Impacts of mountain biking on biodiversity and the environment

A review and management recommendations

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Executive summary

Mountain biking is a popular and fast-growing activity worldwide, but compared to other recreational activities, there is a relative dearth of understanding and scientific studies on its ecological impacts. Yet mountain biking impacts likely differ from those of hikers or vehicles, both in terms of the type of impacts caused, their severity, and the way these impacts permeate the landscape over moderate distances. This knowledge gap is of particular concern for nature protected areas, that must juggle the development of nature-based recreation with the protection of natural resources.

The aim of this report is to review the existing evidence of the biophysical impacts of mountain biking on vegetation, soil and wildlife, to inform the management of Ramat Hanadiv nature reserve. The review identified 29 research studies, mostly in the USA, New Zealand and Australia, that investigate ecological impacts related to mountain biking. Two thirds of these studies considered impacts on pre-existing designated trails, but less than half focused exclusively on mountain-biking. While there is good evidence that mountain biking contributes vegetation trampling, soil compaction and potentially soil erosion on the tread, these impacts are highest at trail creation or when riding off-trail, but level off rapidly afterwards. They depend more on slope and soil condition than on the intensity of trail use, and remain localised in the immediate surrounding of the trail. The impacts of mountain biking on wildlife are much less systematically documented, and the evidence mainly reports various forms of behavioural disturbances, such as increased alert rates, avoidance behaviours, modification of predation or reproduction. The longer-term and landscape scale effects of mountain biking remain under-explored. They include the potential for dispersing seeds, fragmenting or deleting wildlife habitat, long-term modifications in wildlife behaviour with potential consequences on their populations.

Overall, mountain biking thus appears to cause minimal and very local environmental impacts under normal use. Studies comparing the impacts of mountain biking with those of other recreational activities concluded that while visibly different, the impacts of bikes on trails were not any worse than those of walkers overall. However, most mountain biking studies appear to test relatively gentle riding conditions, that may not reflect riders quest for thrill. Higher impacts are linked to riders behaviour, such as tendency to go off trail or to experience ride with intense breaking and skidding. Furthermore, no study adequately considers the overall impacts of mountain biking, taking into account that it has a much wider extent than walking or hiking.

Based on these findings, the following approach is suggested to be developed in Ramat Hanadiv:

1. **Ensure that mountain bikers stay on trail**. Environmental degradation can be substantially reduced when bikers stay on formal trails. To minimise the environmental impacts of formal trails, ensure that they are located on side-hills to minimize erosion, and away from sensitive or critical wildlife habitats. To motivate bikers to stay on formal designated trails, ensure good sign-posting, good maintenance of the trail, provide education for mountain bikers, and perhaps most importantly, design the trails so as to provide them with the experiences they are seeking.
2. **Monitor target habitats and species.** In order to ensure no declines in habitats or species of concern, and to help fill knowledge gaps, monitor a small set of species likely to be impacted by mountain biking, e.g. ground beetles, amphibians, reptiles or small birds.

3. **Early detection of invasive or ruderal plant species dispersal.** As a precautionary measure, monitor the trailside vegetation yearly to detect the arrival of new plant species, in particular invasive alien species or ruderal species, that might have been spread by trail users.

Background

Nature-based outdoor recreational activities are increasing in popularity worldwide. This has led to greater demands for quality outdoor experiences on trail networks that are often in fragile environments. Among these activities, mountain biking has been one of the fastest growing trail-based activity over the last two decades, with a growing demand for dedicated trails. In the traditional form of mountain biking, i.e. cross-country, riders use lightweight bicycles to traverse a range of landscapes on rides typically lasting a few hours. The emphasis is on relaxation, exercise and appreciation of natural scenery (Burgin & Hardiman, 2012). Single track trails are particularly popular amongst mountain bike riders, since the narrow trails, approximately the width of the bike, allow riders to be segregated from cars and to enjoy a closer connection to nature (Bar (Kutiel) 2017). As more physically challenging, extreme forms of mountain biking are growing in popularity, single tracks are becoming increasingly designed to challenge riders. They typically feature a variable number of technical sections, with rocks, jumps, hills, drops and so forth, which provide a diversity of experiences for the riders (Hagen & Boyes, 2016).

As with all recreational pursuits, it is clear that mountain biking contributes some degree of environmental degradation. The rapid increase in popularity of mountain biking, together with its evolution into different forms, has caused concern for land managers about damage to natural resources, conflicts with other user groups and safety issues. In the absence of sound scientific information on these impacts (Newsome & Davies, 2009), managers have frequently been cautious and used a precautionary approach, implementing restrictive regulations (Marion & Wimpey, 2007). But when the trail networks are not developed rapidly enough to meet the demand, become overcrowded, or when the trails are not sufficiently challenging (Koemle & Morawetz, 2016), riders often ride off designated formal trails, in areas where biking is not allowed, potentially creating greater, more diffuse impacts on the natural environment. Providing for recreational demands, while understanding the extent and impact of recreation is thus important. In recent years, a number of studies have been conducted that help clarify the environmental impacts associated with recreational uses of natural surface trails, including those designed for mountain biking (Pickering et al. 2010; Ballantyne & Pickering, 2015).

The aim of this report is to inform an activity assessment of single trail mountain biking in Ramat Hanadiv nature reserve. Ramat Hanadiv is a privately-owned nature protected area operating for the benefit of the general public. The nature reserve covers approximately 450 ha of land on a plateau at the southern tip of the Carmel mountain range. The vegetation in the protected area is mostly Mediterranean scrubland and shrublands, combined with planted pine and cypress groves. The reserve harbours fourty-two plants species which are considered rare for Israel, 35 of them being endemic and six on the IUCN red list. It also supports six species of carnivorous mammals and breeding pairs of five species of both nocturnal and diurnal birds of prey. Until the 1990s, the area allocated to pedestrian trails in the nature reserve remained relatively small (0.16 km2, or 1.6% of the nature reserve's area in 1990 (Bar, 2017), resulting in low trampling intensities. However, under the pressure from bikers, since the summer 2016, a network of single bike trails has been opened, and signposted since October 2016 (Figure 1).

Figure 1 – Map of the bike trail network in Ramat Hanadiv nature reserve (June 2017). Family trails (blue) cover 6.7km, Experienced biking trails (orange) cover 10.6 km, with some overlap among them.

Specificities of mountain biking physical impacts

Mountain bikes cause different types of impacts than other outdoor recreational activities, such as walking, hiking and horse riding. The key distinction between the physical impacts of mountain biking and other non-motorised trail activities (such as walking, hiking, horse riding) lies in the unique effect of wheels on surfaces, relative to those from trampling by feet. The feet of a hiker damage trails and vegetation in two distinct phases: first the heel applies compaction, then the toe applies shearing forces as it rotates through the step. Wheels also apply both compaction and shearing forces, but in different ways (Cessford et al., 1995): unlike feet, which apply an interrupted series of local compactions, wheels apply a constant downward compaction force due to the dynamic load on the wheel. The compaction pressure applied to the trail surface through the tire (about 35-50psi) is much less than that of a human foot (in excess of 1,000 psi) (Cole, 1987). Wheels also apply shearing force from the wheel torque acting around the wheel's axis, mostly exerted during acceleration or braking. These lateral forces have more significance for trail degradation because they break particles apart, lowering shear strength. When lateral forces become stronger, spinning out during acceleration and skidding during braking occur. This results in loosening of the trail surface, and movement of soil material downslope. Together, this means that bicycles are prone to creating a long continuous track of wear, compared to hikers and horses who leave behind distinct pockets (hoofs, foot) in the soil. The linear tracks may lead to water channelling, by creating gullies through which the water can readily flow.

