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Review

The impacts of trail infrastructure on vegetation and soils: Current literature and future directions

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ABSTRACT

Reflecting the popularity of nature-based activities such as hiking and mountain biking, there are thousands of kilometres of recreational trails worldwide traversing a range of natural areas. These trails have environmental impacts on soils and vegetation, but where has there been research, what impacts have been found and how were they measured? Using a systematic quantitative literature review methodology, we assessed the impacts of trails on vegetation and soils, highlighting what is known, but also key knowledge gaps. Of the 59 original research papers identified on this topic that have been published in English language peer-reviewed academic journals, most were for research conducted in protected areas (71%), with few from developing countries (17%) or threatened ecosystems (14%). The research is concentrated in a few habitats and biodiversity hotspots, mainly temperate woodland, alpine grassland and Mediterranean habitats, often in the USA (32%) or Australia (20%). Most examined formal trails, with just 15% examining informal trails and 11% assessing both types. Nearly all papers report the results of observational surveys (90%), collecting quantitative data (66%) with 24% using geographic information systems. There was an emphasis on assessing trail impacts at a local scale, either on the trail itself and/or over short gradients away from the trail edge. Many assessed changes in composition and to some degree, structure, of vegetation and soils with the most common impacts documented including reduced vegetation cover, changes in plant species composition, trail widening, soil loss and soil compaction. There were 14 papers assessing how these local impacts can accumulate at the landscape scale. Few papers assessed differences in impacts among trails (7 papers), changes in impacts over time (4), species-specific responses (3) and only one assessed effects on plant community functioning. This review provides evidence that there are key research gaps including assessing informal trails, comparing trail types, landscape and temporal scale impacts, functional responses and impacts on threatened ecosystems/species. A more diverse geographic spread of research is also required including in regions experiencing rapid growth in tourism and recreation.

Contents

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1. Introduction

Nature-based tourism and recreation is increasing in popularity globally including trail-based activities such as hiking and mountain biking (Buckley, 2004; Balmford et al., 2009; Newsome et al., 2013; Eagles, 2014). Consequently, the creation of recreational trails (e.g. also tracks or paths) is increasing in many regions including in prominent national parks and wilderness areas (Marion and Leung, 2001, 2004; Cole, 2004; Eagles, 2014), but also in urban and peri-urban natural areas (Matlack, 1993; Ballantyne et al., 2014a). In the USA alone, there are over 126,000 km of formal recognised recreational trails built by park agencies; enough to circumvent the globe three times (US National Park Service, 2014). Reflecting the expansion in recreational trail networks is an increasing focus on assessing trail impacts within the discipline of recreation ecology.

There is over 50 years of research on recreational trails documenting an array of impacts on vegetation, soils, animals and water (Wall and Wright, 1977; Liddle, 1997; Hammitt and Cole, 1998; Monz et al., 2009). Numerous observational and experimental studies have assessed use-related impacts of common recreational trail-based activities such as hiking, including comparisons among different activities (Rickard et al., 1994; Wilson and Seney, 1994; Deluca et al., 1998; Törn et al., 2009; Pickering et al., 2011), different intensities of use (Young and Gilmore, 1976; Cole and Bayfield, 1993; Kutiel et al., 2000; Lemauviel and Rozé, 2003; Talbot et al., 2003; Hill and Pickering, 2009; Pickering and Growcock, 2009; Burns et al., 2013), different ecosystems including rating their tolerance to disturbance (Rickard et al., 1994; Pickering and Hill, 2007; Bernhardt-Römermann et al., 2011) and different temporal scales and recovery periods (Bayfield, 1979; Whinam et al., 2003; Scherrer and Pickering, 2006; Growcock and Pickering, 2011). Recent reviews have synthesised many of these results demonstrating how the type, intensity, location, timing and behaviour of people undertaking these activities affects the scale and severity of impacts (Cole, 2004; Monz et al., 2009; Pickering, 2010; Pescott and Stewart, 2014).

Recreation ecology research has been slower in recognising the impacts of the actual trail infrastructure, which although often formed partly as a function of use, can have additional impacts relating to the construction and presence of the trail itself (Marion et al., 2011). Trails can either be formally created and maintained by management agencies or informally created by users (Leung and Marion, 2000; Marion and Leung, 2001). Both types of trails, essentially, are linear corridors of disturbance which cause impacts through their construction and maintenance and change abiotic conditions on and adjacent to the trail affecting local biota. These trail impacts vary, however, depending on the type, design and location of the trails (Marion and Leung, 2004; Wimpey and Marion, 2010). The impacts of trails themselves potentially affect larger areas and have greater temporal effects than some of the more transient use-related impacts of trampling on and off trails (Marion et al., 2011; Ballantyne and Pickering, 2013). Despite the extent of trail networks including in areas of high conservation value, there is no recent review of the academic literature on this topic that parallels those for solely use-related impacts such as trampling off trails (e.g. Hill and Pickering, 2009; Pescott and Stewart, 2014).

We conducted a systematic quantitative literature review to assess the academic research literature on the environmental impacts of trails. The review focuses on impacts to vegetation and soils as they support the majority of terrestrial ecosystems. English language peer-reviewed academic journals were systematically searched to create a database of original research papers on this subject so we could determine: 1) where there is research on trail impacts, 2) what has been assessed including the methods used and variables measured, 3) what impacts have been found, and therefore, 4) where important research gaps remain. Based on the results of this review we then provide recommendations for researchers and decision makers on trail impacts and their management.

2. Materials and methods

To assess the extent and limits to academic literature on the impacts of trails on vegetation and soils, we conducted a systematic quantitative literature review following the methods outlined in Pickering and Byrne (2014) and Pickering et al. (2014) and following the protocol developed by the Preferred Reporting Items for Systematic Review Recommendations (PRISMA) (PRISMA, 2014) (Fig. 1). Original research papers published in English language academic journals were obtained by searching electronic databases including Google Scholar, Web of Science, SCOPUS and Science Direct. These searches were carried out progressively between May 2014 and 2015. The keywords used in these searches were: 'trail* or track + impact*' and a combination of 'plant*', 'plant communit*', 'vegetation', 'flora', 'touris*', 'recreation*', 'trampl*', 'bik*', 'walk*', 'hik*', 'climb*', 'horse rid*', 'ski*', '4x4', 'ORV', 'infrastructure', 'edge effect', 'network', 'soil', 'erosion', 'erode', 'pollut*', 'compact*', 'pH', 'fragment*'. Review papers and book chapters were excluded, however, reference lists in these, and the original research papers, were used to find additional academic papers. Papers addressing solely recreational use-related impacts such as trampling by hikers off trails (e.g. Cole and Bayfield, 1993) were excluded as the focus of the review was on trails and the impacts caused by the trail infrastructure itself or subsequent degradation of the infrastructure resulting from use. There are already concise reviews addressing the impacts of trampling off trails (Cole, 2004; Hill and Pickering, 2009; Pescott and Stewart, 2014).

