Please cite as

Ballantyne, M. and Pickering, C.M., (2015) Differences in the impacts of formal and informal recreational trails on urban forest loss and tree structure. *Journal of Environmental Management* **159**, 94-105.

Differences in the impacts of formal and informal recreational trails on urban forest loss and tree structure

Journal of Environmental Management

Mark Ballantyne[a]* and Catherine Marina Pickering[a]

[a] Environmental Futures Research Institute, Griffith University, Gold Coast, Queensland 4222, Australia
**corresponding author email:* mark.runkowski@griffithuni.edu.au, *phone*: +61(0)405783604

Abstract

Recreational trails are one of the most common types of infrastructure used for nature-based activities such as hiking and mountain biking worldwide. Depending on their design, location, construction, maintenance and use, these trails differ in their environmental impacts. There are few studies, however, comparing the impacts of different trail types including between formal management-created trails and informal visitor-created trails. Although both types of trails can be found in remote natural areas, dense networks of them often occur in forests close to cities where they experience intense visitor use. To assess the relative impacts of different recreational trails in urban forests, we compared the condition of the trail surface, loss of forest strata and changes in tree structure caused by seven types of trails (total network 46.1 km) traversing 17 remnants of an endangered urban forest in Australia. After mapping and classifying all trails, we assessed their impact on the forest condition at 125 sites (15 sites per trail type, plus 15 control sites within undisturbed forest). On the trail sites, the condition of the trail surface, distance from the trail edge to four forest strata (litter, understory, midstorey and tree cover) and structure of the tree-line were assessed. Informal trails generally had poorer surface conditions and were poorly-designed and located. Per site, formal and informal trails resulted in similar loss of forest strata, with wider trails resulting in greater loss of forest. Because there were more informal trails, however, they accounted for the greatest cumulative forest loss. Structural impacts varied, with the widest informal trails and all formal hardened trails resulting in similar reductions in canopy cover and tree density but an increase in saplings. These structural impacts are likely a function of the unregulated and intense use of large informal trails, and disturbance from the construction and maintenance of formal trails. The results demonstrate that different types of recreational trails vary in the type and range of impacts they cause to forests. They highlight the importance of careful consideration towards management options when dealing with trail networks especially in areas of high conservation value.

Keywords: trail impacts, forest structure, forest loss, edge effects, fragmentation, recreation ecology

1. Introduction

Recreational trails are one of the most common types of infrastructure facilitating access to, and movement within natural areas for a range of recreational activities (Leung and Marion, 2000; Cole, 2004; Marion and Leung, 2004). Formal trails are developed and maintained by managers often with hardened trail surfaces constructed from a range of materials (Wimpey and Marion, 2010; Marion and Leung, 2011). In contrast, informal trails are created and maintained by trail users themselves, beyond the formal trail system, and tend to be unhardened and not effectively maintained. The development of informal trails often stems from goal-driven behaviours by hikers and mountain bikers such as exploration, shortcutting and avoidance (Leung and Marion, 2000; Leung et al., 2002; Marion and Leung, 2011; Walden-Schreiner and Leung, 2013).

Both formal and informal trails have impacts as a result of their design, location, construction, maintenance and use (Cole, 2004; Hill and Pickering, 2006; Marion and Leung, 2011). On the trail surface, trampling can result in soil erosion and compaction (Wilshire, 1978; Liddle, 1997; Olive and Marion, 2009), more bare ground and damage to plants resulting in the loss of vegetation cover (Liddle, 1997; Hill and Pickering, 2006; Zhang et al., 2012). On the trail edges lower levels of trampling can still damage soils and vegetation with the loss of more sensitive species and increases in ruderal or weed species (Hall and Kuss, 1989; Nemec et al., 2011; Zhang et al., 2012; Barros and Pickering, 2014; Queiroz et al., 2014). There can also be indirect changes along trail edges that result from the creation and maintenance of the disturbance corridor itself, including alterations to soil microbiology and nutrient content (Hamberg et al., 2008; Malmivaara-Lämsä et al., 2008), changing plant composition (Hill and Pickering, 2006; Nemec et al., 2011), damage to trees (Cole, 2004; Leung et al., 2013), littering (Matlack, 1993) and disruption of key ecological processes (Ballantyne and Pickering, in review).

Often there are greater impacts on the surface of informal trails than formal trails when informal trails are poorly located, constructed and maintained and their use is intense (Wimpey and Marion, 2010; Marion and Leung, 2011). Where trail surfaces have been compared, informal trails were often associated with increased vegetation loss and bare ground (Hill and Pickering, 2006), had poor contour alignment resulting in increased erosion (Olive and Marion, 2009) and their excessive use and lack of hardening often led to trail widening (Wimpey and Marion, 2010; Wimpey and Marion, 2011). Formal trails however tend to experience less erosion and trail widening due to their hardened surfaces and clearly-defined edges (Marion and Leung, 2004; Monz et al., 2010) but can result in large change in plant composition along their edges, due to factors such as disturbance during their construction and maintenance (Godefroid and Koedam, 2004; Hill and Pickering, 2006).

Little is known about how formal and informal trails differ in their impacts on the structure of forests. Structural impacts could include the loss of different forest strata such as litter, understory, midstorey and tree cover as well as changes in the structure of trees close to the trail. Changes in tree structure in forests affect biodiversity (Franklin and Spies, 1991; Kint *et al*., 2003), for example, spatial changes affect light regimes and regeneration (Emborg, 1998; Spies, 1998) while changes in age distribution affect the microclimates and resources present with young saplings and mature trees providing different resources for other organisms (Ernest, 1989; McCune et al., 2000; Kint *et al*., 2003; Gibbons and Lindenmayer, 2002; Boege and Marquis, 2005; Vitz et al., 2006). It is likely that different types of trails may have different effects on both the loss of forest strata and edge tree structure. For formal trails which are often hardened, edged, graded and drained, the degree of change may be greater due to altered abiotic conditions during construction and maintenance, similar to that of roads. For informal trails, despite their often poor surface conditions, their construction and maintenance may involve fewer disturbances and hence fewer changes to forest structure, but overall loss of forest may be higher due to the rapid proliferation of these types of trails.

As of 2014, 54% of the world's population lives in urban areas with this figure expected to rise (United Nations, 2014). With migration to, and expansion of global cities, there is increasing pressure on surrounding natural areas such as forest remnants (McKinney, 2002; Byrne et al., 2010). These forests become important sites for nature-based recreation with outdoor activities largely viewed as a positive opportunity in areas otherwise largely devoid of such experiences (Chiesura, 2004; Florgård, and Forsberg, 2006; Lee and Maheswaran, 2011). As a result, urban forest remnants, already disturbed by external isolation, can become further degraded by the creation and use of internal recreational trails (Matlack, 1993; Pickering et al., 2010; Ballantyne et al., 2014). This includes direct and indirect local impacts along the trails and their edges as well as cumulative impacts from the formation of complex and fragmenting trail networks (Stenhouse, 2004; Pickering et al., 2010; Ballantyne et al., 2014). Such impacts include the loss of habitat for forest-specialist species, cumulative increases in novel abiotic conditions across remnants, loss of mature and hollow-bearing trees, changing community composition, disruption of dispersal and genetic interchange among plant species and ultimately reduced long-term viability of the ecosystem (Hill and Curran, 2001; Ries et al., 2004; Goosem, 2007; Prasad, 2009; Marzano and Dandy, 2012). These types of impacts are especially important in the Australian context where fragmentation is severe and ongoing in urban areas, with many species and ecosystems being regionally endemic, having low resilience to genetic depression and having high susceptibility to even moderate levels of disturbance (Broadhurst and Young, 2007).

This study compares the effects of different types of formal and informal recreational trails on forest loss and structure. It does this in urban remnants of a subtropical endangered forest that has high conservation value and is very popular for hiking and mountain biking. In these forests there are networks of trails of different types that are causing extensive fragmentation of remaining remnants (Pickering et al., 2010; Ballantyne et al., 2014), but what is their impact on the forest vegetation, and does it differ among the trail types? To answer these questions, we first categorised all the trails in this forest, and then compared how they vary in: 1) surface condition, 2) their contribution to loss of vegetative strata (litter, understorey, midstorey, trees), and 3) their impacts on structure of the trees remaining along their edges.

There has been limited research that directly compares the effects of different types of trails on forest structure and addresses both edge and cumulative landscape-scale effects. Most research to date has assessed on-trail conditions, often using inventory methods, and where edge effects have been assessed, they looked predominantly at changes in plant composition. Extending trail research to also address structural impacts is important, especially in forests which contain multiple, interacting structural components. Also, research assessing trail impacts on subtropical forests will help address an important gap in the current literature with few studies in these types of forests compared to recreation ecology research in colder climates (Sun and Walsh, 1998; Prasad, 2009; Newsome and Davies, 2009; Pickering et al., 2010).

2. Materials and Methods

2.1 Study Region

Like many other rapidly developing urban areas around the world, subtropical eastern Australia has experienced extensive land clearance with much of the remaining natural forest occurring as small remnants within a matrix of urban and agricultural land (Sewell and Catterall, 1998; Wilson *et al.*, 2002; McAlpine *et al*., 2007). Many of these forest remnants are popular destinations for nature-based tourism and recreation (Queensland Government, 2007) including remnants of Tall Open Blackbutt forest (Pickering *et al*., 2010; Pickering *et al*., 2012). This forest is endangered due to land clearance in the past with only 19% pre-clearing area remaining (Queensland Government, 2013). As a result it is restricted to < 226 scattered small isolated remnants (ca. 8 ha) spread out over 940 km^2 of coastal urban lowlands between the cities of Brisbane (population > 2.2 million; 27^o 46’ 99.73” S, 153^o 02’ 34.51” E) and the Gold Coast (population > 535,000; 28^o 16’ 75.51” S, 153^o 53’ 86.50” E) (Queensland Government, 2013; Ballantyne et al., 2014) (Figure 1).

Tall Open Blackbutt forest has an open structure dominated by the tall evergreen hardwood *Eucalyptus pilularis* and has a total species richness of 140 vascular plants (Queensland Government, 2013; Queensland Government, 2014). Average canopy height is around 27 m with a crown cover of 38% and average stem density of 265 ha^{-1}, mostly *Eucalyptus* and *Corymbia* species. Shrub cover is sparse (around 7%) with a stem density of 1,390 ha^{-1} and consists largely of *Acacia* and *Allocasuarina* species with intermittent emergent eucalypts. Ground cover is around 40% and consists of up to 117 species of vascular plants with an average of 45 species per site. Ground-cover is largely dominated by the tussock grasses *Themeda triandra* and *Eremochloa bimaculata* and ferns including *Pteridium esculentum* and *Calochlaena dubia* (Queensland Government, 2014). The forest remnants support a number of internationally and nationally-threatened taxa such as International Union for Conservation of Nature (IUCN) Red-listed Green-thighed Frog (*Litoria brevipalmata*), Koala (*Phascolarctos cinereus*) and Glossy Black Cockatoo (*Calyptorhynchus lathami*). The remnants of this forest are either protected as State national parks or council conservation areas or are under freehold lease agreements (Queensland Government, 2013). Like other urban vegetation remnants globally, the close proximity of these forests to densely-populated urban areas, ease of access and open environment, means they are often traversed by recreational trails that are used for a diversity of recreational activities (Stenhouse, 2004; Roovers et al., 2006; Pickering et al., 2010; Pickering et al., 2012; Ballantyne et al., 2014).