In contrast to cars and hikers, mountain bikers also have very different movement patterns. Hikers have a high degree of area permeation, do not necessarily depend on specific infrastructure, travel at low speed and over relatively short distances. In contrast, cars have large range, travel with high speed and are bound to certain infrastructure. Mountain biking combines a relatively large range and high degree of area permeation. In other words, the distance travelled on an average outing by bikers is much greater than that travelled by hikers. This means that even if impacts or hiking and mountain biking were comparable per incident, mountain bikes have the potential to impact much larger areas.

There may also be behavioural differences between mountain bikers and other tourist groups. Bikers may be more or less likely to go off trail, to litter or to take interest in nature.

Behavioural preferences of mountain bikers

Mountain bikers' behaviour may contribute to trail degradation in two main ways, through their tendency to go off trail, which is shared with other recreational activities, and through their riding preferences in a quest to enhance experience.

In areas with established trail systems, a common problem reported by managers is the tendency of users to go off-trail, creating impromptu paths (Ballantyne & Pickering, 2015a). Off-trail use can result in parallel tracks or trail widening where the main trail is more difficult to traverse than adjacent surfaces. It may also result in new, informal trails where users cut through undisturbed vegetation as a shortcut or to gain access to attractions (Cessford et al., 1995). Networks of informal trails created by hikers and other visitors within natural environments greatly enhance the footprint of trail-based activities, simply because they increase trail abundance. Further, the informal networks can internally fragment vegetation into smaller functional patches, each exposed proportionally to greater edge effects that can reduce habitat quality and favour the spread of non-native animals and weeds (Liddle 1997). The capacity for these remnants to persist as functional ecosystems is likely to be compromised (Pickering et al., 2012). Informal trails also generally tend to have poorer surface conditions, be poorly designed, and located on sensitive sites with potential for degrading high conservation value plant communities (Davies & Newsome, 2009; Pickering et al., 2010a; Ballantyne & Pickering, 2015a).

A number of studies have profiled mountain bikers preferred recreation settings and experiences. First, mountain biking emerges as a social activity, with over three quarters of mountain bikers riding in groups of two to five people. Second, most studies show that riders have a strong preference for rough, uneven, tight and narrow tracks, with a variety of vegetation, topography and trail-tread conditions (Cessford et al., 1995; Symmonds et al., 2000; Hagen & Boyes, 2016; Koemle & Morawetz, 2016). In a questionnaire survey from bikers in the USA, New Zealand and Australia, Symmonds et al. (2000) show that on average, biking experience is enhanced by trail erosion factors, such as presence of rocks, roots, gullies. The only erosion factor that detracted from biker experience was the presence of mud. In terms of trail design, bikers preferred a mix of steep and gentle slopes, and in general the presence of bumps, turns and jumps. The presence of obstacles added to experiences (Symmonds et al., 2000). There is however a relationship between biker preference and level of experience: novice bikers preferred smooth, open or clear trails and had low preference for obstacles (Koemle & Morawetz, 2016).

Scope and objectives of the study

AIM

The aim of this study is to carry out an evidence based review of the available literature to assess the likely impacts of single trail mountain biking in Mediterranean environments and propose a protocol for monitoring those impacts in Ramat Hanadiv nature reserve.

SCOPE

Mountain biking typically takes place on trails. These trails can either be formally created and maintained by management agencies or informally created by users (Marion and Leung 2001). All types of trail activities on unsurfaced trails cause similar types of impacts on the environment, but the severity of impacts may differ depending on the activity and trail type. All studies considering formal or informal trails, multi-use or single-tracks are thus considered for this review, with a focus on single-track where possible. Impacts from other trail activities (e.g. hiking, horse riding) are only considered to understand the general processes causing biophysical impacts on the environment.

A recent systematic review shows that research on the impacts of trails on the environment mostly originate from the U.S.A and Australia, with only a marginal number focusing on Mediterranean habitats (8 studies on Mediterranean forests, woodlands, scrubs and dunes out of 59 studies, Ballantyne and Pickering 2016). Given the paucity of studies focused on Mediterranean habitats, in this review, impacts are first discussed overall, and when possible, the evidence from Mediterranean habitats is described in further details.

This review focuses on the impacts of trail use by mountain bikers, but does not cover impacts related to trail creation, maintenance, and potential repurposing or abandonment of the trails. However, most of the impacts of trail-based activities are related to trail creation (Burgin & Hardiman, 2012). The intensity of these impacts will depend on whether the trail is created from an existing informal trail, or *de novo*. De novo trail creation implies impacts in terms of clearing of vegetation, potential habitat fragmentation, and hardening of the trails with ensuing soil compaction and erosion. An overview of impacts of newly opened mountain bike trails will thus be provided based on available evidence or through the impacts of off-trail mountain biking.

It is clear that a number of mediating factors will influence how much mountain bikers impact the environment, such as the intensity, location, timing and behaviour of mountain bikers, however a comprehensive study of these is not in the scope of this review.

1. Methods and data sources

Overview

This study involved the following steps:

- Identification of the broad impact categories
- Meta-review of impacts on vegetation, soil and water
- Literature review of impacts on wildlife

- Catalogue of experimental protocols for monitoring impacts

Identification of broad impact categories

The environmental impacts associated with the recreational use of trails and considered in this review are grouped in four main categories, commonly used to divide major recreation effects (Mosedale 2003 in Canada review 2010):

- Impacts on vegetation, effect of activity on plant community composition, diversity and structure. This includes vegetation degradation and destruction.
- Impacts on soils, effect of activity on soil structure and composition, through processes such as compaction and erosion
- Impacts on wildlife, effect of activity in terms of species disturbance, through mortality, destruction or alteration of habitat, behavioural stress or disturbance. Effects in terms of spread of IAS and habitat fragmentation are also considered.

Literature review on impacts on wildlife of single-trail biking

A comprehensive review of published literature and other accessible information on the relationship between biodiversity and mountain biking has been carried out by:

- (1) Searching through references cited by reports known to be of relevance (Marion and Wimpey 2007, IMBA 2007, Quinn and Chernoff 2010)
- (2) Systematic literature search using Google scholar with various combinations of the following keywords in the title, keyword or abstract: 'trail* or track or bik* + impact' AND a combination of 'ecologic*', 'bird' 'mammal' 'reptile' 'amphibian' 'insect' 'wildlife'
- (3) Identifying and checking relevant references from the sources identified in (1) and (2)

Meta-review on other environmental impacts of single-trail biking

For impacts on soil and vegetation, the review of single-trail biking in this report relies on a very recent systematic review looking at the impacts of unsurfaced trails on soil and vegetation (Ballantyne et al. 2017), and references therein. Systematic reviews comprehensively summarise evidence on one topic to inform management decisions, based on a transparent and repeatable protocol. This existing database is supplemented by some targeted searches for grey literature, for additional research papers in Mediterranean habitats or for papers published after 2015 and not included in the systematic review.