For each paper, the following information was entered into a topic-specific database: 1) basic data on the paper itself, including year of publication, author(s), paper and journal titles, 2) the type(s) of trail assessed including if it was formal (created and

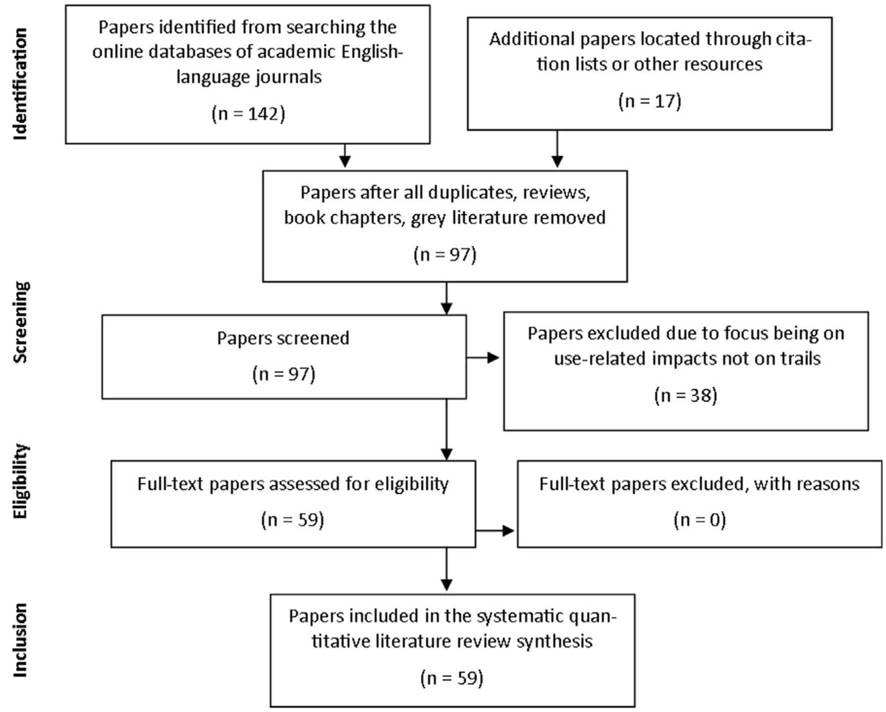

Fig. 1. Preferred Reporting Items for Systematic Review Recommendations (PRISMA) flowchart outlining the process followed and actions taken to compile the systematic quantitative literature review (PRISMA, 2014). N = number of original research papers.

maintained by protected area agencies or other types of land managers) or informal (created by users, outside of the formal trail system) (Marion and Leung, 2011), 3) geographical location of the study including country, whether the trails were in a protected area, whether within 50 km of an urban area (city centre to edge of region), habitat type (according to a modified version of the World Wildlife Fund's global ecoregion network available at http://www.worldwildlife.org/biomes) and whether the study was in a biodiversity hotspot (according to the Critical Ecosystem Partnership Fund which identifies 35 global biodiversity hotspots), 4) information on the methods used including whether the research was experimental (i.e. experimental use of an existing trail), observational (observing effects related to design, location, construction and maintenance of the trail) or predictive (predicting effects of planned trails), and whether data was quantitative or qualitative, if it was spatial (GIS-based) and/or photographic, 5) the spatial dimension of the research categorised into direct local impacts on the trail itself or indirect local impacts across a short gradient starting at the trail edge, and/or dispersed landscape effects occurring cumulatively across the landscape (e.g. using the conceptual model of Brooks and Lair, 2005) (Fig. 2), whether research was at a species or community level and if the site/ecosystem was of high conservation concern (subnational, national and/or international legislation), 6) the responses of the vegetation/soils against the main independent variables, the dimension of the impact (intensity, spatial, temporal), whether the response was compositional, structural and/or functional (according to the categories of Noss, 1990) and the specific variables measured along with the nature of their response (positive, negative, neutral or mixed). Composition, structure and function were used for both vegetation and soils. For example, changes in the structure of vegetation could be the loss of plant height or reduced tree density, while for soils it could be erosion and/or compaction.

The data was analysed using descriptive methods to reveal patterns in the literature, identify gaps and provide advice for researchers and managers. To compare research effort against visitation for those papers conducted in protected areas, we used data on images in Flickr provided by the Flickr API portal. Specifically, we tallied the total number of papers per protected area and compared it against a surrogate for visitation for each protected area. We used 'photo user days' as a surrogate (as in Wood et al., 2013), which is defined as the average annual total number of users per day who took at least one photograph within the protected area and uploaded them to https://www.flickr.com, from 2005 to 2012. Average annual 'photo user days' has been shown to be strongly related to surveyed visitation rates at recreational sites worldwide by Wood et al. (2013) and at lakes in the Midwestern USA by Keeler et al. (2015).

3. Results

3.1. Where is there research on trail impacts?

A total of 59 original research journal papers were identified that assessed the impacts of trails on vegetation and soils. The majority of these were published in environmental management, ecology and conservation journals (Table 1). Most are recent publications potentially reflecting an increasing recognition of the importance of trail impacts and the ubiquity of recreational trails. There are few researchers however, conducting several studies, with only two, Marion (USA) and Pickering (Australia) having published > 5 papers on this topic (Table 1).