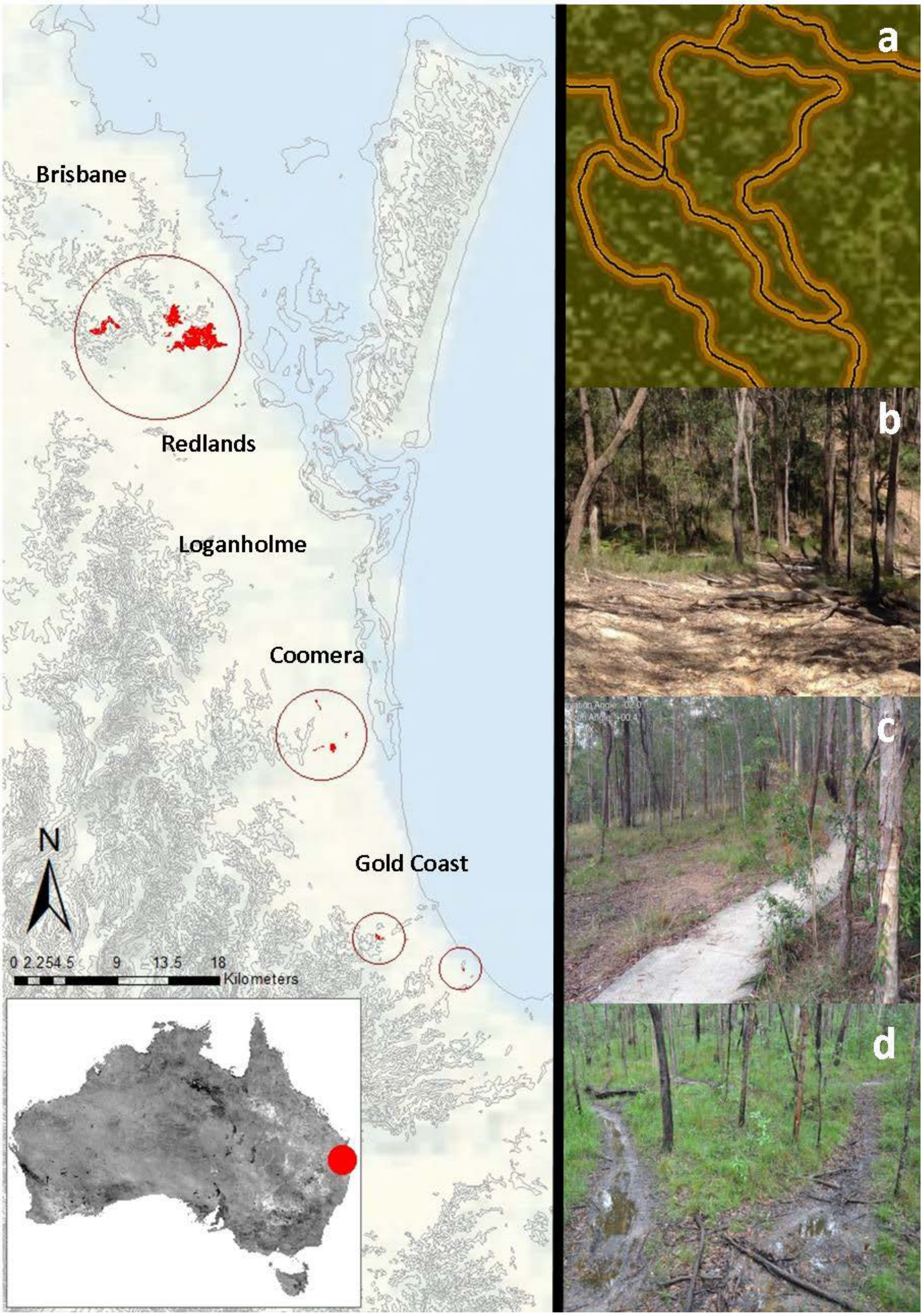

Figure 1: Location of 17 Tall Open Blackbutt forest remnants with extensive recreational trail networks in southeast Queensland, Australia. Inset images show examples of: (a) trails and forest strata loss (parallel banding), (b) extreme trail widening and canopy loss from informal large bare earth trails, (c) hardened concrete trail with high proportions of saplings and (d) narrow bare earth trails responsible for most fragmentation. All photos taken by MB. Contour lines from the Australian Government Geoscience Australia Topography Contours 1:250,000 scale SG56-15 package. Sub-set map of Australia from the Australian Government Geoscience Australia National Dynamic Land Cover Dataset data package. Map created in ArcMap Version 10.

2.2 Field survey

To assess the impacts of formal and informal trails on Tall Open Blackbutt forest, 17 remnants > 5 ha accessible to the public and used for hiking and mountain biking were identified from the 226 remnants mapped in 2006 by the Queensland Government. All recreational trails within these 17 forest remnants (828.4 ha in total) were surveyed using a Trimble JunoST handheld GPS with an accuracy of 1-10 m and a sampling interval of 1 m (Ballantyne et al., 2014).

Trails were classified using a condition class assessment method (Farrell and Marion, 2001; Walden-Schreiner and Leung, 2013). Trail segments were assigned to a trail type based on their overall status (formal vs informal), and then further subdivided based on average width (measured at 100 m intervals) and trail surface (Cole, 2004; Marion and Leung, 2004) (Table 1). Trail widths were categorised as small (0-2 m wide), medium (2-4 m wide) or large (4-7 m wide) while trail surfaces included grass, bare earth, gravel and tarmac/concrete. Formal trails were those with visible maintenance, signage and/or access infrastructure and/or mapping 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). A total of seven trail types were identified that accounted for > 95% of all trails in these forests (Table 1).

The impacts of the trail type on trail surface conditions, loss of forest strata and tree structure were assessed at 125 sites across the 17 remnants using a stratified random sampling method. A total of 15 replicate sites were randomly located along the total extent of each trail type across the 17 remnants using a 'Create Random Points on Polylines' tool from the extension ET GeoWizards Version 10.2 (available online http://www.ian-ko.com) in ArcMap Version 10.1. Control sites were located in the core of the largest 15 patches created by the trails within each remnant (Ballantyne et al., 2014). A 50 m buffer from other types of disturbance (e.g. roads, forest edges, urban areas) was used for all trail and control sites to avoid confounding anthropogenic edge effects. Sites were not assessed if surrounding vegetation had been burnt within the previous 10 years.

At each trail site, data was collected about the trail surface condition, loss of forest strata and the structure of trees as well as general site variables. Trail surface variables were used to measure the condition of the trails at the centre of the trail tread (Wimpey and Marion, 2010). They included the maximum trail width, cross-sectional area of the trail tread, trail-slope alignment angle, soil compaction and trail slope. Maximum trail width was measured at right angles to the trail from one edge of the trail tread to the other. Cross-sectional area and trail-slope alignment angle were used to estimate soil loss using the methodology in Olive and Marion (2009). Soil compaction was measured using a pocket penetrometer with a maximum capacity of 4.5 kg/cm^2 at five equally-spaced points across the trail surface. The trail slope was recorded using the Hunter Research and Technology LLC Theodolite HD Version 3.2 app for iPad (available online http://hunter.pairsite.com/theodolite/) by aligning the top of two poles of equal height 5 m either side of the survey point and measuring the difference in elevation angle.

The effect of trail type on the loss of forest strata was measured at each trail site. Specifically, the linear distance from the trail edge to the start of each of four strata (the average line of litter, understorey, midstorey and mature tree trunks) was measured perpendicular to, and on both sides of the trail. This data was combined with the length of each trail type to estimate total and per unit area loss of the four forest strata due to each trail type.

To quantify structural changes to the trees on the trail edge, seven tree variables were measured at each site using a 50m^2 belt transect set out parallel to the trail. Variables were: (1) percentage canopy cover over the trail, (2) litter depth, (3) tree density, (4) % living trees, and % trees that are (5) saplings, (6) mid or (7) mature-aged trees. Percentage canopy cover over the trail was calculated by photographing the quadrangle of airspace directly above the trail point and then calculating the number of pixel cross-hair points occupied by canopy, sky or other (Monz *et al*., 2010). At the tree strata line, five litter depths at 10 cm-spaced intervals were recorded. Finally, the density, health and life-stage of all trees were measured using a T-square method (Diggle, 1983; Sutherland, 2006). Twenty trees (10 either side of the trail) were randomly selected and nearest-neighbour distance measured to give average density per transect. For each tree condition information was recorded including whether a tree was alive or dead, and if it was a sapling, middle-age or mature tree.

At 20 control sites within the forest, tree structure variables were measured using the T-square method, but this time selecting 20 trees along a 5 x 50 m band transect running through the control site parallel with the direction it was approached. Finally, general site variables were recorded at all sites including aspect and the average altitude and slope.

2.3 Data analyses

To analyse differences in trail surface conditions between trail types, One-way Analyses of Variance (ANOVAs) were performed first on formal vs informal trails and then separately for the seven trail types in SPSS Version 21 on log-transformed trail slope alignment angle and compaction data. The other dependent variables could not be analysed statistically due to strong heteroscedasticity: instead they were compared using descriptive statistics. Where the trail type was significant in the analysis, Tukey post hoc tests were used to identify which trail types differed.

Loss of the four forest strata was compared among trail types per unit length using One-way ANOVAs to compare formal vs informal trails and then the seven trail types. The distances between trail edges and litter, understorey, midstorey and tree layers were the dependent variables. Distances were log transformed and where the trail type was significant in the analysis, Tukey post hoc tests were used to identify which trail types differed. Analysis of variance provides a robust means of testing whether there are significant differences between the means of multiple independent samples, and is reasonably robust to slight non-normality and heteroscedasticity with Tukey post hoc tests used to detect pair wise differences between categorical independent variables (Underwood, 2002).