Comparative analysis of impacts of single-trail biking

A database of all 29 relevant studies identified by the literature review was compiled and is provided in Appendix 1. For each study, this database outlines the impact categories covered (Plants, Soil, Wildlife or Others) and the indicators used to assess these impacts. It also shows whether the impacts were considered on or off trail, the type of trail (Mountain bike only or Multi-purpose, including mountain-biking) and its surface (Bare or Paved). Given the lack of comparability among study designs and the lack of quantitative data on impacts, these data were reviewed and a qualitative overall analysis is provided in conclusions.

Review of experimental protocols

The study designs and sampling protocols used for assessing mountain biking impacts were compiled for each of the mountain biking studies identified in the literature review. All sampling methods identified were applicable to a range of conditions, including Mediterranean habitats.

2. Biophysical impacts

There is relatively little published research on the biophysical impacts of mountain biking (Marion & Wimpey, 2007), although this trend is starting to reverse (Ballantyne & Pickering, 2015b). Documented impacts of mountain biking on existing trails include trail widening, vegetation damage on trail verges, soil compaction and erosion (Wilson & Seney, 1994; Goeft & Alder, 2001; Pickering et al., 2010a). Riding off existing trails can also cause damage resulting in the loss of vegetation and soil surface organic layers, leading to soil exposure, compaction and erosion (Thurston & Reader, 2001; Davies & Newsome, 2009; Pickering et al., 2010a). The scale of these impacts will depend on the usage and skills of the mountain rider, as well as on geo-physical conditions, such as slope and soil structure. Assessing the biophysical impacts of mountain bikes is complicated by the fact that few trails are used exclusively by mountain bikes, and therefore on most trails it is difficult to distinguish mountain bike impacts from those of other users (Goeft, 1999). Moreover, studies of newly opened mountain bike trails are scant.

Impacts on vegetation

Overall impacts

Under normal trail use, damage to vegetation is a minor factor, since trails by definition have minimal or no vegetation, so as to facilitate travel (Weir, 2000). Damage to vegetation is thus mostly an issue in the case of the creation of new, formal or informal trails, or in the case of off-trail use. Off-trail use typically results in parallel tracks or trail widening, or in new informal trails where users cut through undisturbed vegetation. Trail construction and maintenance in contrast requires the removal of shrubs and trees on (or in direct proximity of) the trail, and may lead to the removal of sensitive or rare plants, or to their isolation. These changes to the vegetation may open-up areas, thereby favouring different types of plants, such as plants that have a higher sun-tolerance or resistance to treading. It follows that the trailside plant communities may be modified.

- Trampling

Trampling is by far the most studied impact of trail-based recreation activities. It can be defined as the mechanical destruction and mortality of ground level vegetation on undeveloped terrain. It contributes damage to plant leaves, stems and roots, reduction in vegetation height, change in species composition and reduction of vegetation cover (Thurston & Reader, 2001). In the case of trail-based activities, once a route is clearly defined by managers and a new 'hardened' trail surface is formed, subsequent trampling may continue with use, although the impact is likely minimal. Further, it should be noted that generally, the effect of trampling is fairly limited, extending only about one metre from the trail's edge.

Plants are not equally resistant to withstand the direct effect of trampling, nor are they equally resilient in their capacity to recover from trampling. In a systematic review, Pescott & Stewart (2014) found that the intrinsic properties of the vegetation community appear more important to explain resilience to trampling than the magnitude of the actual disturbance. For instance, woody plants tend to decrease near trails since they are brittle and more delicate than herbaceous plants. Grasses and sedges in contrast are more tolerant to trampling (Jordan, 2000). In a meta-analysis of the impact of foot and vehicles on vegetation, York (1997) found that graminoids appear to have the greatest resistance and recovery capacity among plant forms, whilst shrubs and trees suffer the greatest long-term reductions in diversity following traffic impacts.

- Vector of seed dispersal and spread of IAS

Common recreational activities can act as forms of habitat disturbance, potentially facilitating species invasion. In a systematic review and met-analysis, Anderson and colleagues (2015) found that the abundance and richness of non-native species are significantly higher in sites where tourist activities take place than in control sites, across freshwater and terrestrial environments, and across a variety of vectors. The review did not specifically include mountain biking, but covered hiking. Recent reviews of over 45 research papers on the role of vehicles, horses and hikers show that they can be a major vector for non-native seeds dispersal (Pickering & Mount, 2010; Ansong & Pickering, 2014).

Studies have shown that dispersal of even small numbers of seeds, especially over large distances, can cause disproportionally large changes in ecological patterns (Nathan, 2006), and dispersal is a critical step in biological invasions (Kueffer et al., 2013). The number of seeds dispersed by shoes or clothing can be large, about 1,300 on a walker's sock after a 5 min hike through roadside vegetation (Mount and Pickering 2009). This is particularly a concern for protected areas. As recreation is one of the few activities allowed in areas of high conservation value, any seed dispersed by these activities is important. Recreation activities can also transport seeds over long distances, well away from roads, in otherwise remote areas (Pickering & Mount, 2010).

Specific impacts of single-track mountain biking relevant to Mediterranean regions

A review of the impacts of tourism on plant species in Australia, suggests that mountain biking has only a minor impact on vegetation compared to other impacts of tourism, related to trampling by foot or flower collection (Kelly et al., 2003). This conclusion is corroborated by other studies (Thurston & Reader, 2001; Marion & Wimpey, 2007; Pickering et al., 2010b).

Mountain biking can cause vegetation trampling, when the torque applied to the wheel exceeds the strength of the plant material and rips it. Trampling intensity typically increases with the weight and speed of the mountain bike, as well as with the width of the trail and length of travel. Mountain biking may also favour exotic species or act as seed vectors (Pickering et al., 2010b).

Thirteen studies looked at least to some extent at the specific impacts of mountain biking on vegetation. These studies typically considered multi-purpose trails in forest habitats and examined vegetation cover or composition (Appendix 1). Only a two of these are experimental studies looking specifically at the impacts of mountain bike use on plant species diversity (Thurston & Reader, 2001; Pickering et al., 2011).

- Trampling

In a landmark study, Thurston & Reader (2001) experimentally compared the trampling impacts of bikers and hikers on vegetation. They applied five different intensities of hiking and biking (0, 25, 75, 200 and 500 passes) on forest lanes in Ontario, Canada. They found that the impacts of mountain biking on vegetation loss and species loss were similar to those of hiking. Their findings also corroborated general research on recreation, by showing that both species loss and vegetation loss occurred rapidly but then levelled off. After 25 passes, about 75% most plant stems of vegetation and species were lost in the centre of the trail, but no further degradation was observed at higher intensities of use. One year following treatment, vegetation cover and species richness were similar between treatment and control trails, suggesting that for low/moderate levels of yearly use (max 500 passes), rapid recovery is possible.

In sub-alpine grassland, Pickering et al. (2011) found that mountain bike riding reduced absolute vegetation cover, vegetation composition and vegetation height. After 25 passes, vegetation height was reduced by one third. Reductions in vegetation cover were observed after 75 passes, reductions in plant species richness were only observed at 500 passes.

A study on a mountain bike racing trail and a mixed trail in Mediterranean forest in Australia, mostly focused on the impacts of soil, but also reported minimal disturbance to trailside vegetation cover (Goeft & Alder, 2001).