Despite papers demonstrating trail impacts from 25 countries, much of the research is in the USA (19 papers, 32%) and Australia (12 papers, 20%) (Fig. 3). Overall, 36 (61%) papers looked at trails in more remote areas such as wilderness areas and remote national parks, while the remaining 23 papers looked at trails in, or near

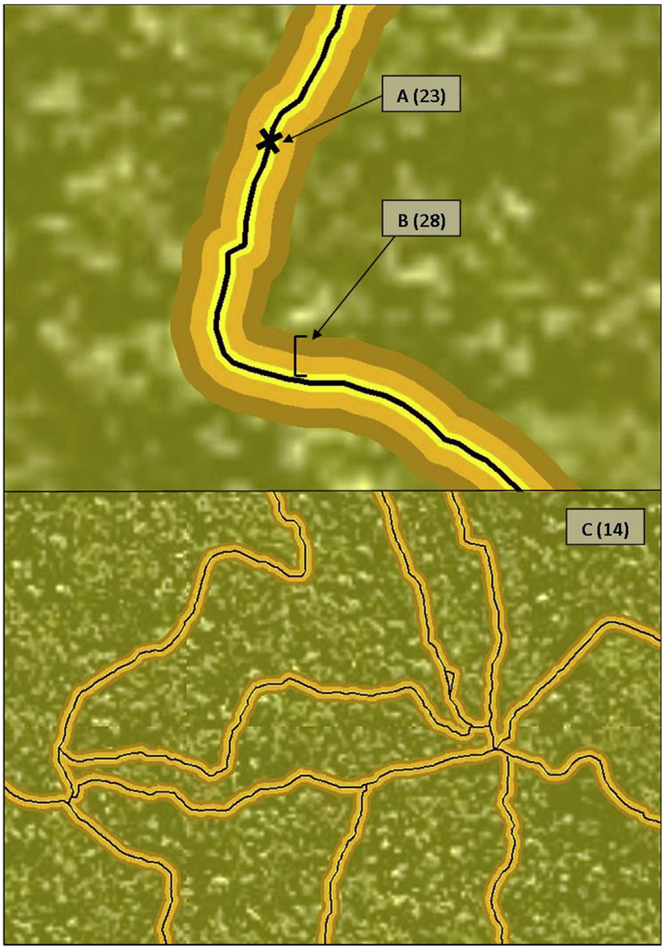

Fig. 2. The spatial scales of trail infrastructure impacts. 'A' shows direct local impacts; that is those impacts confined to/measured on the trail itself. 'B' is indirect local impacts that occur across a gradient away from the trail edge. 'C' shows dispersed landscape level impacts from larger-scale changes to community or ecosystem quality. The numbers in brackets indicate the number of original research papers at each of the three scales that examined the impacts of trail infrastructure on plants and soils. Figure modified from Brooks and Lair (2005).

cities (Table 2). Most papers assessed trail impacts in protected areas (71%), with several papers from just two Parks: Acadia National Park in the USA (4 papers) and Kosciuszko National Park in Australia (4 papers) (Table 3). Interestingly, there were no papers from some of the world's most popular protected areas with recreational trails (based on 'photo user days' data) such as the Golden Gate National Recreation Area, USA and Jiuduansha Nature Reserve, China (Table 3).

The geographical bias in research was also apparent when examining the types of habitats and biodiversity hotspots assessed. Most research is for trails in cool temperate broadleaf and mixed forests (15 papers, 22%), alpine and montane grasslands/shrublands (14 papers, 20%) and Mediterranean forests, woodlands and scrub (8 papers, 11%) (Table 2). There were very few papers on trails in dune and beach habitats, deserts, wetlands, tropical and subtropical grasslands/savannahs and tropical montane forest habitats, and none from tropical and subtropical coniferous forests, flooded grasslands, mangroves, lake systems, xeric basins, estuaries or rupicolous habitats (Table 3). There were 21 (36%) papers that looked at trail impacts in biodiversity hotspots, but these only included the Mediterranean Basin (5 papers), southwest Australia (3), Mesoamerica (2) and the Forests of East Australia (2) (Fig. 4), while the other 22 hotspots have no academic papers on trail impacts to date.

Table 1
Number of original research papers (1978–2014) examining the impacts of trail infrastructure on vegetation and soils.

Category	Total
All papers	59
Post 2005	40 (68%)
Journal type	
Environmental Management	17 (29%)
Ecology	13 (22%)
Conservation	8 (14%)
Planning & Development	6 (10%)
Geography & Geology	6 (10%)
Tourism & Recreation	5 (8%)
Botany	4 (7%)
Authors	
Marion	7
Pickering	6
Newsome	3
Leung	3
Wimpey	3
Manning	3
Type of trail	
Formal	40 (68%)
Informal	9 (15%)
Both	10 (17%)
Bare earth	43 (60%)
Not specified	11 (15%)
Gravel	6 (8%)
Tarmac	4 (6%)
Paved	4 (6%)
Sand	2 (3%)
Grass	1 (1%)
Raised metal walkway	1 (1%)
Sampling Methods	
Observational	53 (90%)
Experimental	4 (7%)
Predictive	2 (3%)
Data Type	
Quantitative	39 (66%)
Mixed	17 (29%)
GIS	14 (24%)
Photography	1 (2%)
Qualitative	0
Spatial dimension of research	
Indirect local effects	28 (47%)
Direct local effects	23 (39%)
Dispersed landscape effects	14 (24%)
Focus	
Community (incl. soils)	48 (81%)
Plant Species	3 (5%)
Not specified	8 (14%)
Threatened community/species	8 (14%)
Dimension of effect	
Spatial (change over space)	37 (63%)
Intensity (change amongst trail types)	21 (36%)
Temporal (change over time)	4 (7%)
Response	
Compositional	38 (57%)
Landscape	15 (23%)
Structural	12 (18%)
Functional	1 (2%)
Negative	57 (39%)
Positive	41 (27%)
Mixed	35 (24%)
Neutral	16 (10%)

3.2. Which trails have been assessed and what methods were used?

The most common types of trails assessed were formal (68%) and unsurfaced (60%), with very few papers assessing other trail types such as gravel, tarmac, pavers and raised walkways (Table 1), but 15% of papers did not specify the trail surface(s). Only nine