The impact of the seven trail types on the four strata were also analysed using ordinations in the multivariate statistical package PRIMER Version 6. A dissimilarity matrix based on Euclidean distance to each strata was computed and a non-metric multi-dimensional scaling (MDS) plot was drawn. To test for significant differences among trail types, a One-way Analysis of Similarity (ANOSIM) was computed using 999 random permutations. Similar to the analysis of variance (ANOVA), this test is non-parametric so has the added benefit of not requiring normalised distributions (Clarke, 1993). For a difference to be significant, p values had to be < 0.05 and global rho < 0.5 as a nonparametric measure of statistical dependence between the variables. A SIMPER analysis was used to determine which of the dependent variables contributed most strongly to dissimilarities between trail types. Dissimilarities were graphically portrayed using a Pearson correlation on the MDS plot. This method visually portrays patterns by clustering and ordinating samples and tests for significance using a non-parametric permutation-based test (9,999 permutations) and so increasing the power of analysis (Clarke, 1993).

In addition to per unit area loss of strata, the total area of each forest strata lost due to each trail type was calculated using ArcMap. This was done by mapping the distances from each trail edge to the line of each of the four strata and drawing them as adjacent trail buffers using the Buffer Analysis tool. Each of these buffer areas (measured in ha) was then subtracted from the overall size of the remnants they traversed and totalled across all remnants in which that trail type was present.

To analyse differences between trails in their impact on tree structure, we used three separate tests. First, we used a series of One-way Analyses of Variance with covariates (ANCOVAs) to determine how tree structure may differ along the edge of formal and informal trails using the tree variables: (1) percentage canopy cover over the trail, (2) litter depth, (3) tree density, (4) % living trees, and % trees that are (5) saplings, (6) mid or (7) mature-aged trees. We analysed each of the dependent tree variables separately using raw litter depth data but log-transformed density data and arcsine squareroot transformed percentage data to satisfy assumptions of homogeneity of variance. We used remnant as a random factor to account for possible spatial autocorrelation and the environmental variables aspect, slope and altitude as covariates.

Secondly we used an ordination and clustering analysis similar to that used for assessing loss of forest strata to assess how tree structure varied among the seven trail types and against controls using the seven tree variables. Finally, to specifically analyse the structural effects of any clustering among trail types and controls, we used a series of ANCOVAs as before except, to compare any significant main effects, we estimated marginal means and performed planned pairwise comparisons using least significant differences.

3. Results

3.1 What types of trails occur in the forest remnants?

There was 46.1 km of trails across the 17 forest remnants surveyed (828.4 ha). This included 13,951 m of formal trail (30% of trails) and 32,115 m of informal trail. The formal trails consisted of: medium grass trails (1%), medium gravel trails (26%), large gravel trails (6%) and medium tarmac/concrete trails (4%). The informal trails consisted of small (43%), medium (17%) and large (3%) bare earth trails (Table 1).

3.2 Does trail surface condition differ among trails?

Average trail slope and compaction did not differ between formal and informal trails ($F = 0.127$, $p = 0.723$; $F = 1.447$, $p = 0.232$) (Table 1). Based on descriptive data, there appears to be some differences between formal and informal trails, with informal trails generally on steeper slopes and characterised by greater soil loss (2486.9 ± 3358.5 cm^2) than formal trails (437.2 ± 404.1 cm^2). Average trail width was similar between formal and informal trails, although the width of informal trails was much more variable (informal = 6.6 m, formal = 3.3 m) (Table 1).

There were significant differences in soil loss ($F = 26.632$, $p < 0.001$) and slope ($F = 6.911$, $p < 0.001$) among the seven trail types. Soil loss was lowest for small informal bare earth trails compared to all other types of trails (189.2 ± 199.1 cm^2), and greater for large informal bare earth trails (6422.8 ± 3089.3 cm^2) compared to other trail types. Slopes were steeper on large informal bare earth trails ($14.7 \pm 6.2^{\circ}$), while all other trails had similar slopes. Trail slope alignment angle did not differ significantly between the seven trail types ($F = 0.771$, $p = 0.596$). Descriptive statistics showed little variation in compaction or average width (Table 1).

3.3 Does the loss of forest strata differ among trails?

There were no differences in the per unit area loss of the four forest strata along the edge of the trails between formal and informal trails (Table 2). When the seven trail types were compared, however, there were significant differences in the loss of understorey, midstorey and tree strata, but not litter along trail edges (Table 2). Formal gravel trails resulted in the greatest loss of understorey per unit area, more than formal medium grass and informal small bare earth trails (Table 2). Informal large bare earth and formal large gravel trails resulted in the greatest loss of midstorey, more than formal medium grass and informal small bare earth trails. The greatest loss of tree strata was caused by large informal bare earth and both formal medium and large gravel trails (Table 2).

When data on the per unit area loss of the four strata were combined there were significant differences among some trail types (One-way ANOSIM, Year Global Rho = 0.152, $p < 0.001$, Stress = 0.09). Informal small bare earth trails and formal medium grass trails had similar impacts to each other on the trail edges and differed to those of the formal gravel trails and informal large bare earth trails. According to the SIMPER function, these differences were mainly due to the loss of the understorey (37.3% contribution to observed dissimilarities). Based on these results, there are three distinct groups of trails in terms of their effects on forest strata: 1) informal small bare earth trails and formal medium grass trails which had the least impact, 2) formal medium tarmac/concrete trails and informal medium bare earth trails, and 3) informal large bare earth trails and both formal medium and large gravel trails which had the greatest impact (Figure 2).

When the width of the impacts from each trail type was combined with trail length, informal trails caused the greatest overall loss of forest (63% contribution to total loss, Table 2). Although per unit area, the informal small bare earth trails resulted in the least loss of strata, their total cumulative impact was actually the greatest (12.9 ha, 43% contribution to total loss), as they comprised 52% of all trails (Table 2). The formal trail which contributed greatest to the loss of strata was medium gravel (7.8 ha, 26%) which comprised 21% of all trails. In total, 48.1 ha (5.8%) of forest was lost to the recreational trail network with 18 ha (2.2%) lost to the trails themselves, and an additional 0.9 ha of litter, 5.8 ha of understorey, 18 ha of midstorey and 30.1 ha of trees lost along the trail edges.

3.4 Does tree structure differ among trail types?

Not only were there differences in the amount of forest lost to trails, there were also changes in the structure of trees remaining along the trail edges. Although the density of trees along the edges of formal trails was similar to that of informal trails, forest on the edge of formal trails contained a higher proportion of saplings, especially on steeper slopes (Table 3). This did not however, result in differences in the percentage of living trees, percentage of saplings, mid or mature-age trees, percentage canopy cover or litter depth on the edge of the forest.

When the structure of the trees adjacent to the trails was compared with controls, there were clear differences including in the density of trees, percentage of saplings and percentage canopy cover (Table 4**,** Figure 3, One-way ANOSIM, Global Rho = 0.323, $p < 0.001$, Stress = 0.21). As expected, natural forest away from trails was characterised by a moderate to high density of trees, the lowest percentage of saplings and the greatest canopy cover (Table 4). In comparison, trails with the lowest density of trees adjacent to them were the formal medium tarmac/concrete trails and informal large bare earth trails. Median tree densities were found alongside small and medium bare earth trails and both gravel trails. Tree density was positively correlated with altitude (Quadratic $R^2 = 0.43$) and remnant ($p < 0.001$), but there was no interaction between trail type and remnant (Table 4).

The percentage of saplings was low in both controls and forest adjacent to small bare earth trails (Table 4). The forest adjacent to all other trails had higher proportions of saplings. The percentage of saplings was also affected by remnant but not by the interaction between trail type and remnant (Table 4).

Percent canopy cover was lowest over large bare earth trails, which were generally the widest, and large gravel and medium grass trails (Table 4). Controls had highest canopy cover with similar cover to medium concrete, small bare earth and medium gravel trails, all of which were consistently narrower. Interestingly, medium gravel trails were statistically similar in canopy cover to all other trails. The percentage of mid, mature and dead trees and the depth of litter at the tree-line did not vary between trails and controls.

According to the global ANOSIM, all seven trail types, except small bare earth trails, differed to controls and there were differences among trail types (Figure 3, One-way ANOSIM, Global Rho = 0.323, $p < 0.001$, Stress = 0.21). Differences to controls included all trails (except small bare earth) having altered tree density (27% contribution, SIMPER), higher presence of saplings (27%) and lower percentage canopy cover (25%), cumulatively affecting at least 28.1 ha (3.4% of the total area) of the 17 remnants.

Table 1: Average values and ranges of trail surface conditions among seven recreational trail types in Tall Open Blackbutt forest in southeast Queensland. Data collected from 46.1 km of trails across 17 urban remnants of the forest. Values in brackets indicate the total length of each of the trail types, followed by their percentage contribution to the total length of the entire trail network. CSA = cross-sectional area (soil loss), TSAA = trail slope alignment angle. For variables that could be statistically tested using ANOVA, those with significant differences in mean values ($p < 0.05$) are highlighted in bold with lettering indicating significant post-hoc differences.

			Trail Type [total length (m) and percentage of total network]						
			Informal	Informal	Informal	Formal	Formal	Formal	Formal
Variable	Formal	Informal	Small Bare Earth (23,916, 52%)	Medium Bare Earth (7,015, 15%)	Large Bare Earth (1,184, 3%)	Medium Grass (674, 1%)	Medium Gravel (9,795, 21%)	Large Gravel (1,692, 4%)	Medium Tarmac/Conc. (1,790, 4%)
Width	2.8 ± 0.8	2.9 ± 1.8	1.0 ± 0.5	2.8 ± 0.6	4.8 ± 1.3	2.9 ± 0.7	2.6 ± 0.3	3.8 ± 0.5	1.9 ± 0.4
(m)	1.3 - 4.6	0.5 - 7.1	0.4 - 2.2	2 - 4.4	2.9 – 7.1	1.9 - 3.9	2.2 - 3.0	2.9 - 4.6	1.5 - 2.5
CSA	437.2 ± 404.1	2486.9 ± 3358.5	**189.2 ± 199.1** **b**	**848.9 ± 859.2** **a**	**6422.8 ± 3089.3** **c**	**522.4 ± 286.1** **a**	**434.7 ± 436.8** **a**	**711.5 ± 413.3** **a**	n/a
(cm^2)	0 - 1458.6	5 - 9812.9	**5 - 792.1**	**203.5 - 3407.8**	**218.6 - 9812.9**	**235.2 - 1206.5**	**0 - 1458.5**	**125.1 - 1270.3**	n/a
Compaction	4.2 ± 0.7	3.9 ± 0.6	4.0 ± 0.6	3.9 ± 0.5	4 ± 0.6	2.5 ± 1.5	n/a	n/a	n/a
(kg/m^2)	1.8 - 4.5	2.5 - 4.5	2.4 - 4.5	3.1 - 4.5	2.8 - 4.5	0 - 4.1	n/a	n/a	n/a
TSAA	52.6 ± 30.3	39.6 ± 35.6	66.3 ± 24.8	46.4 ± 31.9	6.1 ± 18.6	38.4 ± 30.7	56.6 ± 32.8	54.7 ± 29.8	60.5 ± 27.5
(^{o})	0 - 90	0 - 90	10 - 90	0 - 90	0 - 70	0 - 80	0 - 90	0 - 90	20 - 90
Trail slope	4.7 ± 2.5	7.4 ± 6.7	**3.6 ± 2.1** **a**	**4 ± 3.1** **a**	**14.7 ± 6.2** **b**	**6.1 ± 3.1** **a**	**4.6 ± 1.9** **a**	**4.4 ± 2.1** **a**	**3.9 ± 2.6** **a**
(^{o})	0.9 - 11	0 - 23	**0 - 6.5**	**0.6 – 14**	**2.2 – 23**	**2.4 – 11**	**2 - 7.7**	**1.5 - 8.3**	**0.9 – 8.6**

Table 2: Total contributory effects of the seven trail types to the loss of the four forest strata and their contribution to the overall loss of Tall Open Blackbutt forest in southeast Queensland. Litter = litter layer, Under = understorey layer, Mid = midstorey layer and Tree = tree layer. For mean distance to each strata, bold values indicate significant differences between trail types with letters signifying post-hoc differences ($p < 0.05$).