A few studies focused more specifically on the impacts of new mountain bike trails or mountain bike features on vegetation. Bjorkman et al. (1996) examined changes on newly opened bike trails in a state forest and found that vegetation cover disappeared almost entirely on the trail tread, while trailside vegetation remained unaffected. Ballantyne et al. (2015), found that trail creation resulted in loss of forest strata. Pickering et al. (2010a) investigated the impacts of mountain bike trail features, such as ditches, jumps or logs, on vegetation. They found that all features involved removal of some vegetation (Pickering et al., 2010a). A couple of studies also point to the fact that trails can create edge effects, promoting exotic and non-ruderal species (Potito & Beatty, 2005; Crisfield et al., 2012).

- Vector of seed dispersal and spread of IAS

Three recent studies investigate the potential of mountain bikes to act as seed dispersers. All three studies are experimental pilot protocols to test seed attachment potential. Weiss et al. (2016) find that although seeds attach relatively fast to mountain bike tires, most of them drop off within a few metres. Similarly, Hardiman et al. (2017) found that seeds had a negligible probability to attach to bikes (<0.1%), when they compared artificial seed attachment rates of hikers and mountain bikes, over distances of 15 m and 150 m (Hardiman et al., 2017). Pickering et al. (2016) found higher seed attachment rates in natural conditions, with about 20 seeds from 10 species on average attached over 100 m passage through seeding grassland. They also found that bikes were selective seed vectors, since many of the seeds attached were from non-native plant species. Soil conditions largely influence seed attachment rates, with dry conditions typically resulting in negligible or no seed collection on the bike (Pickering et al., 2016; Weiss et al., 2016). Seed loads could vary among different parts of a bike, and according to whether the bike is ridden on or off-track. Overall, these studies indicate that mountain bikes have only a moderate seed dispersal capacity compared to hikers or cars (Weiss et al., 2016), although it may be comparable to that of horses (Pickering et al., 2016). Weiss et al. (2017) found that m light seeds could stay attached over several hundred meters, which corresponds to seed dispersal at the landscape scale. In comparison, seed dispersal on clothing of hikers is estimated to be up to 5,000 – 10,000 m (Pickering et al. 2011; Wichmann et al. 2009).

- Impact on rare of threatened plant species

A single study considered the impact of mountain biking on rare or threatened plant species. It identified only one taxa among 72 plant taxa found to be threatened by tourism, threatened, inter-alia, by mountain biking activity (Kelly et al., 2003).

Management recommendations

- Keep trails only wide enough to allow intended use. Trails wider than this represent a form of avoidable impact on the environment.
- Limit off trail riding, by designing trails to provide the experience that mountain riders seek, providing education, or using prohibitive means (access fees, controls).
- Locate trails away from sensitive species and habitats, in particular bearing in mind the potential for habitat fragmentation.
- Educate mountain riders to be aware of the risk to transport non-native plant species on their bikes or clothing, and encourage to remove the seeds by cleaning their bikes and shoes.

Impacts on soils

Overall impacts

As with damage to vegetation, much soil disturbance is related to the initial construction of the trail. During trail construction, surface organic materials and soil are removed from the tread, and the underlying soil layer is compacted to provide a consolidated surface. This compaction process can be part of the trail construction or occur during initial use. Subsequent damage to soils resulting from the use of the trail may involve erosion, with exposure of rocks and plant roots and the creation of an un-even trail surface.

There is debate as to the intensity of activity needed to cause impacts on existing trails, since this also depends on other variables, such as soil characteristics (Lathrop, 2003). In an early study, Cole (Cole, 1987) found that below 100 passes per year by people, soil exposure was negligible, whilst Quinn and others (1980) observed that bare ground did not appear until after 250 passes were made. Nevertheless, the general finding from previous research is the overwhelming evidence that the relationship between use and impact is curvilinear, with the greatest damage occurring with initial use (Cole, 1987; Marion & Wimpey, 2007).

- Soil compaction

Soil compaction is caused by the weight of the trail users and their equipment. Compacted soils are denser and less permeable to water, but provide a more durable tread for transport. If the trail is not compacted by managers during trail construction, but only through trail use, the risk is that it will be more compacted in the centre of the trail. This creates a cupped section in the middle of the trail that can intercept or channel water. In a study of off-road motorbiking in sand dunes of Israel, Kutiel et al. (2001) found that soil compaction increased with use, but that soil moisture and organic matter content were not affected. One year after the experiment, the soil was similar to pre-experimental conditions.

- Soil erosion

Continuous trampling stresses reduce vegetation and consequently litter cover and organic matter content, which eventually results in exposure of the mineral soil and its aggregates (Kutiel et al. 2001). The subsequent destruction of soil aggregates is followed by a reduced micro-organism activity and organic matter decomposition. In addition, a mechanical crust on the exposed mineral soil is formed, resulting in reduced soil porosity, and thus soil moisture.

Assessment of factors causing soil loss from trails finding that wider, bare trails built on steep contour-perpendicular slopes were much more degraded, with high soil loss (Olive & Marion, 2009).

Crisfield explored impacts of recreational trail use on dry alpine meadows in the northern Canadian Rockies of Alberta. Unsurprisingly, they found that trails had greater soil compaction levels than undisturbed tundra habitat (2.75 vs. 1.25 kg cm-2).

Specific impacts of single-track mountain biking relevant to Mediterranean regions

About half of the studies on mountain biking impacts consider impacts on soils (Appendix 1). Most of them look at soil compaction, and fewer at erosion. Overall, they find that compaction and erosion impacts are greatest at the early stages of use, thereafter, the negative impacts of additional use slow considerably (Cessford et al., 1995). Indeed, initial bicycle passes tend to compress the soils of trail, pushing particles together and increasing shear strength. An increase in the shear strength of the soil means it will have greater ability to resist erosive forces. Thus, trails tend to erode significantly when young and then stabilise.

Most studies focus on impacts on pre-existing trails as a function of intensity of use rather than type of activity (Lathrop, 2003). In one of the few studies looking at trail creation, Bjorkman (1996) found that soil compaction impacts occurred predominantly within the first year of use, with minor changes after. Trailside soil compaction remained constant. Even under high intensity of use, erosion appears to remain localised to the trail. When they looked at the impacts of a mountain bike race with 870 participants, Wohrstein (1998) found that compaction resulting from bikes was less important and less persistent than that from spectators. Ballantyne and Pickering (Ballantyne & Pickering, 2015b)found that informal trails generally had poorer surface conditions than formal trails.

Goeft & Adler (2001) explored the impacts of a multi-purpose trail and of a mountain bike racing trail in Australian Mediterranean forest over one year of use. Different sections of the trail were created at different times, such that some sections were new and others up to five years old. Overall, they found minimal impacts, with percentage changes in erosion and soil compaction below 4%. Older sections were more compacted than newer features, and downhill slopes and curves were the most susceptible to erosion impacts.

Five studies compared the soil damage caused by mountain biking to that caused by other recreational activities. Overall, they found that mountain biking causes similar or less damage than hiking at low intensities, but more damage at high intensities. It is important to note that the standard comparisons used in experimental studies typically involve slow mountain bike riding, which may not be representative of real-life use.