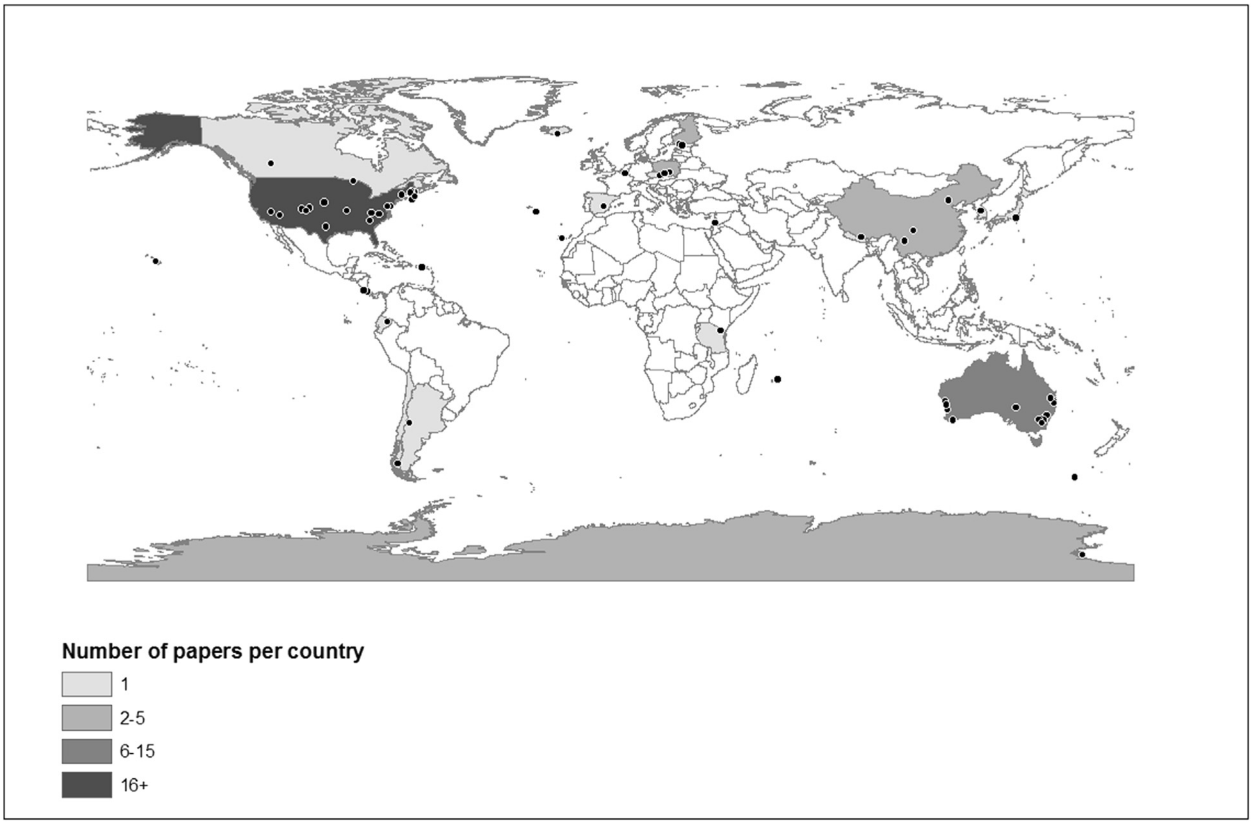

Fig. 3. Location of countries and the number of original research papers published in English language peer-reviewed journals that assessed the impacts of trail infrastructure on vegetation and soils from those countries. Country and continent shapefiles obtained from Natural Earth (http://www.naturalearthdata.com/downloads/10m-cultural-vectors/10m-admin-0-countries/).

Table 2
Number of original research papers by habitats examining the impacts of trail infrastructure on vegetation and soils. Habitat types according to a modified version of the world wildlife fund's global ecoregion network available at http://www.worldwildlife.org/biomes.

Research	Number of papers
Peri-urban areas (<50 km distance from urban centres)	23 (39%)
Habitat type	
Temperate broadleaf and mixed forests	15 (22%)
Alpine and montane grasslands and shrublands	14 (20%)
Mediterranean forests, woodlands and sclerophyll scrub	8 (11%)
Tropical and subtropical moist broadleaf forests	4 (6%)
Tropical and subtropical dry broadleaf forests	4 (6%)
Temperate grasslands, savannahs and shrublands	4 (6%)
Tundra	4 (6%)
Temperate coniferous forests	3 (4%)
Boreal forests and taiga	3 (4%)
Rocky islands	3 (4%)
Dune and beach systems	2 (3%)
Deserts and xeric shrublands	2 (3%)
Riparian wetland	2 (3%)
Tropical and subtropical grasslands, savannahs and shrublands	1 (1%)
Tropical montane forest	1 (1%)
Tropical and subtropical coniferous forests	
Flooded grasslands and savannahs	
Mangroves	
Lake wetland	
Xeric basins	
Estuaries	
Rupicolous (gorges, cliffs, ravines etc.)	

papers specifically assessed the impacts of informal trails. While 10 papers made reference to formal and informal trail systems, only seven directly compared impacts between formal and informal trails (Table 4).

Most research used observational methods (90%) to collect quantitative data (66%), such as point sampling and transect surveys (Table 1). Some collected both quantitative and qualitative data (29%) using methods such as trail condition class assessments. There were 24% of papers that used geographical information systems (GIS) (Table 1). Trail condition class assessments and GIS studies tended to be more descriptive, site-specific inventories of conditions on the trails themselves and rarely assessed impacts along the trail edges.

Several papers assessed local-scale effects of trails by comparing impacts at increasing distances from a trail and against undisturbed conditions (47%; Table 1). Twenty-three papers (39%) looked at the intensity of impacts occurring directly on a pre-existing trail, and 24% looked at landscape-scale effects such as fragmentation and cumulative degradation from trails.

Eighty-one percent of papers assessed the effects of trails on plant or soil communities/assemblages, while only 5% looked at species-level effects, mostly on orchids. Eight (14%) papers assessed trails in threatened ecosystems, and only one looked at threatened plants (30 species, in Laojun Mountain National Park, China (Yang et al., 2014)). The most commonly measured dependent variables were compositional: species cover (28 papers), species abundance (12) and species richness (12) (Table 2). In contrast, only 12 papers (18%) looked at structural responses such as soil compaction (12), erosion (9), trail depth (6) and plant height (5), with just one paper

Table 3
Protected areas with more than one original research paper that examined the impacts of trail infrastructure on vegetation and soils in comparison to the most popular protected areas based on Flickr photo user days (PUD) which is defined as the average annual total number of users per day who took at least one photograph within the protected area and uploaded them to https://www.flickr.com, from 2005 to 2012 (Wood et al., 2013). Biosphere reserves were excluded from the list of PUDs as they often encompass multiple smaller protected areas and have less distinctive managing authorities.