			Mean distance (± SD) to each strata (cm)				Area of each strata lost to trail edge effect (ha)					
Trail Type	Total Trail Length (m)	Average widths (m)	Litter	Under	Mid	Tree	Litter	Under	Mid	Tree	Cumulative loss of four forest strata	% contribution to overall forest loss
Formal trails	13,951	2.8	10.6 ± 16.4	77.2 ± 51.1	234.6 ± 86.5	406.7 ± 127.4	0.33	2.36	6.55	11.09	20.33	37
Informal trails	32,115	2.9	11.7 ± 19.3	62.6 ± 36.7	224.9 ± 102.5	381.7 ± 154.9	0.55	3.48	11.49	18.97	34.49	63
Statistic			F = 0.083 p = 0.774	F = 2.333 p = 0.130	F = 0.219 p = 0.641	F = 0.646 p = 0.424						
Informal trails												
Small Bare Earth	23,916	1	6.0 ± 8.6	**48.5 ± 39.9 a**	**170.6 ± 61.4 a**	**281.4 ± 78.9 a**	0.3	2.33	7.99	12.97	23.59	43
Medium Bare Earth	7,015	2.8	14.8 ± 24.9	70.2 ± 30.6	203.1 ± 73.9	**359.3 ± 142 ac**	0.21	0.98	2.84	4.98	9.01	17
Large Bare Earth	1,184	4.8	14.3 ± 20.5	68.9 ± 40.2	**301.1 ± 117.9 b**	**504.6 ± 146.5 b**	0.04	0.17	0.66	1.02	1.89	3
Formal												
Medium Grass	674	2.9	5.1 ± 8.3	**41.5 ± 28.9 a**	**160.8 ± 42.3 a**	338.9 ± 82.3	0.02	0.06	0.22	0.45	0.75	1
Medium Gravel	9,795	2.6	10.1 ± 8.4	**88.2 ± 21.1 b**	239.2 ± 36.7	**413.4 ± 91.3 bc**	0.2	1.71	4.58	7.84	14.33	26
Large Gravel	1,692	3.8	23.7 ± 24.7	**127.4 ± 63.5 b**	**291.5 ± 82.9 b**	**493.9 ± 170.5 bc**	0.09	0.43	1.02	1.68	3.24	6
Medium Tarmac/Concrete	1,790	1.9	3.6 ± 11.4	51.8 ± 30.3	247.1 ± 111	380.5 ± 108.7	0.02	0.16	0.73	1.12	2.02	4
Statistic			F = 1.795 p = 0.111	**F = 4.927** **p < 0.001**	**F = 5.123** **p < 0.001**	**F = 5.598** **p < 0.001**						
Total	46,066						0.88	5.84	18.04	30.06	54.83	

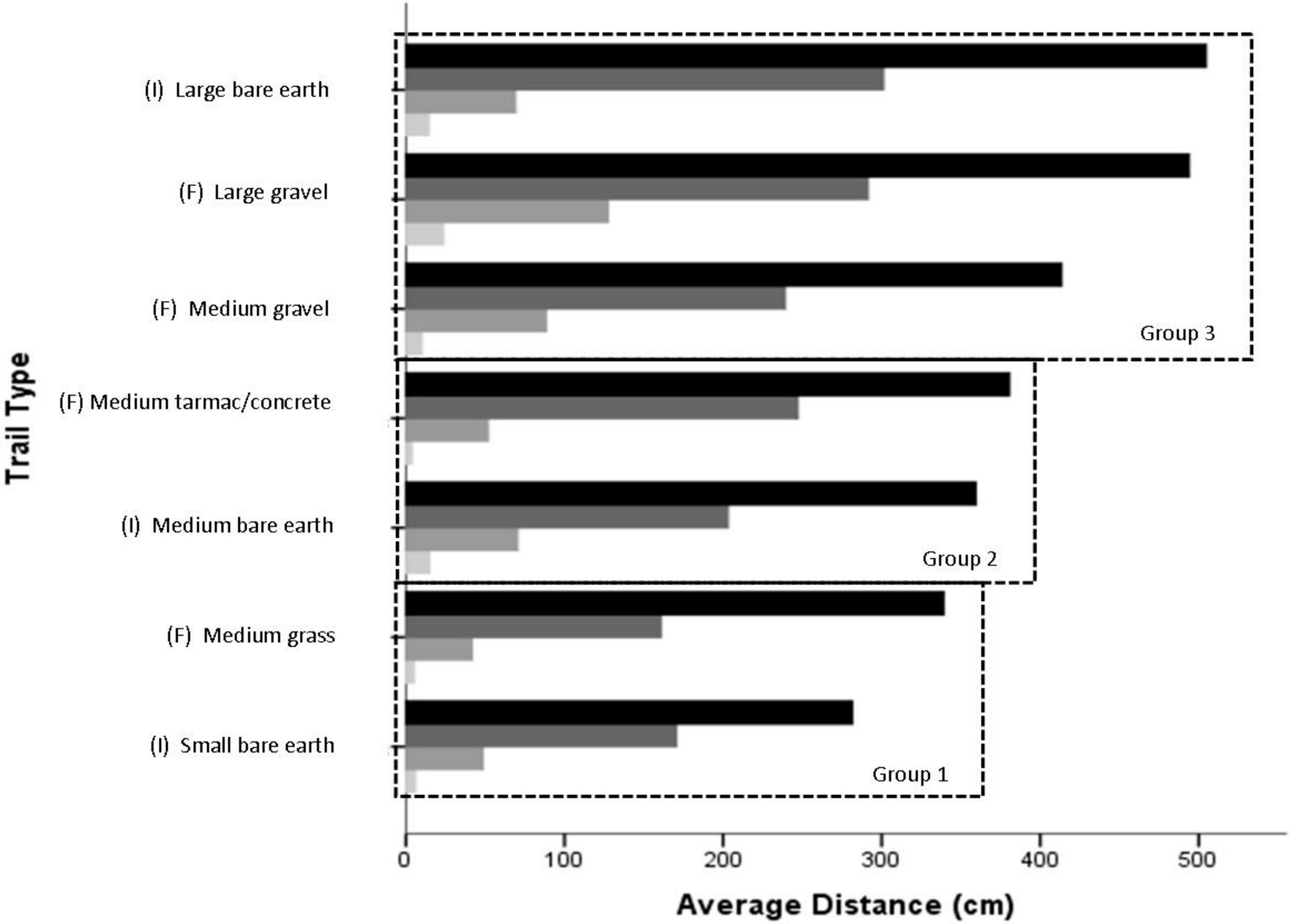

Figure 2: Mean distances to each of the forest strata: trees (black bars), midstorey (dark grey), understorey (mid grey) and litter (pale grey) across the seven trail types sampled across Tall Open Blackbutt forest in southeast Queensland. Three distinct groups show a gradual increase in forest strata loss with increasing trail width (small to large). F = formal, I = informal trails.

Table 3: Results of One-way Analyses of Variance with covariance (ANCOVAs) comparing tree structure along the edges of formal and informal trails in remnants of Tall Open Blackbutt forest in southeast Queensland. Covariates include remnant, the interaction trail type*remnant (which if significant indicates spatial autocorrelation), slope, aspect and altitude. Bold values indicate significant differences ($p < 0.05$).

	Tree density (trees m^{-2})	% saplings	% mid	% mature	% dead	% canopy cover	Litter depth (cm)
Means and Standard Deviations for Formality							
Formal	0.32 ± 0.24	**42.5 ± 19.1**	40.5 ± 19.2	16.9 ± 9.9	16.1 ± 11.9	55.3 ± 16.2	4.4 ± 1.4
Informal	0.31 ± 0.18	**33.9 ± 15.1**	34.2 ± 15.8	31.9 ± 15.2	14.8 ± 10.9	56 ± 20	4.8 ± 1.9
Statistics							
Trail type							
F	1.613	**14.319**	0.071	0.106	0.085	2.249	0.706
p	0.251	**0.002**	0.797	0.753	0.777	0.139	0.421
Remnant							
F	2.564	2.331	0.998	1.085	0.852	**2.285**	3.496
p	0.162	0.119	0.537	0.492	0.613	**0.030**	0.066
Trail type*Remnant							
F	**3.080**	0.642	1.833	1.653	1.138	0.105	1.155
p	**0.022**	0.634	0.133	0.172	0.346	0.980	0.339
Slope							
F	0.044	**9.533**	1.207	1.115	3.036	**13.378**	0.029
p	0.834	**0.003**	0.276	0.295	0.086	**0.001**	0.865
Aspect							
F	0.944	0.072	0.068	0.019	1.648	1.093	0.473
p	0.335	0.789	0.795	0.890	0.204	0.300	0.494
Altitude							
F	**29.400**	1.487	0.141	0.185	0.458	1.015	**5.189**
p	**<0.001**	0.227	0.709	0.669	0.501	0.318	**0.026**

Table 4: Results of One-way Analyses of Variance with covariance (ANCOVAs) comparing tree structure along the edges of the seven trail types that comprised the 46.1 km of recreational trails in 17 remnants of Tall Open Blackbutt forest in southeast Queensland. Covariates include remnant, the interaction term of Trail type*remnant (which if significant indicates spatial autocorrelation), slope, aspect and altitude. Bold values indicate significant differences ($p < 0.05$) according to the ANOVA. Different adjacent letters indicate significant differences between trail types (Tukey HSD post hoc tests).