In a landmark study, Wilson & Seney (1994) applied 100 experimental passes by hiker, horse, mountain bike and motorcycle on existing trails in forest habitat. They found that only about one third of the total sediment mobilisation (indicator for erosion) could be attributed to activities from various user groups, and the remaining two thirds to the texture and slope and of the sample trail. They also found that users on foot (hikers, horses) make more sediment available than do users on wheels (mountain bikes and motorcycles). The authors concluded that trail degradation occurred regardless of specific uses, and that impact was more dependent upon geomorphic processes, such as slope, rainfall intensity and soil structure, texture and moisture, than on the type or amount of activity.

Thurston & Reader (2001) compared the impacts of mountain biking and hiking in Ontario forest trails. They found that soil exposure was greater for biking than hiking only at high intensities (500 passes), but not at lower intensities (0-200 passes). Mean soil exposure reached 49% in the centre of the trail, whereas vegetation loss reached 99%. Accordingly, first vegetation is killed and damaged at low levels of use, and only then surface organic layers start being severely attacked.

In Southeastern Kentucky, Marion & Olive (2006) compared the impacts of horseback riding, ATV use, hiking and mountain biking on the park's trail system, comprising single and multi-use roads and trails. They found that horse and ATV trails were significantly more degraded than hiking and biking trails. Specifically, mean soil loss was only 6 inches2 on bike trails, compared to 19 inches2 on hiking trails and 150 inches 2 for horse trails. Similarly, the proportion of trails with severe erosion (> 12 cm deep) was only 0.6% for bike trails, compared to 4% for hiking trails, 9% for horse trails and 24% for ATV trails.

A similar study in Southwest USA assessed trail width and maximum incision on 262 km of trails predominantly used for mountain biking in five ecological regions of the US, including arid and semi-arid climates (White et al., 2006). They found that mountain bike trails were generally in good condition, and that erosion and tread width differed little on the mountain biking trails, compared to other shared-use trails that receive little or no mountain biking.

Pickering et al. (Pickering et al., 2011) experimentally compared the impacts of mountain biking and hiking on grassland soils. They found that although there was greater soil compaction immediately after biking than hiking, two weeks later, both activities had similar highly compacted soils. Two weeks after 200 bike passes, soil compaction doubled compared to control conditions. They concluded that hiking and mountain biking caused similar impacts on soils.

Management recommendations

- To remedy excessive erosion from enhanced water flows and disturbed soil surfaces on sloping sections of the track, trails that can be routed across slopes. They then have less potential for erosion and water runoff than trails that run straight downslope (Olive & Marion, 2009).
- Muddy stretches in eroded, water saturated, sections of the track is one of the major issues reported, but not considered an issue relevant for dry Mediterranean habitats. Prohibiting uses of trails prone to muddiness, installing trail drainage or re-routing the trail can be options to deal with these issues.
- When possible, build trails in dry, cohesive soils that easily compact and contain a larger percentage of rocks, since they better resist erosion by wind, water or displacement (Marion & Wimpey, 2007).

Impacts on wildlife

Overall impacts

Outdoor activities in which wildlife is not physically removed or affected, such as mountain biking, bird watching or hiking are often assumed to be benign to wildlife. However, it has been argued that due to the growing extent of these activities over the landscapes, they may in fact have as much of an effect on wildlife as consumptive uses (Davis et al., 2008). To date, investigations into the effects of recreation on wildlife have been less systematic than those of vegetation and soils. Consequently, current knowledge is somewhat less definitive and generalizable, nevertheless a large body of disparate evidence has investigated the effects of recreation on wildlife (Kerlinger et al. 2013).

Recreation activities such as mountain biking can affect wildlife in three main ways: disturbance, habitat alteration or direct mortality. Disturbance is when wildlife alters its behaviour in response to human activity. The immediate response of many animals to disturbance is a change in behaviour, such as interruption of foraging, fleeing or altering reproductive behaviour (Taylor & Knight, 2003). In the longer term, energetic losses from flight, decreased foraging time, or increased stress levels come at the cost of energy resources needed for individual survival, growth and reproduction. Animals may also start avoiding parts of their normal habitat ranges, which may reduce the carrying capacity of wildlife habitat (Taylor and Knight, 2003). Alteration of habitat occurs when the recreation activity removes or fragments habitat for wildlife, which can lead to changes in populations dynamics, leading to local species extinctions or on the contrary to encroachment of new species. This is particularly a concern for trail-based activities. Finally, mortality or injury can result from direct collision with wildlife during the recreational activity.

- Disturbance

It has been shown that recreation activities cause disturbances that result in energetic and physiological stresses (e.g., Bélanger & Bédard, 1990), temporal or spatial displacement from preferred environments (Anthony et al. 1995), reductions in reproductive rates and population levels (Garber & Burger, 1995), and alterations in species composition and diversity (Gutzwiller 1995). In a review of the impacts of recreation on birds, Steven et al. (2011) found that recreation had a negative effect on birds in the vast majority of cases (88% of 69 papers), and in all three cases looking at the impacts of mountain biking or cycling. Negative effects were found for 70 species of birds, 24 of which threatened. All papers investigating impacts on bird physiology found a negative impact, while effects on behaviour and reproductive success were mostly negative. In their review, Hockin et al. (1992) show that human-induced disturbances can have significant negative effect on bird breeding success by causing nest abandonment and increased predation. Outside the breeding season, recreation reduces the use of sites by birds. For example, Miller et al. (1998) investigated the influence of recreational trails, including single biking trails, on bird communities in forest and mixed-grass prairie habitats. They found that grassland birds were less likely to nest near trails, and that nest predation was greater near trails. Arroyo & Razin (2006) in an observational study comparing the response of bearded vultures breeding in the French Pyrenees to different types of activities occurring within 2 km of their nest, found that people on foot or car/planes only decreased nest attendance if close to the nest (500-700m). Nevertheless, they observed an increased probability of nest failure with the frequency of noisy activities near the nest. In an experimental study along riparian edges, Miller & Hobbs (2000) found that the likelihood of nest predation from birds and mammals depended on distance from trail.

Different animals respond differently to the presence of trail users, some species become habituated to a constant, non-threatening human activity, whilst others may be attracted or avoid the disturbance (Marion & Wimpey, 2007). Some research focused more on how recreational activities disturb wildlife. For instance, direct approaches appear to cause greater disturbance than tangential approaches. Jordan (Jordan, 2000) found that joggers were more disturbing to wildlife than slower hikers, but that passing or stopping vehicles were less disturbing than people on foot (Jordan 2000).

- Habitat alteration

Trails are a main source of habitat alteration. They might impede movement and dispersal of some animals that are reluctant to cross openings, especially openings with exposed bare soil. The creation of informal trails is also a recognised problem that increases the area of disturbance and can cause fragmentation of habitats (Tomczyk, 2011).

Trails may also act as vectors and serve as corridors for the movement of species, including alien species that have the potential to become invasive. In line with this hypothesis, evidence shows that exotic plant species tend to be more abundant near trail edges, and on more heavily used trails (Jordan, 2000). A correlation analysis of literature from 184 studies from around the world found that the number of exotic species in nature reserves increased with the number of visitors, but no conclusions could be drawn about roles of dispersal and disturbance since other variables were involved (Lonsdale, 1999).

- Direct mortality (collision)

Direct mortality is virtually unstudied (Lathrop, 2003). Anecdotal evidence suggests that small mammals are vulnerable to impact and are not uncommonly killed (Lathrop, 2003).