Protected areas in which research conducted	Number of papers	Most visited protected areas *Flickr data	Number of PUD
Total in protected areas	42 (71%)		
Acadia National Park, USA	4	Golden Gate National Recreation Area, USA	16,013
Kosciuszko National Park, Australia	4	Jiuduansha Nature Reserve, China	6686
Boston Harbour Islands National Recreation Area, USA	2	Lake District National Park, UK	4707
Rocky Mountain National Park, USA	2	Peak District National Park, UK	3208
Gorce National Park, Poland	2	Yosemite National Park, USA	2944
Great Falls National Park, USA	2	Grand Canyon National Park, USA	2336

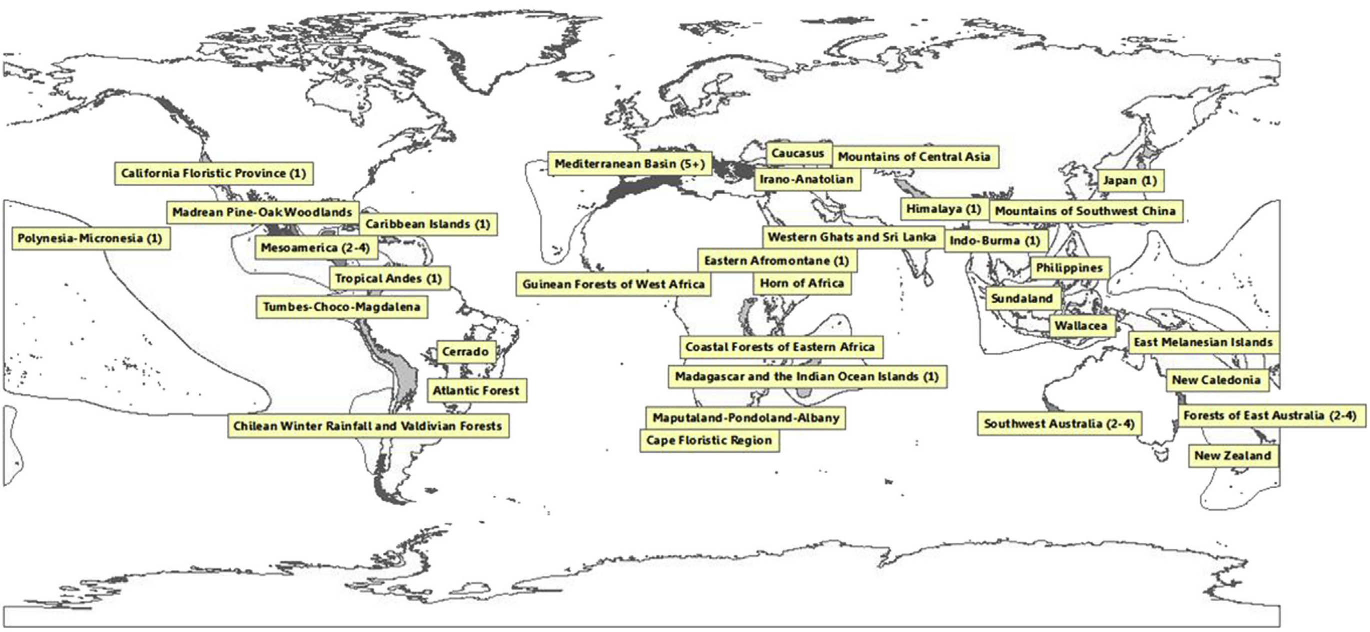

Fig. 4. Location of biodiversity hotspots and the number of original research papers published in English language journals that assessed the impacts of trail infrastructure on vegetation and soils in those hotspots. Numbers in brackets represent the number of papers per hotspot. Hotspots without numbers represent 0 papers. Biodiversity hotspots map according to the Critical Ecosystem Partnership Fund and shapefiles obtained from http://www.cepf.net/resources/hotspots/Pages/default.aspx.

assessing functional responses (succession; McDougall and Wright, 2004) (Table 4).

3.3. What are the impacts of trails?

Trails have a range of impacts on vegetation and soils, but the type and severity of impacts often varied among papers/trails. Impacts of trails on vegetation and soils were most often quantified in terms of changes in composition (57%) and to some degree, structure (18%) (Table 1). Compositional and structural effects were mostly negative (39% of papers). This included where increasing distance from a trail meant there was a decrease in weed cover and increasing trail degradation led to a decline in species richness and soil microbial activity. Twenty-seven percent of papers showed positive relationships. This included where increasing trail density lead to increases in weed and ruderal species richness and where increasing trail degradation lead to increases in erosion and surface-runoff. Twenty-four percent of papers showed mixed responses such as differential increases/decreases in species abundance depending on the species tolerance of disturbance (Table 1).

Most responses involved changes over space (63%), e.g. distance from the trail (indirect local effects; Fig. 2) (Table 4). All of them found some differences in vegetation and soils close to trails compared to undisturbed/less disturbed sites. Often there was a spatial gradient in the severity of impacts away from trails, with some differences in vegetation and soils only apparent within 1 m of the edge of the trail (e.g. compaction), while other trails impacts were still apparent 20 m from the trail (e.g. decreased microbial biomass). Spatial impacts on plant composition often involved changes in species richness and abundance close to the trail. This included the increased dominance of more stress-tolerant, ruderal or weed plants near trail edges while less competitive, slower-growing plants were often more common away from trails. For instance, vegetation adjacent to bare formal trails in a Mediterranean woodland consisted largely of herbaceous weeds and natives with cryptophytic or hemicryptophytic growth forms, while 10 m from trails vegetation consisted of more woody, sclerophyllous chaemaphytes (Gómez-Limón and De Lucio, 1995; Lucas-Borja et al., 2011). Spatial impacts on vegetation structure close to trails included decreases in plant height, tree size and canopy cover. For example, in temperate woodland in Canada, saplings were more abundant near formal bare trail edges while trees with larger basal areas were more common further from trails (Parikesit et al., 1995).

There were also spatial effects on soil composition and structure close to trails with soils near trails often drier with less nutrients and higher pH. Changes in soil structure included more

Table 4
Impacts of trails based on changes in variables measured in the 59 original research papers on vegetation and soils. Totals may exceed 59 as papers could assess more than one independent and/or dependent variable.# = number of papers, + = positive response, − = negative response, 0 = neutral response, ∞ = mixed response.