	Tree density (trees m^{-2})	% saplings	% trees mid	% trees mature	% trees dead	% canopy cover	Litter depth (cm)
Means and Standard Deviations for Trail Type							
Control	**0.39 ± 0.18 a**	**11.3 ± 11.6 a**	39.7 ± 9.3	49 ± 9.9	18 ± 11	**71.5 ± 9.3 a**	4.7 ± 1.2
Informal							
Small Bare Earth	**0.36 ± 0.19 c**	**23 ± 7.9 ac**	35.3 ± 15.6	41.7 ± 13	17 ± 12.1	**69.6 ± 16.5 a**	5.3 ± 1.7
Medium Bare Earth	**0.35 ± 0.16 c**	**33.3 ± 12.9 bc**	42.7 ± 17	24 ± 11.1	17 ± 11.3	**63.2 ± 13.1 c**	4.3 ± 1.7
Large Bare Earth	**0.22 ± 0.13 d**	**45.3 ± 14.9 bc**	24.7 ± 8.8	30 ± 16.1	10.3 ± 8.1	**38.1 ± 15 bc**	4.7 ± 2.3
Formal							
Medium Grass	**0.5 ± 0.19 b**	**42.5 ± 22.8 bc**	47.5 ± 22.8	10 ± 7.8	15.5 ± 8.9	**53.6 ± 11.3 bc**	3.7 ± 0.7
Medium Gravel	**0.26 ± 0.17 c**	**43.5 ± 20.3 bc**	34.5 ± 14	22 ± 11.4	14 ± 11.7	**59.2 ± 11.9 abc**	5.1 ± 1.6
Large Gravel	**0.34 ± 0.34 c**	**42.5 ± 17.7 b**	44 ± 18.7	13.5 ± 6.7	25 ± 12.9	**44 ± 17.3 b**	4.7 ± 0.9
Medium Tarmac/Conc.	**0.19 ± 0.08 d**	**41.5 ± 18.3 b**	36 ± 19.9	22 ± 7.9	10 ± 9.7	**64.4 ± 17.5 a**	4 ± 1.7
Statistics							
Trail Type							
F	**3.813**	**12.009**	0.895	0.962	0.873	**4.614**	0.426
p	**0.012**	**<0.001**	0.534	0.491	0.549	**0.006**	0.871
Remnant							
F	**6.888**	**2.703**	1.259	1.365	0.404	1.160	**3.092**
p	**<0.001**	**0.021**	0.322	0.270	0.936	0.373	**0.018**
Trail Type*Remnant							
F	0.728	0.570	1.232	1.178	1.245	0.913	1.389
p	0.729	0.869	0.278	0.35	0.270	0.545	0.189
Slope							
F	0.002	1.291	1.259	1.131	0.359	2.710	0.238
p	0.966	0.260	0.266	0.291	0.551	0.105	0.628
Aspect							
F	0.205	0.645	0.001	0.013	1.203	0.762	0.534
p	0.651	0.425	0.977	0.909	0.277	0.386	0.467
Altitude							
F	**30.037**	0.29	0.047	0.027	0.303	1.106	**6.761**
p	**<0.001**	0.592	0.828	0.869	0.584	0.297	**0.012**

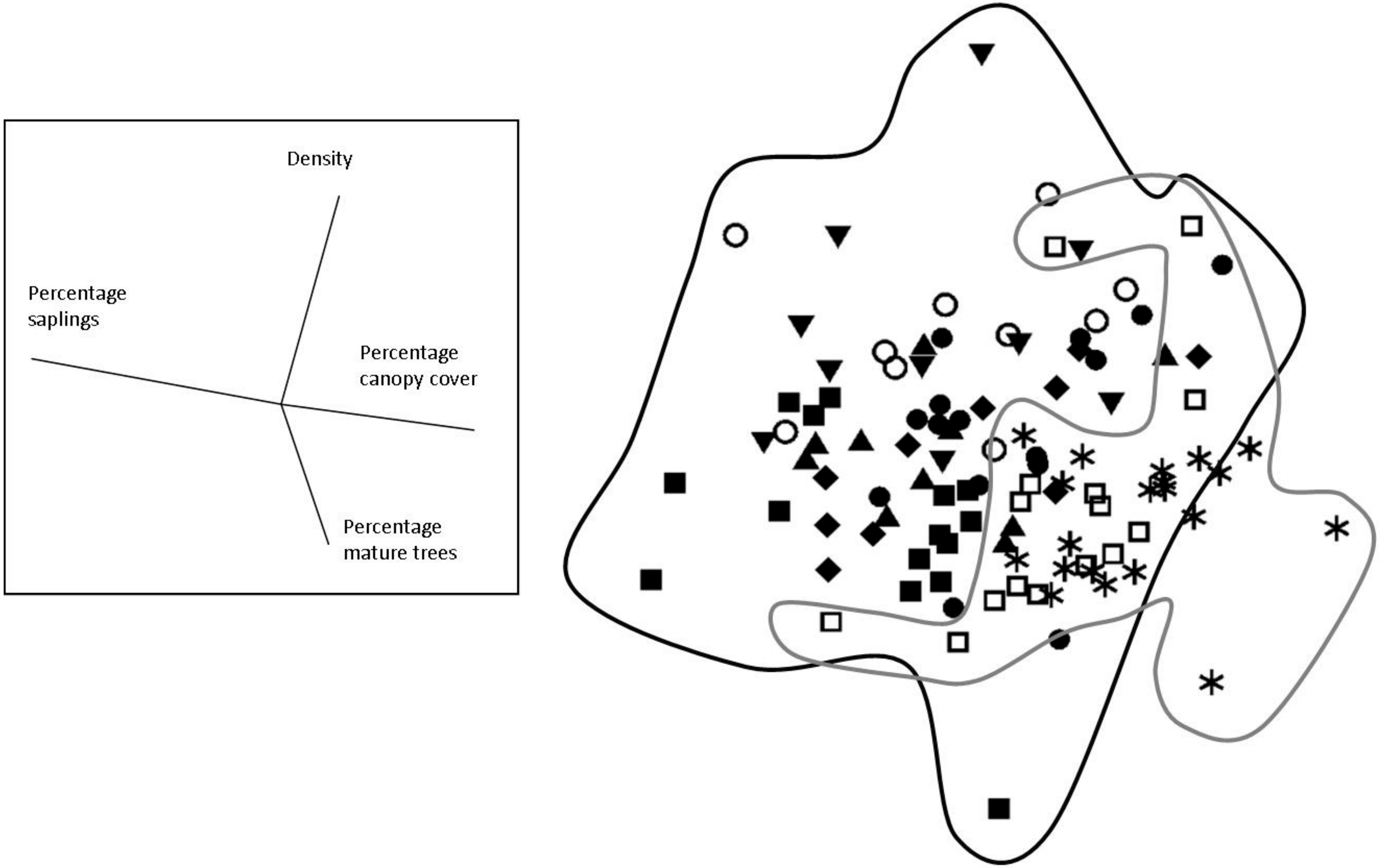

Figure 3: MDS plot based on normalised data and Euclidean distance matrix showing clustering of the seven trail types dependent on their effect on tree structure. There is separation between control and small bare earth trails (* and □, respectively) having little effect on changing forest structure, and all other trails (medium grass (○), medium bare earth (●), large bare earth (■), medium gravel (▲), large gravel (▼), medium tarmac/concrete (♦)). Stress = 0.21. Top left Pearson correlation shows strongest influences on this separation with length of the line indicating strength.

4. Discussion

We found clear differences in trail surface, loss of forest strata and changes in tree structure between trails. Overall we found that there were poorer trail surface conditions along informal trails with greater soil loss and variation in trail width, especially on slopes, than formal trails. The per unit area loss of forest along the edge of trails did not differ between formal and informal trails, but increased relative to the trail width. However, because there were more informal trails (70% of trails) they accounted for most of the forest lost overall. The structure of the trees along the trails differed from natural forest with large informal trails and hardened formal trails causing high canopy loss, reductions in tree density and an increase in the proportion of saplings. These results are important for the management of a wide range of landscapes as trails occur in both urban and remote natural areas including areas that are both of high conservation value and that are popular recreation destinations.

4.1 Trail surface conditions were generally poorer on informal trails

We found large, bare earth informal trails to have poorest surface conditions with large variance in width, intense erosion and poor slope alignment, all of which is corroborated by other research (Brooks and Lair, 2005; Manning *et al.*, 2006; Pickering *et al.*, 2010; Wimpey and Marion, 2010; Wimpey and Marion, 2011). The degradation on these trails from soil loss, is often initiated by poor contour alignment (Wimpey and Marion, 2010), with trails on steep slopes on sedimentary substrates particularly at risk, in some cases losing > 1 metric tonne m^{-2} of soil per year (Wilshire et al., 1978). The use of informal trails exacerbates the problem. Frequent use for activities involving accelerating and braking behaviour such as dirt-biking contributes to erosion (Wilshire et al., 1978; Buckley, 2004). Such activities can loosen substrate and facilitate surface run-off leading to gullying along trails (Brooks and Lair, 2005). When subsequent users start to avoid degraded areas, they contribute to trail widening (Whinam and Comfort, 1996; Liddle, 1997; Olive and Marion, 2009). The result is that poorly aligned informal trails may degrade rapidly (Wilshire et al., 1978; Buckley, 2004; Liddle, 1997).

Interestingly in this study, narrower informal trails (1 m) primarily used for hiking and mountain biking had little soil loss and tended to be aligned along contours. Despite not being part of a formally-managed trail system, the surface condition of these trails was actually better than some formal trails such as gravel trails which experienced greater substrate loss. The unauthorised use of informal trails, however, means they experience other problems such as the construction of unauthorised technical trail features by mountain bikers, littering and vandalism (Matlack, 1993; Pickering et al., 2010).

Formalised, hardened trails generally had better trail surface conditions than most informal trails. In the past, managers relied on resource hardening to reduce degradation of trails, including upgrading informal trails (Leung and Marion, 2000; Cahill et al., 2008; Wimpey and Marion, 2010). Hardened trails limit soil erosion and maintain surface conditions reducing trail widening (Wimpey and Marion, 2010). They can also reduce other impacts such as trail-braiding and the construction of unauthorised trail technical features (Pickering et al., 2010; Leung et al., 2011). Hardening can be a highly effective long-term method of maintaining trails in protected areas (Hill and Pickering, 2006; Cahill et al., 2008; Tomczyk, 2011; Zhang et al., 2012).

Trail hardening, however, can also detract from the natural appeal of these areas and in some cases hardening trails may be opposed by recreationists (Cahill et al., 2008). Moreover, resource hardening can be costly, and, as in this case, where there is no single managing authority for the mixture of protected and unprotected forests, funding for such a programme is difficult. An alternative measure to reduce the spread of informal trails may be the closure of the informal trails and the promotion of non-conservation land for hiking and mountain bike riding, such as plantation forests; a method that has been successful elsewhere (Goeft and Alder, 2001; Newsome and Davies, 2009).

4.2 The loss of forest strata differed among trail types

As with other forms of infrastructure such as roads and power lines, we found that formal and informal recreational trails resulted in the loss of forest strata. Increasing trail width per unit area resulted in proportionately greater loss of forest strata with no interactive effects. As a result, both large formal and informal trails (> 4 m), had similar effects on forest loss with > 5 m either side of these trails bare of mature trees; impacts comparable with edge effects of some roads (Delgado et al., 2007). Due to the unregulated use of informal trails and their tendency to widen over time however, these trails may pose a greater threat to forest loss than formal trails.