Specific impacts of single-track mountain biking relevant to the Mediterranean regions

The literature review yielded seven studies that investigate the impacts of mountain biking activity on wildlife (Appendix 1). All studies consider disturbance to wildlife and indicate that mountain biking can modify wildlife behaviour (Cessford et al., 1995; Taylor & Knight, 2003; George & Crooks, 2006; Naylor et al., 2009). However, evidence of long term negative impacts on behaviour are very limited (one study). Little comparative research on the impacts of activity type on wildlife is available (4 studies), but existing evidence suggests that the impacts of mountain biking are similar to those of walking or hiking. Nevertheless, since bikes cover more ground per unit time than hikers, they have the potential to disturb more wildlife per unit time that people on foot.

- Disturbance

In a controlled study, Taylor & Knight (2003) assessed the impacts of hikers and mountain bikers on wildlife. An observer measured bison, deer, and pronghorn antelope response to a hiker or biker passing on the trail: alert responses to hikers or bikes riding on a trail. They found that wildlife reacted similarly to hikers and bikers, with a 70% chance of flight when located within 100 m of a trail. Wildlife reacted more strongly to off-trail recreationists.

In another attempt to understand the comparative effects of different types of use on wildlife, Papouchis et al. (2001) examined flight response of desert bighorn sheep to mountain biking, hiking and ATV. They found that bighorn sheep were much more likely to flee from hikers (61% chance), who are more likely to approach the animals directly and to venture off-trail when they observe one, than from mountain bikers (6% chance).

Similarly, in a study of bald eagles response to disturbance, Spahr (1990) found that bald eagles were much more likely to flush in the presence of walkers (46%) than with mountain bikers (15%). Eagles were least tolerant when recreationists approached slowly or stopped to observe them, and less alarmed when cyclists passed quickly and at constant speed.

In contrast, a similar study looking at the response of chamois to hiking, jogging and mountain biking in alpine pastures found no difference in alert distances, flight distances and distances fled among the three different types of uses (Gander & Ingold, 1997).

Naylor et al. (2009) found different results in a controlled experiment looking at elk responses to all-terrain vehicles, mountain biking, hiking and horseback riding. Compared to control periods where elks spent most of their time resting and grazing, travel time increased in response to all activities, mostly ATV and mountain biking. Both mountain biking and hiking were found to significantly reduce resting time for elks.

A couple of studies looked at the impacts of mountain biking on golden-cheeked warblers populations (Davis et al., 2008, 2010). Davis et al. (2008) compared the population structure and territory sizes of golden-cheeked warblers before and after the opening of mountain biking trails and found no differences. In a later study, they however found that the breeding success of Golden-cheeked warblers was nearly 50% lower in biking areas than in non-biking areas (Davis et al., 2010). But they did not find any difference in parental behaviour or food availability between the biking and non-biking areas.

- Habitat alteration

A single study was identified that considered the impacts of mountain biking on habitat alteration, but it did not look at the wildlife population consequences (Appendix 1). The main concern in terms of habitat fragmentation is the development of informal trail networks. In a study comparing the impacts of formal hardened trails and informal trails in urban forest remnants, Ballantyne and colleagues (2014) found that informal trails have a higher fragmentation capacity than formal trails. The greater spatial proliferation and complex networks of informal trails cumulatively resulted in greater loss of forest than formal trails. Overall, mountain bike trails resulted in the loss of forest, litter layer, understorey and mid-storey along the trail edges. Although per unit area of trail there was no difference between the impact of formal and informal trails, the greater length of informal trail meant that they accounted for about 65% of the forest area lost in the study area.

- Direct mortality/injury

Incidence of direct mountain-bike caused wildlife mortality are rare, the most frequent casualties being insects or reptiles. In Australia, the red-bellied black snakes or the local blue tongue lizard often bask on the trails and are prone to being accidently ridden over and killed (Burgin & Hardiman, 2012).

Management recommendations

- Design trails so as to avoid sensitive or critical wildlife habitats
- Restrict access during sensitive times/seasons to protect wildlife from stress (e.g. mating and birthing season)
- Discourage informal trail creation

Conclusions

The main conclusions that can be drawn from the literature review are:

- Impacts of mountain biking are mostly restricted to the trail tread and have been relatively well studied. They include soil erosion and compaction, trail widening, damage to plants, including reduction in plant height and biomass and changes in species composition. The wider impacts of mountain biking are more difficult to assess and far less studied. They include potential for spreading weeds, fragmenting or deleting wildlife habitat, modifying wildlife behaviour with potentially long-term consequences on their populations.
- Trail creation creates the largest environmental impacts. Once a trail exists and is in (reasonable) use, no further trampling, soil compaction or erosion is expected. Therefore discouraging the creation of unofficial trails is essential. This can be achieved by providing a trail network adapted to the needs of the riders, with sufficient challenges and connections to other trails.
- Most available comparative studies have concluded that while visibly different, the impacts of bikes on trails (per unit area) were not any worse than those of walkers overall (e.g. Wilson & Seney, 1994; Cessford et al., 1995; Weir, 2000; Thurston & Reader, 2001). However, no study adequately considers the overall impacts of mountain biking, taking into account that it has a much wider extent than walking or hiking.
- Overall, the impacts of mountain biking on formal trails on vegetation, soil and wildlife under reasonable use appear to cause negligible environmental impacts. The potential for larger environmental impacts appears to be more linked to mountain-bike riders behaviour than to the activity per se. In other words, higher impacts are linked to riders the tendency to go off trail, to experience high thrill and ride with intense breaking and skidding, or to throw litter.

However, these conclusions should be taken with caution given a number of important knowledge gaps to adequately assess the biophysical impacts of mountain biking on the environment. The literature review highlighted the following main limitations:

- Most mountain biking studies appear to test relatively 'gentle, straight line mountain biking' conditions, with no skidding or speeding, which does not reflect real-life use. The studies identified tested the impacts of up to 500 passes (e.g., Pickering et al., 2010b). Arguably, users will exceed these levels of use very fast, especially since mountain bikers tend to ride in groups of 2-5 individuals.
- Longitudinal studies to determine the long-term, chronic impacts of mountain biking are lacking.
- Studies of the impacts of mountain biking at a landscape scale, considering habitat fragmentation or threat to sensitive habitats are lacking.
- To provide informative impact assessments, comparative studies with other forms of trail-based recreation activities need to take a broader perspective, and consider not only activity type and impact per unit area, but also the extent of the activity, its intensity, and the number of users.
- Studies identifying the threshold level of yearly mountain biking use on formal trails, accounting for trail characteristics, are needed to provide guidance for managers.

3. Assessing the biophysical impacts of mountain bikes

Review of existing indicators and methods used to assess the biophysical impacts of mountain biking

The literature review yielded 29 studies that investigate to some extent the biophysical impacts of mountain biking on the environment. About half of these studies were experimental ones, either comparing mountain-biking impacts to the impacts caused by other recreational activities in standard conditions, or assessing mountain-biking impacts under different intensities of use. Eight studies were observational studies, typically longitudinal studies looking at trail conditions. Table 1 summarises the biophysical indicators used in each of these studies, along with the sampling design and sampling methodology used.

Table 1 – Indicators and sampling methodology used to assess the biophysical impacts of mountain biking*.