	Independent variables																									
	Total #	Distance from trail edge (n = 37)					Intensity of use of pre-existing trail (n = 21)					Comparison between trail types (n = 7)					Time since creation (n = 2)					Time since closure (n = 2)				
Dependent variables		#	+	−	0	∞	#	+	−	0	∞	#	+	−	0	∞	#	+	−	0	∞	#	+	−	0	∞
Vegetation cover	28	20	8	4		8	6		6													2	2			
Trail width	16	1		1			13	10		2	1						2	2								
Plant species abundance	12	6		4		2	3		2		1	2				2						1				1
Plant species richness	12	7		3	1	3	3		3			1				1						1				1
Compaction	12	4	1	3			6	3	3			1				1						1		1		
Erosion	9	3		3			6	4	1		1															
Soil nutrients	8	1		1			4	1	3			1				1						1		1	1	
Trail depth	6						5	4		1							1			1						
Species density	6	4		2	1	1	2		1		1															
Plant height	5	1				1	3		2	1							1		1							
Litter depth	5	4		3	1		1			1																
Fragmentation	5											5				5										
Tree trunk diameter	4	2			1	1	2			2																
Root exposure	4	2		2			1	1				1				1										
Soil moisture	3	1		1			2		1	1																
Soil microbial abundance	2						2		1		1															
Succession	2																2		2							
Loss of plant parts	2	2		2																						
Muddiness	1						1	1																		
Surface run-off	1						1	1																		
Canopy cover	1	1	1																							
Photosynthetic rate	1	1	1																							
Species tolerance	1	1				1																				
Evenness	1						1	1																		
TOTAL	147	61	11	29	4	17	62	26	23	8	5	11				11	6	2	3	1		6	2	2	1	2

compacted, eroded soils close to trails, often with thinner litter layers (Table 4). For example, soils along trails in boreal forests in Scandinavia showed decreased biological and physico-chemical activity with significant increases in activity 5–20 m from the trails (Malmivaara-Lämsä et al., 2008). Close to bare trails in dune environments however, soils showed decreased porosity and higher compaction which resulted in higher moisture retention and positive effects on native trail-side flora compared to loose, drier substrate further from trails (Lemauviel and Rozé, 2003).

Around 36% of papers documented changes on the trail itself (direct local effects; Fig. 2) often in relation to the intensity of use of the trail. They often found that popular trails without hardened surfaces tended to be subject to greater soil compaction, erosion and exposure of roots than hardened trails. Compositional changes included reductions in species richness and abundance of species overall and for soils, lower pH and poor microbial activity along trails with more intensive use/degradation. Structurally, these trails were defined by low vegetation cover and absence of canopy species, were wider, had high soil erosion, low soil porosity and high compaction (Table 4).

There were seven papers comparing different types of trails (Farrell and Marion, 2002; Manning et al., 2005; Hill and Pickering, 2006; Monz et al., 2010; Kim and Daigle, 2011, 2012; Ballantyne et al., 2014a). They found mixed results with hardened formal trails often associated with the largest impacts on edge vegetation, but unhardened informal trails showing the most on-trail degradation especially for soils. Vegetation on the edge of hardened trails such as tarmac and gravel trails often had greater weed richness, changes to soil pH and decreased abundance of disturbance-sensitive plants. Unhardened trails often experienced soil erosion and surface run-off, but generally had more 'natural' vegetation along their edges and fewer cumulative impacts.

Only four papers looked at temporal changes, e.g. time since closure of trails (Table 4). One paper assessing a closed trail traversing alpine grassland found that even 15 years post closure, vegetation on the trail differed from natural vegetation with less vegetation, no shrubs, more weeds and few herbs on the trail surface (Scherrer and Pickering, 2006). The other paper looking at track closures was in a heathland community and found that shrubs were amongst the slowest to return following the closure of a trail, but that mosses and lichens also recovered poorly, even after 8 years (Bayfield, 1979).

4. Discussion

This systematic quantitative literature review evaluated the current literature in English language journals on the impacts of trails on vegetation and soils. In doing so, it has provided insights into where, how and what research has been published and where there appear to be gaps in the research literature.

By focussing on peer reviewed academic journals we were able to use a consistent sampling method to identify a literature that has contains similar levels of detail about the study and standards of research. It follows on from the approach used in other systematic quantitative literature reviews (Guitart et al., 2012; Pickering et al., 2014) including in recreation ecology (e.g. Steven et al., 2011; Ansong and Pickering, 2013). We do this while recognising that original research on trail impacts occurs in other sources including peer reviewed academic journals published in languages other than English and in a range of 'grey' literature such as protected area management plans and reports. Reviewing non-English language peer reviewed journals, however, was beyond the expertise of the authors. As more than 90% of sciences papers are in English (Hamel, 2007) including papers in other languages may not dramatically alter the general patterns found in the current review apart from than those relating to the geographical spread of studies (see below).

We did not include grey literature such as protected area management plans and reports as much of this literature tends to be very specific to certain regions or problems and is often not publically available and hence included in online searchable databases. Also there can be less consistency in the details provided within grey literature about how research was conducted and data analysed and the work often have not been subject to peer review. Future reviews encompass such 'grey' literature are likely to provide important insights particularly for certain regions, although consistent access to grey literature globally remains a challenge.

4.1. Research on trail impacts is geographically limited

Geographically, trail impact research publish in English language journals is concentrated in a few countries, habitats and biodiversity hotspots. Probably due to the small number of authors focussing on this topic in English language journals, most papers in the review were from IUCN category II national parks in the USA and Australia, where there is an increasing network of trails and a dedicated authorship (Queensland Government, 2007; Pickering et al., 2010; Marion et al., 2011). For other wealthy nations, including in Europe, there is limited research in such journals despite often extensive and popular networks of recreational trails. In some cases this may not only reflect where the literature is published, but also where, and whether impacts occur. For instance, as a result of legislation such as the right to roam in United Kingdom and Friluftsliv in Scandinavia mean that impacts may be more diffuse as hiking and other trail-based activities occur in a wide range of land tenures in addition to protected areas (Fredman et al., 2013).

There are a few papers in English language journals from some countries experiencing a rapid growth in trail-based recreation (Li et al., 2005; Leung, 2012; Zhang et al., 2012; Yang et al., 2014). In China, for example, nature-based tourism is increasingly promoted in many of its protected areas (Zhong et al., 2015). In some of these protected areas, over >100,000 visitors take part in trail-based activities every day (Zhong et al., 2015). Where there were some papers on trails from China in English language journals, they were often focused on visitor satisfaction rather than environmental impacts (e.g. Li et al., 2005; Chen et al., 2009). Reviews of the literature encompassing publications in other languages, as well as generally more research from regions with increasingly extensive trail networks such as Asia (Leung, 2012), will provide important insights into trail impacts.