There were more informal trails and overall they accounted for the greatest total loss of forest. Previous work has highlighted one of the main issues surrounding informal trails is their rapid spatial proliferation and hence their impacts can accumulate over large areas (Leung et al., 2011; Pickering et al., 2010; Ballantyne et al., 2014). The informal small bare earth trails in this study proliferated through the remnants causing considerable fragmentation by geometrically-complex networks. Although the narrow width of these informal trails may not impede many large-scale functional processes such as fire and larger/more mobile animal movement at any one location, their cumulative effect may be much greater given the very small sizes of many urban remnant forests (Ballantyne et al., 2014). Fragmentation due to informal trails is a threatening process in a number of regions including popular national parks in the United States of America (Moskal and Halabisky, 2010; Leung et al., 2011). In urban settings, with the popularity of urban green spaces for recreation, informal trails could facilitate weed invasions, behavioural changes in edge-sensitive fauna, poaching, firewood gathering and dumping rubbish amongst many other impacts (Matlack, 1993; Pickering et al., 2010; Marzano and Dandy, 2012). Essentially these trails contribute to forest loss directly through their creation and act as conduits for other impacts deep into the remnants' cores.

4.3 Tree structure differed among trail types

The structure of the trees remaining along the edge of formal and informal trails differed to natural forest. The informal large bare earth trails that are up to 7 m wide had less canopy cover over the trail, reduced density of trees in the adjacent forest and more saplings. Interestingly, all hardened trails that were narrower than informal large bare earth trails (average widths between 2.3 m and 3.8 m), had similar effects on tree structure. It is possible that the similar impacts of formal and informal trails may be a result of different processes.

Large informal trails were very wide and the resulting large canopy gaps may have likely altered local abiotic conditions such as increased light and heat infiltration, as occurs along roads and power lines (Delgado et al., 2007; Pohlman et al., 2007; Goosem, 2007). In Blackbutt forests with their relatively open structure however, canopy gaps from trails are unlikely to amplify these factors (Harper and MacDonald, 2002). Instead, it is possible that the linear shape of gaps along the trails have increased wind funnelling and turbulence within the forest (Laurance, 1997; Laurance et al., 1998b; Harper and MacDonald, 2002). Enhanced wind-blow can damage and destabilise mature trees and disturb edge soils which in turn promotes the growth of saplings (Boucher et al., 1991; Young and Perkocha, 1994; Laurance et al., 1998b; Harper and MacDonald, 2002). As surface conditions on informal trails degrade and trails widen, a positive feedback loop of increased canopy opening and wind-blow could occur favouring saplings along forest edges (Boucher et al., 1991; Laurance et al., 1998a; Chen et al., 1992; Harper and MacDonald, 2002; Prasad, 2009). Consequently, the structure of forest edges may be transformed into regenerate-dominant ecosystems (Parikesit et al., 1995; Laurance, 1997; Farreira and Laurance, 1997).

Formal hardened trails also changed the tree structure, with strong effects along even comparatively small trails (ca. 3m wide). In addition to any effects of the trail on canopy openings, the construction and maintenance of these formal trails may damage the forest. The use of machinery to create hardened trails can damage trees along trail corridors (Cole, 1978) and edge soils can be disturbed and polluted from materials and nutrients used during trail construction (Godefroid and Koedam, 2004; Müllerová *et al.*, 2011). Trail maintenance such as mowing verges and cutting overhanging branches may add to these impacts. Damage to mature trees along trail edges during the construction and maintenance of formal trails may promote sapling regrowth favouring secondary succession.

Given the small size of the forest remnants in this study and their high conservation status, follow-on effects from structural changes in the forest along trail edges could affect the compositional and functional biodiversity of these forests. A multitude of young successional forest edges could result in increased alpha diversity if the forest increasingly contains ruderal species that respond well to canopy opening and a decline in tree density (Franklin and Spies, 1991; Buckley *et al.*, 2003). As these edge effects spread with trail creation, habitat structure may become simplified limiting beta diversity (Franklin and Spies, 1991) at the expense of core forest species (Didham *et al.*, 1996; Hill and Curran, 2001; Guirado et al., 2006). As such, plants such as ruderal weeds, C4 species favouring high light conditions, wind-dispersing Asteraceae species and rapidly-growing vines can colonise and dominate edge forest. Faunal composition may also change becoming increasingly dominated by opportunist or edge-tolerant species (Miller et al., 1998; Yates and Muzika, 2006; Wolf et al., 2013) with animals adapted to low winds and more dense vegetation such as Microchiropteran bats, owls and arboreal reptiles isolated in core forest (Crome and Richards, 1988). Trail use may also increase the risk of biological invasions by weeds and pathogens able to establish and persist along trail edges deep into the remnants (Janzen, 1988; Wilson and Crome, 1989; Nemec et al. 2011).

4.4 Management Recommendations

There is increasing interest in trail-based recreation such as hiking and mountain biking in forests (Goeft and Alder, 2001; Kuvan, 2005; Newsome et al., 2013). The formal and informal trails used for these activities however, can damage forests. Therefore trail impacts need to be minimised particularly when the trails traverse already endangered communities or ecosystems (Marion and Wimpey, 2007; Marion and Leung, 2011; Wimpey and Marion, 2011). How this can be done depends largely on the type of trail and the intensity, timing and type of use, as well as the tolerance of the ecosystem to these types of disturbance (Cole, 2004; Pickering, 2010). In case of the type of trail, it is important to take into account both the impacts caused per unit area of the trail, and across the landscape as a whole, as each produces different results and in some cases quick resource-hardening and formalising trails may not be the best management response. Based on this study, we highlight some key issues for trail management.

To maintain trail surface conditions, there are two common responses: trail hardening, and/or better trail network design. Resource hardening, particularly using boardwalks, concrete and pavers can reduce soil loss from the trail surface and limit trail widening thereby improving surface condition (Wimpey and Marion, 2010). The selection of substrates is important as they should not result in long-term problems such as nutrient leaching (Müllerová et al., 2011) and pH changes (Godefroid and Koedam, 2004). Also, wider hardened trails can result in increased canopy gaps and hence changes to the structure of the forest along the trails. Therefore, rehabilitation of the forest edges after the construction of hardened trails is important. This could include heterogeneous planting of species native to the site and actively managing their re-establishment. Rehabilitation of the forest can minimise behavioural changes in local birds and other organisms (Creel et al. 2002; Gaines et al., 2003; Tews et al., 2004; Wolf et al., 2013), reduce further trail widening and the canopy gap feedback loop (Murison et al., 2007) and making the trails more aesthetically appealing to recreationists (Englin et al., 2006; Roovers et al., 2006).

In some cases narrow unhardened trails may be preferable to hardened trails. Interestingly, informal small bare earth trails in the Blackbutt forest do not appear to have resulted in changes in tree structure possibly because they have small canopy gaps and there is likely to have been less disturbance during their creation. Many of these trails bypassed large trees, avoided steep inclines and had little exposed canopy. Instead of resorting to hardening trails, it may be more cost-effective and environmentally beneficial to monitor existing, well-located informal trails to make sure they do not deteriorate, rather than hardening them. Management could complement these trails by designing additional formal narrow and unhardened trail networks avoiding steep slopes and areas sensitive to disturbance to concentrate visitor flows (Malcolm and Ray, 2000). These trails could be particularly appropriate in more remote settings (Cahill et al., 2008).

5. Conclusions

There has been limited research comparing different types of formal and informal trails in any ecosystem. The results of this research in Blackbutt forest emphasise why such studies are important, by providing novel results including the relative impact of different types of trails on forest loss and tree structure. Although the loss of forest strata and structural change caused by trails may seem negligible in comparison to whole-scale clearance from forestry and agriculture, many of the edge effects caused by trails may persist in the long-term across a complex network often reaching deep into core forest. In this respect, any impacts of these trails can accumulate in space, and should be regarded as a conservation concern especially in already endangered forest ecosystems and in urban areas where trail networks are rapidly increasing (Malcolm and Ray, 2000; Ballantyne et al., 2014).

Further research on trails should include studies assessing their impacts on functional processes such as seed dispersal, pollination and facilitation (Ballantyne and Pickering, in review). The current study provided a ‘snapshot’ of impacts, with no data on the amount of use and age of trails. Consequently, some confounding temporal information that could have contributed to the observed differences may have been missed (Thorpe et al., 2008). These types of limitations are common to non-experimental studies in recreation ecology where important sources of variance cannot be removed. It is unlikely however, that landscape level trail creation using an experimental approach would be ethically or physically feasible.

Acknowledgements

The authors would like to thank the Redlands City Council, Queensland National Parks and Wildlife Service and Griffith University for granting research access to the forests in this study. Thanks also to Donna Treby, Diana Kiss, Jodie Hills, Kyle Debets, Madaleine Rogers, Tahlie Page and Daniel Hawkins for their assistance with data collection. Finally, we would like to give our gratitude to Dr Clare Morrison for her comments on previous drafts of this manuscript.

References

Ballantyne, M. and Pickering, C.M., (in review) Recreational trail causes negative effects on facilitation in an alpine shrub-dominated plant community.

Ballantyne, M., Gudes, O. and Pickering, C.M., (2014) Recreational trails are an important cause of fragmentation in endangered urban forests: a case-study from Australia. *Landscape and Urban Planning* **130**, 112-124.

Barros, A. and Pickering, C.M., (2014) Non-native plant invasion in relation to tourism use of Aconcagua Park, Argentina, the highest protected area in the southern hemisphere. *Mountain Research and Development* **34**, 13-26.

Bhuju, D.R. and Osawa, M., (1998) Effects of nature trails on ground vegetation and understory colonisation of a patchy remnant forest in an urban domain. *Biological Conservation* **85**, 123-135.

Boege, K. and Marquis, R.J., (2005) Facing herbivory as you grow up: the ontogeny of resistance in plants. *Trends in Ecology and Evolution* **20**, 441-448.

Boucher, D.H., Aviles, J., Chepote, R., Domínguez Gil, O.E. and Vilchez, B., (1991) Recovery of trailside vegetation from trampling in a tropical rain forest. *Environmental Management* **15**, 257-262.

Broadhurst, L. and Young, A., (2007) Seeing the wood and the trees - predicting the future for fragmented plant populations in Australian landscapes. *Australian Journal of Botany* **55**, 250-260.

Brooks, M.L. and Lair, B., (2005) *Ecological effects of vehicular routes in a desert ecosystem*. US Geological Survey, Henderson, USA. 11 p.