ID	Authors	Year	Indicator	Sampling design	Method
1	Ballantyne and Pickering	2015	-Trail condition -Loss of forest strata -Tree structure	**Observational.** Mapping of all trails in 17 forest remnants >5 ha, and classification into 7 categories based on status (formal vs informal), trail width (0-2m, 2-4m, 4-7m) and trail surface (grass, bare earth, gravel, tarmac/concrete). 15 replicate sites randomly located along each trail type, using a 50 m buffer from other types of disturbances (e.g. roads, forest edge), and if surrounding vegetation had not been burnt in the last 10 years. 20 control sites within the forest measured for tree structure. Comparison formal vs informal trail	<u>Trail surface variables</u>: maximum trail width, cross-sectional area of trail tread, slope, <u>Soil compaction</u>: measured using a penetrometer (max cap. 4.5 kg/cm2 at 5 equally spaced points on the trail surface) <u>Tree structure</u>: Linear distance from trail edge to the start of each of 4 strata: litter line, understorey, midstorey, and mature tree trunks. 50 m2 belt transect parallel to the trail measuring: % canopy cover on trail, litter depth (5 measures at the tree line at 10 cm intervals), tree density, % living trees, % saplings, % mid-aged trees, % mature trees. Density, health and life stage of all trees using T-square method (20 trees randomly selected). <u>General</u>: aspect, slope, altitude
2	Ballantyne et al.	2014	-Fragmentation	**Observational.** Mapping of all trails in 17 forest remnants >5 ha and accessible to the public. Loss of forest strata assessed at 60 points identified by stratified random sampling, based on trail width categories (0-1 m 1-3 m, >4 m). Remnant forest perimeters and trail layers were built.	GIS calculation of weighted mean patch index (WMPI) and Largest 5 patches Index (L5PI).
5	Davis et al.	2007	-Mountain bike use -Bird nesting success -Parental behaviour -Foraging behaviour -Food abundance -Territory size	**Experimental.** Comparison of golden-cheeked warbler behaviour in 2 biking areas vs. 2 control areas.	<u>Trail use:</u> TrailMaster photoelectric trail counters <u>Behavioural data:</u> Birds were observed throughout the breeding season, with focal individual sampling observations to collect behavioural data. Cameras were

ID	Authors	Year	Indicator	Sampling design	Method
					placed in nests and checked daily. A nest was considered successful if more than one young fledged. Arthropod sampling was performed during a 2-day period every 2 weeks throughout the breeding season. Within each territory, one tree was randomly selected and 3 small branches, each at a different height category (,3m, 3-5m, >5m) were shaken and their content was bagged. Territory size: at least 30 GPS locations of sightings for each male.
6	Davis et al.	2010	Ibid ID(5)	ibid ID(5)	ibid ID(5)
7	Gander and Ingold	1997	-Flight distance	**Experimental.** 32 trials (12 hiking, 10 jogging, 10 mountain biking) carried out by 11 different people.	No description of the trial method (distance travelled, where on the path, how flight distance is measured - use of telemetry).
8	Goeft and Alder	2001	-Plant cover -Soil compaction -Soil erosion	**Observational.** Longitudinal study of two forest trails (one multi-purpose trail, one bike racing trail) containing sections that were new or up to 5 year old. 3 replicated transects were selected on each trail, representing combinations of uphill, downhill and flat sections. All indicators examined for one year, sampled five or six times in summer and twice in winter.	Vegetation cover assessed within 2-m on either side of the trail. Trail width was defined as the maximum width of ground used by mountain bikers, evidenced by tyre marks. Soil compaction was measured with a penetrometer at 5 cm intervals across the trail. Soil erosion was measured on % change in cross-sectional area of the trail profile compared to the start of the study. Soil samples were taken immediately next to the trail.
9	Hardiman et al	2017	-Seed attachment	**Experimental.** Pre-fabricated track sprinkled evenly with bright blue coloured synthetic seeds measuring between 1.6-2.1 mm at a density of 0.001 seed/mm2. The test included two treatments (boots vs bike), two soil conditions (moist vs wet) and two distances (short vs long), seven times each. Moist soil ranged between 18.7-21.6%, wet was >50%; short was one track circuit, about 15m, and long was 10 circuits, about 150 m.	After completion of trial, brushing off all soil and beads for 10min and counting of the seed analogs (synthetic seed beads of 1.6-2.1mm).
10	Kutiel et al.	2001	-Plant diversity (Shannon-wiener index) -Plant ground cover -Mean plant height -Plant species relative cover -Soil compaction	**Experimental.** Before-During-After experiment with one treatment (off road mountain bike vs control) at four intensities (0, 20, 50, 100, 200 passes). It was carried out on four replicate plots of 220m2, >30 m away from each other. In each plot, 5 lanes 2 x 10 m (control, off road mountain bike at different	Vegetation: plant composition and relative cover were measured in each subplot; measurements on Day -1, Day 18, and Day 45 and Day 372 after the experiment. Soil: compaction estimated by penetrometer at 25 cm horizontal intervals; measurements on Day 1, Day 72, and Day 365 after the

ID	Authors	Year	Indicator	Sampling design	Method
			-Soil organic matter -Soil moisture	intensities). 2 sub-plots of 0.5 x 2 m in turns (150 turns / subplot).	experiment. Soil samples taken to estimate soil organic matter from a depth of 0-2cm after removal of litter layer. Soil moisture samples taken at 0-2cm and 5-10cm on days -1, 19, 45, 61, 73, 86 and 103 after the experiment.
11	Marion and Olive	2006	-Trail condition -Soil erosion	**Observational.** Random selection of 126 km of trail segments within the reserve and categorisation of these segments by experts based on level of use (low, intermediate, high) and main activity (>75% of one use type). Sample points were located using a point measurement method, with systematic sampling at 500 ft intervals from a random start. At each sample point, a transect was established perpendicular to the trail.	Measurement of trail width and maximum incision (maximum distance between stakes at the edge of the trail and trail surface) Cross-sectional area of soil loss measured using a variable interval method. Trail condition: % vegetation cover, organic litter, exposed soil, muddy soil, rock, gravel and roots on the tread (by 10% bins), assessed across each transect.
12	Naylor et al.	2009	-Activity budget	**Experimental.** Treatment: 4 types of disturbances, ATV, mountain biking, hiking and horseback riding. 16 female elks were fitted with radiocollars containing activity monitors and released into the study area. Following a 14 day period without human activity; an alternating pattern of 5-day treatment, 9-day control was implemented, so that each of the 4 treatments was repeated 3 times each year.	Elk activity monitored through motion-sensitive accelerometers to record elk behaviours (calibrated for resting, feeding and travelling; altogether elks observed for 1,073 min over 12 observation periods ranging from 25-106 minutes each). Wild elk activity was monitored every 5 min and attributed a class interval associated with one of the three activities.
13	Nemec et al.	2011	-Plant species abundance -Plant species richness (native, non-native)	**Mapping.** Aerial photo identification of five forest corridors along paved bike trails, at least 200 m in length, consisted mostly of woody vegetation and originated from a larger patch of mostly native vegetation. The corridors were surveyed in the natural vegetation adjacent to the trail at 30 m intervals, such that 10-19 points were measured on each transect.	Survey points were located midway through the forest corridor and surveyed using the point quarter method. The tree or shrub >0.6 m in height and closest to the midway point in each of the four cardinal directions was identified and its diameter recorded.
15	Olive and Marion	2009	-Soil loss	**Observational.** Stratified random sample of 47 trail segments representative of amount and type of use (as estimated by expert). Sampling locations along each trail segment were determined by point-sampling method using systematic 152 m intervals following a randomised start. At each sample point, a transect was established	Trail position (3 categories, valley, ridge slope or ridge top). Soil texture was assigned to one of 9 categories. Tread drainage was assessed by two measures on the transect and also in the vicinity. Soil loss was measured using variable interval cross-sectional area method (i.e. measuring only when trail incision >2.5 cm)