There were few papers on threatened ecosystems and even fewer assessing the responses of individual species of plants to trails. This is an important area of study as trails are often created in threatened ecosystems that offer desirable destinations for visitors, for example mountain tops, cliffs and waterfalls; places where rare species/communities are often found (Wimpey and Marion, 2011; Marion and Leung, 2011; Ballantyne and Pickering, 2012, 2013). Moreover, people may actually seek threatened species or ecosystems as part of their experience (Turpie and Joubert, 2004·Ballantyne and Pickering, 2012). Not only do trails bring disturbance to these communities through their construction and maintenance, but they also act as conduits facilitating illegal use such as plant collection (Power Bratton, 1985; Baret and Strasberg, 2005; Ballantyne and Pickering, 2013), vandalism (Matlack, 1993) and the spread of weeds, pathogens and feral animals (Pickering and Mount, 2010; Leung et al., 2012). With the number of threatened plant communities and species increasing due to other factors, trails in areas of high conservation value can exacerbate existing threats (Ballantyne et al., 2014a). Just as the opening of new roads contributes directly to increases in poaching and plant collection (Wilkie et al., 2000; Suárez et al., 2009), trails are also likely to facilitate these types of activities, especially in biodiversity hotspots and developing nations (Baret and Strasberg, 2005).

There were several papers from urban and peri-urban natural areas (39%) reflecting both the rapid development of cities and increasing numbers of trail networks in remnant natural vegetation close to cities (Matlack, 1993; Stenhouse, 2004; Ballantyne et al., 2014a). With urban areas occupying at least 3% of the earth's terrestrial surface, remnant natural vegetation close to cities is increasingly important for both conservation and recreation (Swanwick et al., 2003; Florgård and Forsberg, 2006; Tratalos et al., 2007). Trails should be designed and constructed more strategically to balance conservation and recreation in these remnants. With such close proximity to dense human populations, urban natural areas may be particularly prone to the creation of dense informal trail networks (Ballantyne et al., 2014a). Managing this is especially important in order to limit further landscape-scale degradation on what are already 'at risk' ecosystems (Leung et al., 2011; Ballantyne et al., 2014a).

Given the growth of nature-based tourism in many countries, the total length and spread of recreational trail systems are likely to increase across many of the world's natural areas. Although research has been conducted in some regions in the USA, Australia and elsewhere, the severity and types of impacts can be ecosystem-specific, as has been found for use-related trail impacts such as trampling (Pickering and Hill, 2007; Bernhardt-Römermann et al., 2011). This means that the current 50% of the research in this review that focuses on just three biomes and four biodiversity hotspots is rather under-representative. There are highly likely to be trail impacts in other biomes and hotspots such as dune, desert, wetland and riparian systems and the Brazilian Atlantic Forest, Carribbean, Mountains of south-west China and Wallacea regions, as these areas are popular nature-based tourism destinations (Turpie and Joubert, 2004; Buta et al., 2014; Yang et al., 2014; Zhong et al., 2015). Hence research assessing trail impacts from these regions is important.

4.2. Most research has been on the impacts of formal trails

Unlike research on use-related impacts where there are increasing numbers of comparative studies (Talbot et al., 2003; Hill and Pickering, 2009; Pickering and Growcock, 2009; Törn et al., 2009; Pickering et al., 2011; Burns et al., 2013), authors such as Godefroid and Koedam (2004), Hill and Pickering (2006) and Müllerová et al. (2011) are among the few to specifically compare impacts among different types of trails, including between formal and informal trails. The scale and intensity of impacts can vary among trail types. For example, the extent to which vegetation along the edge of trails differs from more natural conditions varies among trails made of compacted soil, gravel, pavers and raised metal walkways (Hill and Pickering, 2006). Often wider trails with large canopy gaps, and hardened surfaces composed of foreign materials have impacts apparent up to 20 m from the trail edge (Delgado et al., 2007; Hamberg et al., 2008; Ballantyne and Pickering, 2015a). Differences in impacts among trail types are likely to be due to factors associated with their construction and maintenance including the types of materials brought into the site (Müllerová et al., 2011) and their use. More comparative research is needed among these and other new trail types, such as Geoweb® and 'soft' tarmac trails. What is clear is the importance of minimising disturbance during the construction and maintenance of formal trails and actively rehabilitating vegetation along the edge of trails once built (Wolf et al., 2013).

4.3. Most research is at a local scale

While ecology in general is increasingly focussing on landscape-scale research, recreation ecology has stagnated to some extent with a dominance of ad-hoc papers providing snapshots of trail conditions at relatively limited spatial scales. Despite increasing recognition that the impacts of trail infrastructure occurs at a range of spatial scales (Brooks and Lair, 2005), most research has focused on the local scale assessing impacts on the trail surface and close to the edge of the trail (Fig. 2). Most of these papers either used inventories of trail condition assessing physical damage such as soil erosion, compaction, muddiness, tree-scarring and braiding (Olive and Marion, 2009; Wimpey and Marion, 2010), and/or point sampling analyses to detect changes in vegetation over gradients away from the trail (McDougall and Wright, 2004; Potito and Beatty, 2005; Hamberg et al., 2008). Although this research is important for developing and supporting management including improving the design and location of trails (e.g. Marion and Leung, 2004; South Australian Government, 2011; American Trails, 2015), more research is required assessing larger-scale impacts (Leung et al., 2011; Ballantyne et al., 2014a) including using GIS methods and analyses (e.g. Wimpey and Marion, 2011; Ballantyne et al., 2014a).

Landscape-scale impacts of trails largely arise as a result of the creation of trail networks. These can have large spatial impacts including habitat fragmentation, habitat loss, the disruption of important community processes, introduction of invasive species and large-scale compositional change; all ultimately leading to reduced native biodiversity across the landscape (Leung et al., 2011, 2012; Ballantyne et al., 2014a). While there is an increasing interest in, and research on, the effects of fragmentation from road networks (Goosem, 2007; Laurance et al., 2009), there appears to be a dearth of similar research for recreational trail networks. This is despite trails often (1) forming denser networks, and therefore potentially resulting in greater cumulative impacts, and (2) occurring in areas of high conservation value where roads may not be allowed. Mostly, it is informal, user-created trails that form the largest and most complex trail networks and therefore are likely to have the greatest cumulative impacts (Leung et al., 2011; Marion and Leung, 2011; Ballantyne et al., 2014a). Future work should address the sociological and ecological drivers behind the creation of informal trails and the ecological impacts of trail-based fragmentation.