Buckley, D.S., Crow, T.R., Nauertz, E.A. and Schulz, K.E., (2003) Influence of skid trails and haul roads on understory plant richness and composition in managed forest landscapes in Upper Michigan, USA. *Forest Ecology and Management* **175**, 509-520.

Buckley, R. (2004). Environmental impacts of motorised off-highway vehicles. In R. Buckley (Ed.), *Environmental impacts of ecotourism*. CABI Publishing, London, UK. pp. 83-98.

Byrne, J., Sipe, N and Searle, G., (2010) Green around the gills? The challenge of density for urban greenspace planning in SEQ. *Australian Planner* **47**, 162-177.

Cahill, K.L., Marion, J.L. and Lawson, S.R., (2008) Exploring visitor acceptability for hardening trails to sustain visitation and minimise impacts. *Journal of Sustainable Tourism* **16**, 232-245.

Chen, J., Franklin, J.F. and Spies, T.A., (1992) Vegetation responses to edge environments in old-growth Douglas Fir forests. *Ecological Applications* **2**, 387-396.

Chiesura, A., (2004) The role of urban parks for the sustainable city. *Landscape and Urban Planning* **68**, 129-138.

Clarke, K.R., (1993) Non-parametric multivariate analyses of change in community structure. *Australian Journal of Ecology* **18**, 117-143.

Cole, D.N., (1978) Estimating the susceptibility of wildland vegetation to trailside alteration. *Journal of Applied Ecology* **15**, 281-286.

Cole, D.N., (1994) Backcountry impact management: lessons from research. *Trends* **31**, 10-14.

Cole, D.N., (2004) Impacts of hiking and camping on soils and vegetation: a review. In R. Buckley (Ed.), *Environmental impacts of ecotourism*. CABI Publishing, London, UK. pp. 41-60.

Creel, S., Fox, J.E. and Hardy, A., Sands, J., Garrott, B. and Peterson, R.O., (2002) Snow mobile activity glucocorticoid stress responses in wolves and elk. *Conservation Biology* **16**, 809-814.

Crome, F.H.J. and Richards, G.C., (1988) Bats and gaps: microchiropteran community structure in a Queensland rainforest. *Ecology* **69**, 1960-1969.

Delgado, J.D., Arroyo, N.L., Arévalo, J.R. and Fernández-Palacios, J.M., (2007) Edge effects of roads on temperature, light, canopy cover and canopy height in laurel and pine forests (Tenerife, Canary Islands). *Landscape and Urban Planning* **81**, 328-240.

Didham, R.K., Ghazoul, J., Stork, N.E. and Davis, A.J., (1996) Insects in fragmented forests: a functional approach. *Trends in Ecology and Evolution* **11**, 255-260.

Diggle, P.J., (1983) *Statistical analysis of spatial point patterns*. Academic Press, London, UK. pp. 4-5.

Emborg, J., (1998) Understorey light conditions and regeneration with respect to the structural dynamics of a near-natural temperate deciduous forest in Denmark. *Forest Ecology and Management* **106** 83-95.

Englin, J.E., McDonald, J.M. and Moeltner, K., (2006) Valuing ancient forest ecosystems: an analysis of backcountry hiking in Jasper National Park. *Ecological Economics* **57**, 665-678.

Ernest, K.A., (1989) Insect herbivory on a tropical understorey tree: effects of leaf age and habitat. *Biotropica* **21**, 194-199.

Farreira, L.V. and Laurance, W.F., (1997) Effects of forest fragmentation on mortality and damage of selected trees in central Amazonia. *Conservation Biology* **11**, 797-801.

Farrell, T.A. and Marion, J.L., (2001) Identifying and assessing ecotourism visitor impacts at eight protected areas in Costa Rica and Belize. *Environmental Conservation* **28**, 215-225.

Florgård, C. and Forsberg, O., (2006). Residents' use of remnant natural vegetation in the residential area of Järvafältet, Stockholm. *Urban Forestry and Urban Greening* **5**, 83-92.

Franklin, J.F., Cromack, K., Denison, W., McKee, A., Maser, C., Sedell, J., Swanson, F. and Juday, G., (1981) *Ecological characteristics of old-growth Douglas Fir forests*. USDA Forest Service general technical report PNW-118. Pacific North-west Forest and Range Experiment Station, Portland, USA. 48 p.

Franklin, J.F. and Spies, T.A., (1991) *Composition, function and structure of old-growth Douglas Fir forests.* USDA Forest Service general technical report PNW-GTR-285. Pacific North-west Forest and Range Experiment Station, Portland, USA. pp. 71-80.

Gaines, W.L., Singleton, P.H., Ross, R.C., (2003) *Assessing the cumulative effects of linear recreation routes on wildlife habitats on the Okanogan and Wenatchee National Forests*. USDA Forest Service general technical report PNW-GTR-586. Pacific North-west Forest and Range Experiment Station, Portland, USA. pp. 1-79.

Gibbons, P. and Lindenmayer, D., (2002) *Tree hollows and wildlife conservation in Australia*. CSIRO Publishing, Melbourne, Australia. 217 p.

Godefroid, S. and Koedam, N., (2004) The impact of forest paths upon adjacent vegetation: effects of the path surfacing material on the species composition and soil compaction. *Biological Conservation* **119**, 405-419.

Goeft, U. and Alder, J., (2001) Sustainable mountain biking: a case study from the southwest of Western Australia. *Journal of Sustainable Tourism* **9**, 193-208.

Goosem, M., (2007) Fragmentation impacts caused by roads through rainforests. *Current Science* **93**, 1587-1595.

Guirado, M., Pino, J. and Rodá, F., (2006) Understory plant species richness and composition in metropolitan forest archipelagos: effects of forest size, adjacent land use and distance to the edge. *Global Ecology and Biogeography* **15**, 50-62.

Hall, C.N. and Kuss, F.R., (1989) Vegetation alteration along trails in Shenandoah National Park, Virginia. *Biological Conservation* **48**, 211-227.

Hamberg, L., Lehvävirta, S., Minna, M.L., Rita, H. and Kotze, D.J., (2008) The effects of habitat edges and trampling on understorey vegetation in urban forests in Helsinki, Finland. *Applied Vegetation Science* **11**, 83-98.

Harper, K.A. and MacDonald, S.E., (2002) Structure and composition of edges next to regenerating clear-cuts in mixed-wood boreal forest. *Journal of Vegetation Science* **13**, 535-546.

Harper, K.A., MacDonald, S.E., Burton, P.J., Chen, J., Brosofske, K.D., Saunders, S.C., Euskirchen, E.S., Roberts, D., Jaiteh, M.S. and Esseen, P.A., (2005) Edge influence on forest structure and composition in fragmented landscapes. *Conservation Biology* **19**, 768-782.

Hauru, K., Niemi, A. and Lehvävirta, S., (2012) Spatial distribution of saplings in heavily worn urban forests: implications for regeneration and management. *Urban Forestry and Urban Greening* **11**, 279-289.

Hill, J.L. and Curran, P.J., (2001) Species composition in fragmented forests: conservation implications of changing forest area. *Applied Geography* **21**, 157-174.

Hill, W. and Pickering, C.M., (2006) Vegetation associated with different walking track types in the Kosciuszko alpine area, Australia. *Journal of Environmental Management* **78**, 24-34.

Janzen, D.H., (1988) Tropical dry forests. In E.O. Wilson (Ed.), *Biodiversity*. National Academies Press, Washington D.C., USA. pp. 130-137.

Kint, V., Van Meirvenne, M., Nachtergale, L., Geudens, G. and Lust, N., (2003) Spatial methods for quantifying forest stand structure development: a comparison between nearest-neighbour indices and variogram analysis. *Forest Science* **49**, 36-49.

Kuvan, Y., (2005) The use of forests for the purpose of tourism: the case of Belek Tourism Center in Turkey. *Journal of Environmental Management* **75**, 263-274.

Laurance, W.F., (1997) Hyper-disturbed parks: edge effects and the ecology of isolated rainforest reserves in tropical Australia. In W.F. Laurance and R.O. Bierregaard (Eds.), *Tropical forest remnants: ecology, management and conservation of fragmented communities.* University of Chicago Press, Chicago, USA. pp. 71-83.

Laurance, W.F., Ferreira, L.V., Rankin-de Merona, J.M., Laurance, S.G., (1998a) Rain forest fragmentation and the dynamics of Amazonian tree communities. *Ecology* **79**, 2032-2040.

Laurance, W.F., Ferreira, L.V., Rankin-de Merona, J.M., Laurance, S.G., Hutchings, R.W. and Lovejoy, T.E., (1998b) Effects of forest fragmentation on recruitment patterns in Amazonian tree communities. *Conservation Biology* **12**, 460-464.

Laurance, W.F., Goosem, M. and Laurance, S.G.W., (2009) Impacts of roads and linear clearings on tropical forests. *Trends in Ecology and Evolution* **24**, 659-669.

Lee, A.C.K. and Maheswaran, R., (2011) The health benefits of urban green spaces: a review of the evidence. *Journal of Public Health* **33**, 212-222.

Leung, Y.F. and Marion, J.L., (2000) Recreation impacts and management in wilderness: A state-of-knowledge review. *USDA Forest Service Proceedings* **15**, 23-48.

Leung, Y.F., Shaw, N., Johnson, K., and Duhaime, R., (2002) More than a database: integrating GIS data with the Boston Harbor Islands carrying capacity study. *George Wright Forum* **19**, 69-78.

Leung, Y.F., Newburger, T., Jones, M., Kuhn, B. and Woiderski, B., (2011) Developing a monitoring protocol for visitor-created informal trails in Yosemite National Park, USA. *Environmental Management* **47**, 93-106.

Leung, Y.F., Walden-Schreiner, C., Matisoff, C., Naber, M. and Robinson, J., (2013) A two-pronged approach to evaluating environmental concerns of disc golf as emerging recreation in urban natural areas. *Managing Leisure* **18**, 273-285.

Liddle, M.J., (1997) *Recreation ecology*. Chapman and Hall Publishing, London, UK. 664 p.

Malcolm, J.R. and Ray, J.C., (2000) Influence of timber extraction routes on Central African small mammal communities, forest structure and tree diversity. *Conservation Biology* **14**, 1623-1638.

Malmivaara-Lämsä, M., Hamberg, L., Haapamäki, E., Liski, J., Kotze, D.J., Lehvävirta, S. and Frtize, H., (2008) Edge effects and trampling in boreal urban forest fragments - impacts on the soil microbial community. *Soil Biology and Biochemistry* **40**, 1612-1621.

Manning, R., Jacobi, C. and Marion, J.L., (2006) Recreation monitoring at Acadia National Park. *The George Wright Forum* **23**, 59-71.

Marion, J.L. and Leung, Y.F., (2004) Environmentally sustainable trail management. In R Buckley (Ed.), *Environmental impacts of ecotourism*. CABI Publishing, London, UK. pp. 229-244.

