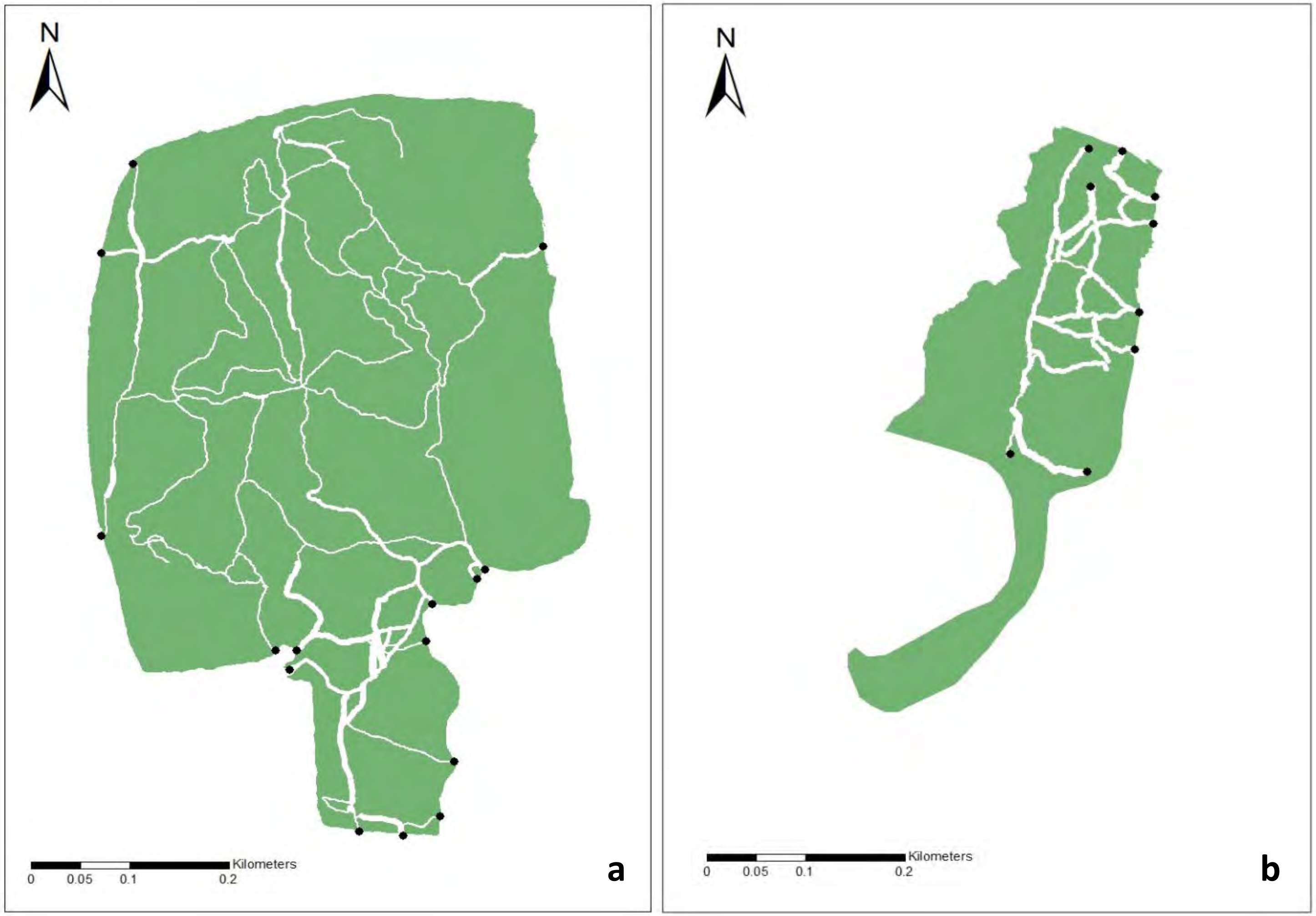

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