4.4. A need for more temporal research on trails

There is limited research assessing changes in trail impacts over time (Baret and Strasberg, 2005; Scherrer and Pickering, 2006; Ballantyne et al., 2014b). This is in contrast to research on use-related recreational impacts which has often assessed temporal changes allowing researchers to identify trends in the resistance, resilience and hence tolerance of different types of vegetation and soils (Sun and Liddle, 1993; Pickering and Hill, 2007; Bernhardt-Römermann et al., 2011). Results from some of the temporal studies assessing trail infrastructure found that vegetation is often very slow to recover from this type of damage, particularly in alpine regions (Scherrer and Pickering, 2006; Ballantyne et al., 2014b). Temporal studies will help determine how, and potentially why, vegetation communities change following the creation or closure of trails, how trail impacts can act in synergy with other anthropogenic stressors such as changing climate, how maintenance regimes (e.g. mowing, herbicide-use, grading) affect vegetation and soils and help in the development of predictive models of trail impacts over time. Such research can demonstrate the long-term effects of trail infrastructure and therefore assist with long-term active adaptive management.

4.5. Need for more research on ecosystem structure and functioning

With ecosystems composed of compositional, structural and functional biodiversity (Noss, 1990), it is important to assess trail impacts on all three components. To date, most trail infrastructure research has focused on compositional changes in vegetation and soils noting strong trends towards disturbance-tolerant and secondary successional edge communities with lower soil microbial activity and poorly-structured soils. These edge effects can be a result of use, but also additive changes in abiotic conditions such as increasing light and space caused by clearing and construction along trails. These changes in turn alter structure and benefit plants such as ruderals and cloning species (Gómez-Limón and De Lucio, 1995; Buckley et al., 2003; Pescott and Stewart, 2014). For many trails, edge effects are often relatively narrow gradients running parallel to the trail, but in some cases, they can extend up to 20 m from the trail (Malmivaara-Lämsä et al., 2008) where conditions along trails are very different to those of undisturbed sites, as found for roads or intensively-used trails in closed forest environments (Delgado et al., 2007; Prasad, 2009).

There was much less research directly assessing the impacts of trail infrastructure on vegetation structure. We also found only one paper assessing changes in ecosystem functioning due to trails (McDougall and Wright, 2004). Structural and functional impacts are as important to ecosystem health as compositional ones, and as all three are inextricably linked, it is necessary to assess how trail infrastructure affects all three factors. Structural impacts of trails recorded to date include increased density/number of saplings near trails (Parikesit et al., 1995), increased dominance of woody shrubs near trails (Nemec et al., 2011) and decreased canopy cover near trails (Delgado et al., 2007; Ballantyne and Pickering, 2015a). Functional impacts include changes in plant succession caused by trails acting as barriers to the spread of nurse plants (McDougall and Wright, 2004). Additional structural studies could look at the effects of trails on the density of trees, loss of key resources such as hollow-bearing and mature trees, and changes in litter layers. Functional studies could assess how trails affect fire regimes, competition, facilitation, dispersal, pollination and plant-soil feedback loops (Ballantyne and Pickering, 2015b).

5. Management recommendations

The results of this systematic quantitative literature review provide important insights for those responsible for managing natural areas. Based on the results, some key recommendations for the creation and management of trail systems include:

1) Avoid creating trails in particularly sensitive ecosystems/sites and in ecosystems of high conservation value. This includes avoiding soft humus-rich or Aeolian soils, ecosystems containing many disturbance-susceptible species (e.g. interior forest birds and slow-growing, non-clonal plants), sites slow to recover from disturbance (e.g. alpine) and sites close to known threatened species and communities.
2) Avoid building trails perpendicular to contours, i.e. up and down slopes, especially in sites with high precipitation, high use and/or with loose or deep, friable soils. Instead try to ensure that trails have steady descents and ascents that run parallel to contours such as side trails.
3) Design trail networks so they minimise cumulative spatial impacts including from fragmentation. This includes reducing trail widths to a narrow, but practicable tread, limiting trail networks to the minimum acceptable number of trail segments and actively managing the creation of informal trails.

4) Avoid direct local impacts from use on the trail surface when there is a risk of erosion by hardening the surface and use, where possible, use local materials as the substrate.
5) If sites are relatively level, soils are not easily eroded and use is moderate, consider leaving trails unsurfaced and maintain trail width and braiding by using berms, rocks and pass points and maintain drainage using boulders.
6) If hardening is necessary and local materials not available or appropriate, consider raising the infrastructure. Raised metal walkways, for example, constructed of cut-corrugated galvanised steel mesh are weather-resistant, long-lasting and have a perforated surface allowing light and water to penetrate to the vegetation below. Raised infrastructures often have fewer impacts than ground-level trails, but are generally more costly.
7) If hard-surfacing such as tarmac or gravel is required, then actively rehabilitate vegetation on the edge of the trails post-construction. This will reduce secondary succession along trail verges by invasive or ruderal species, quickly build up a complex vegetation structure and allow the recovery of soil structure and composition.
8) Obtain visitor data including using qualitative and quantitative sociological research and use this information when designing trails so they match visitor demand and motivation with visitor experience and therefore reduce the potential for the creation of informal trails by users.
9) Provide information about appropriate trail use to visitors. This could be as simple as providing signage or stakeholder workshops, or using more technical methods such as free, publicly-available apps to allow people to access maps and learn about the environment they are using.
10) Relocate activities that promote informal or off-trail use to areas of lower conservation value such as plantation forest and/or heavily altered ecosystems such as farmland or city parks.
11) Increased applied research on how human use can damage natural areas in general.

6. Conclusions

There are increasing numbers of recreational trails across the globe. In contrast to the more extensive literature on use-related trail impacts, we found that research on the effects of recreational trail infrastructure itself is still limited. Current research is disproportionately focused on trails in protected areas in developed nations and in temperature woodland, alpine and Mediterranean habitats. Most trails assessed are formal trails with little comparative work and with a spatial scale that rarely extends beyond the trail surfaces and immediate edges. Responses measured are mostly compositional with limited work on ecosystem structure and only one study looking at ecosystem functioning. There is great scope for more research on how trails change ecosystems including understanding their landscape-scale effects, structural and functional impacts, temporal changes and impacts they pose to threatened communities/species particularly in urban areas, unprotected natural areas and developing nations where nature-based tourism is increasingly popular.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2015.08.032.

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