Marion, J.L. and Wimpey, J., (2007) *Environmental impacts of mountain biking: science review and best practises. In: Managing mountain biking: IMBA's guide to providing great riding*. International Mountain Biking Association Publishing, Boulder, USA. 256 p.

Marion, J.L. and Leung, Y.F., (2011) Indicators and protocols for monitoring impacts of formal and informal trails in protected areas. *Journal of Tourism and Leisure Studies* **17**, 215-236.

Marzano, M. and Dandy, N., (2012) Recreationist behaviour in forests and the disturbance to wildlife. *Biodiversity and Conservation* **21**, 2967-2986.

Matlack, G.R., (1993) Sociological edge effects: spatial distribution of human impact in suburban forest fragments. *Environmental Management* **17**, 829-835.

McAlpine, C.A., Spies, T.A., Norma, P. and Peterson, A., (2007) Conserving forest biodiversity across multiple land ownerships: lessons from the Northwest Forest Plant and the Southeast Queensland regional forests agreement (Australia). *Biological Conservation* **134**, 580-592.

McCune, B., Rosentreter, R., Ponzetti, J.M. and Shaw, D.C., (2000) Epiphyte habitats in an old conifer forest in Western Washington, USA. *The Bryologist* **103**, 417-427.

McKinney, M.L., (2002) Urbanisation, biodiversity and conservation. *BioScience* **52**, 883-890.

Miles, L., Newton, A.C., DeFries, R.S., Ravilious, C., May, I., Blyth, S., Kapos, V. and Gordon, J.E., (2006) A global overview of the conservation status of tropical dry forests. *Journal of Biogeography* **33**, 491-505.

Miller, S.G., Knight, R.L. and Miller, C.K., (1998) Influence of recreational trails on breeding bird communities. *Ecological Applications* **8**, 162-169.

Monz, C.A., Cole, D.N., Leung, Y.F. and Marion, J.L., (2010) Sustaining visitor use in protected areas: future opportunities in recreation ecology research based on the USA experience. *Environmental Management* **45**, 551-562.

Moskal, L.M., and Halabisky, M., (2010) Analysis of social trails in Mt. Rainier National Park: a pilot study. http://www.cfr.washington.edu/research.cesu/reports/J8W07090020_final_report.pdf. Accessed 3rd July 2014.

Müllerová, J., Vítková, M. and Vítek, O., (2011) The impacts of road and walking trails upon adjacent vegetation: effects of road building materials on species composition in a nutrient poor environment. *Science of the Total Environment* **409**, 3839-3849.

Murison, G., Bullock, J.M., Underhill-Day, J., Langston, R., Brown, A.F. and Sutherland, W.J., (2007) Habitat type determines the effects of disturbance on the breeding productivity of the Dartford Warbler (*Sylvia undata*). *Ibis* **149**, 16-26.

Nemec, K.T., Allen, C.R., Alai, A., Clements, G., Kessler, A.C., Kinsell, T., Major, A. and Stephen, B.J., (2011) Woody invasions of urban trails and the changing face of urban forests in the Great Plains, USA. *The American Midland Naturalist* **165**, 241-256.

Newsome, D. and Davies, C., (2009) A case study in estimating the area of informal trail development and associated impacts caused by mountain bike activity in John Forrest National Park, Western Australia. *Journal of Ecotourism* **8**, 237-253.

Newsome, D., Moore, S.A. and Dowling, R.K., (2013) *Natural area tourism: ecology, impacts and management – 2nd edition*. Channel View Publications, Bristol, UK. 457 p.

Noss, R.F., (1990) Indicators for monitoring biodiversity: a hierarchical approach. *Conservation Biology* **4**, 355-364.

Olive, N.D. and Marion, J.L., (2009) The influence of use-related, environmental and managerial factors on soil loss from recreational trails. *Journal of Environmental Management* **90**, 1483-1493.

Parikesit, P., Larson, D.W. and Matthes-Sears, U., (1995) Impacts of trails on cliff-edge forest structure. *Canadian Journal of Botany* **73**, 943-953.

Pickering, C.M., (2010) Ten factors that affect the severity of environmental impacts of visitors in protected areas. *AMBIO* **39**, 70-77.

Pickering, C.M., Castley, J.G., Newsome, D. and Hill, W., (2010) Environmental, safety and management issues of unauthorised trail technical features for mountain bicycling. *Landscape and Urban Planning* **97**, 58-67.

Pickering, C.M., Castley, J.G. and Richardt, K., (2012) Informal trails fragmenting endangered remnant vegetation in Australia (extended abstract). Sixth international conference on monitoring and management of visitors in recreational and protected areas, Stockholm, Sweden. pp. 362-363.

Pohlman, C.L., Turton, S.M. and Goosem, M., (2007) Edge effects of linear canopy openings on tropical rain forest understorey microclimate. *Biotropica* **39:1**, 62-71.

Prasad, A.E., (2009) Tree community change in tropical dry forest: the role of roads and exotic plant invasion. *Environmental Conservation* **3**, 201-207.

Queensland Government, (2007) *South-east Queensland outdoor recreation demand study*. Queensland Government, Brisbane, Australia. pp. 1-106.

Queensland Government, (2013) Regional ecosystems descriptions database (REDD). http://www.ehp.qld.gov.au/ecosystems/biodiversity/regional-ecosystems/index.php. Accessed 3rd July 2014.

Queensland Government, (2014) Regional ecosystems technical descriptions. https://publications.qld.gov.au/storage/f/2014-09-18T23%3A49%3A36.560Z/re-seq-landzones.pdf. Accessed 17th March 2015.

Queiroz, R.E., Ventura, M.A. and Silva, L., (2014) Plant diversity in hiking trails crossing Natura 2000 area in the Azores: implications for tourism and nature conservation. *Biodiversity and Conservation* **23**, 1347-1365.

Ries, L., Fletcher, R.J., Battin, J. and Sisk, T.D., (2004) Ecological responses to habitat edges: mechanisms, models and variability explained. *Annual Review of Ecology, Evolution and Systematics* **35**, 491-552.

Roovers, P., Dumont, B., Gulinck, H. and Hermy, M., (2006) Recreationists' perceived obstruction of field and shrub layer vegetation. *Urban Forestry and Urban Greening* **4**, 47-53.

Sewell, S.R. and Catterall, C.P., (1998) Bushland modification and styles of urban development: their effects on birds in south-east Queensland. *Wildlife Research* **25**, 45-63.

Sklodowski, J., Bartosz, S., Dul, L., Grzybek, D., Jankowski, S., Kajetanem, M., Kalisz, P., Korenkiewicz, U., Mazur, G., Myszek, J., Ostasiewicz, M., Primka, B., Puczylowska, I., Radzikowski, M., Roeding, P. and Serek, B., (2009) An attempt to assess the effect of tourist trail width on adjacent forest environment. *Sylwan* **143**, 699-709.

Spies, T.A., (1998) Forest structure: a key to the ecosystem. *Northwest Science* **72**, 34-39.

Stenhouse, R.N., (2004) Fragmentation and internal disturbance of native vegetation reserve in the Perth metropolitan area, Western Australia. *Landscape and Urban Planning* **68**, 389-401.

Sun, D. and Walsh, D., (1998) Review of studies on environmental impacts of recreation and tourism in Australia. *Journal of Environmental Management* **53**, 323-338.

Sutherland, W.J., (2006) *Ecological census techniques: a handbook – second edition*. Cambridge University Press, Cambridge, UK. 446 p.

Tews, J., Brose, U., Grimm, V., Tielbörger, K., Wichmann, M.C., Schwagerand, M. and Jeltsch, F., (2004) Animal species diversity driven by habitat heterogeneity/diversity: the importance of keystone structures. *Journal of Biogeography* **31**, 79-92.

Thorpe, H.C., Thomas, S.C. and Caspersen, J.P., (2008) Tree mortality following partial harvests is determined by skidding proximity. *Ecological Applications* **18**, 1652-1663.

Tomczyk, A.M., (2011) A GIS assessment and modelling of environmental sensitivity of recreational trails: the case of Gorce National Park, Poland. *Applied Geography* **31**, 339-351.

Underwood, A.J., (2002) Analysis of variance. In AJ Underwood (Ed.), *Experiments in ecology – their logical design and interpretation using analysis of variance*. Cambridge University Press, Cambridge, UK. pp. 140-197.

United Nations, (2014) *World urbanisation prospects: the 2014 revision highlights.* http://esa.un.org/unpd/wup/Highlights/WUP2014-Highlights.pdf. Accessed 10th November 2014.

Vitz, A.C. and Rodewald, A.D., (2006) Can regenerating clearcuts benefit mature-forest songbirds? An examination of post-breeding ecology. *Biological Conservation* **127**, 477-486.

Walden-Schreiner, C., and Leung, Y.F., (2013) Spatially characterising visitor use and its association with informal trails in Yosemite Valley Meadows. *Environmental Management* **52**, 163-178.

Whinam, J. and Comfort, M., (1996) The impact of commercial horse riding on sub-alpine environments at Cradle Mountain, Tasmania, Australia. *Journal of Environmental Management* **47**, 61-70.

Wilshire, H.G., Nakata, J.K., Shipley, S., and Prestegaard, K., (1978) Impacts of vehicles on natural terrain at seven sites in the San Francisco Bay area. *Environmental Geology* **2**, 295-319.

Wilson, M.F. and Crome, F.H.J., (1989) Patterns of seed rain at the edge of a tropical Queensland rain forest. *Journal of Tropical Ecology* **5**, 301-308.

Wilson, B.A., Neldner, V.J. and Accad, A., (2002) The extent and status of remnant vegetation in Queensland and its implications for state-wide vegetation management and legislation. *The Rangeland Journal* **24**, 6-35.

Wimpey, J. and Marion, J.L., (2010) The influence of use, environmental and managerial factors on the width of recreational trails. *Journal of Environmental Management* **91**, 2028-2037.

Wimpey, J. and Marion, J.L., (2011) A spatial exploration of informal trail networks within Great Falls Park, VA. *Journal of Environmental Management* **92**, 1012-1022.

Wolf, I.D., Hagenloh, G., Croft, D.B., (2013) Vegetation moderates impacts of tourism usage on bird communities along roads and hiking trails. *Journal of Environmental Management* **129**, 224-234.

Yates, M.D. and Muzika, R.M., (2006) Effect of forest structure and fragmentation on site occupancy of bat species in Missouri Ozark Forests. *Journal of Wildlife Management* **70**, 1238-1248.

Young, T.P. and Perkocha, V., (1994) Treefalls, crown asymmetry and buttresses. *Journal of Ecology* **82**, 319-324.

Zhang, J.T., Xiang, C.L. and Li, M., (2012) Effects of tourism and topography on vegetation diversity in the subalpine meadows of the Dongling Mountains of Beijing, China. *Environmental Management* **49**, 403-411.