ID	Authors	Year	Indicator	Sampling design	Method
				perpendicular to the trail, and trail condition estimated.	
17	Pickering et al.	2010	-Trail features characteristics -Bare ground (area, width) -Roots exposed -Width to intact vegetation -Native vegetation removed for construction	**Observational.** All trail technical features were identified on an extensive informal trail network and characterised.	Trail technical feature characteristics: location, slope, aspect, soil type, understorey vegetation condition, canopy type Trail characteristics: type, width, depth Impacts: width of bare ground, width to intact understorey, width to intact shrub layer, width to intact forest, qualitative measurement of roots exposed, presence/absence of litter.
18	Pickering et al.	2016	-Seed attachment	**Experimental.** 20 1 x 50 m transects marked in seeding grassland and randomly assigned to two treatments (horse, mountain bike) with 10 replicates per treatment. Each treatment involved 2 passes of 50 m (back and forth). After treatment the horse was brushed for 5 min / the bike was cleaned entirely, and all seeds collected.	All seeds brushed/cleaned were collected, counted and identified at species level where possible.
19	Pickering et al.	2011	-Vegetation height, -Plant cover -Soil litter -Soil compaction	**Experimental.** 8 treatments, with six replicates each (control, 25, 75, 200, 500 passes by mountain bike, 200 and 500 passes by hiker). Six 0.5 x 40 m transects on moderate slope (8 degrees), 3 m apart from each other + bike slope treatment (6 lanes ridden 200 times, slope of 5 degrees). Each transect divided into seven 4 m long lanes, with 2 m gaps between lanes, and treatments assigned using a stratified random sampling.	Vegetation height and soil compaction measured at 24 evenly spaced points along the middle section of each of the 4m lanes. Plant species richness and composition were recorded in an area of 4 x 0.25 m. Overlapping cover of each species using 120 evenly spaced points, and of species and litter.
20	Potito and Beatty	2005	-Plant species composition (native and IAS)	**Observational.** Two types of trails (> 3 year old vs. newly constructed, not yet opened). Each old trail was divided into two sections: close to the trailhead (high use) and further down (low use). Three equidistant sampling points, at each point a 25 m transect perpendicular to the trail	All plant species were identified along each transect, as well as percentage vegetation cover. Species were classified as native or exotic, and ruderal or non-ruderal. % cover for each of the five categories and indices of change in cover
22	Taylor and Knight	2003	-Alert distance -Flush response -Flight distance -Distance moved	**Experimental.** Trials were performed along designated trails (recreationist + data collector). The recreationist moved a typical pace for each activity, did not stop to look at the animals and avoided talking during the trial. Each animal or animal group observed within 500m of the trail.	Distances measured to the nearest meter with laser rangefinder. Animals that continued fleeing out of sight were tracked to estimate distance moved. For groups, distances were measured from the first animal that responded. Visual landscape cues were used to mark initial locations and during experiment, so that distances could

ID	Authors	Year	Indicator	Sampling design	Method
					be measured once the trial was completed. Trials were conducted daily outside of animals resting periods. Starting locations were randomly chosen, and same section of trail was only sampled once per day.
23	Thurston and Reader	2001	-Plant stem density -Plant species richness -Soil exposure	**Experimental.** Before-After: Ten treatment combinations to represent two activities (hiking or biking) and five intensities (0, 25, 75, 200, 500 passes). The 10 treatment lanes were located within a 50 m x 5 m transect on slopes between 9° and 14.7°. Within this transect, the treatment lanes ran perpendicular to the slope contours. Each lane was 4 m x 1 m (3 zones: center, mid and outer). Two successive lanes were separated by a buffer zone of 5 m and all lanes were located at least 25 m from the forest edge. Before-After: Measurements were made before, two weeks after, and one year after treatment.	<u>Vegetation sampling</u>: 1 m2 quadrat divided in 20 cm x 20 cm cells, over 3 zones (center, mid, outer). The species were categorized as one of six growth forms (tree-seedlings, tree saplings, shrubs and bines, ferns, forbs; graminoids). <u>Soil sampling</u>: bare ground of the A1 horizon, free of macroscopic vegetation, leaf litter, twigs, moss or humus. Visually estimated using a 5-point scale (0-20%, … 81-100%).
24	Tomczyk	2011	-Vegetation cover -Soil erosion	**Mapping.** Mapping of environmental vulnerability.	Potential soil water erosion assessed (6 levels, (0) no water erosion to (5) very strong erosion, causing permanent degradation of an ecosystem) based on soil properties and slope. Surface erosion estimated by using the Soil Loss Equation, based on rainfall, soil erodibility, slope length and steepness and cover management. Vulnerability of plant communities to trampling qualitatively assessed (6 classes based on plant families).
25	Tomczyk and Ewertowski	2013	-Soil erosion	**Mapping.** Development of digital elevation models in 12 test fields with similar amounts of use, and comparison of models in subsequent time periods to estimate the amount of soil loss or deposition.	Elevation measurements, development of digital elevation models with a cell size of 1 cm x 1 cm.
26	Weiss et al.	2016	-Seed attachment	**Experimental.** Creation of an 'attachment area' of 2.13 x 0.5 m, with 2,500 coloured seeds of 5 species evenly distributed on the ground, such that each wheel can have a full rotation (seed density about 1.17 seed/cn2). Treatment: the bike was ridden through the attachment area and stopped adter	Seed count.

ID	Authors	Year	Indicator	Sampling design	Method
				0, 5, 10, 20, 50, 100, 200, 500 m. Afte each run, the mountain bike was cleaned and seeds counted. Replicates for each distance and soil condition (wet - 20-22mm rain 48 hrs prior, semi-wet). Speed between 10-15 km/hr, representing average uphill speed.	
27	White et al.	2006	-Trail width -Trail incision	**Observational.** Point-measurement trail assessment procedure, with systematic sampling points at intervals of 805 m (1/2 mile) along the trail.	Trail boundaries were visually defined as the area where the vast majority of trail use (>90%) occurred. Trail width was the distance between the trail boundary points. Maximum trail incision was the maximum depth from a taut nylon cord stretched across the trail to the trail surface.

*five studies included in the database are not reviewed here since the full text of the paper could not be accessed.

Suggested protocol for Ramat Hanadiv

While land managers are concerned about the impacts of mountain biking, the evidence suggests that these impacts are minimal and very local. However, the longer-term and landscape-scale effects of mountain biking, notably on wildlife populations, have so far barely been explored. An emerging body of evidence also suggests that mountain bikes can act as seed vectors, notably for invasive alien species.

Based on the findings from the literature review, the following approach is suggested to be developed in Ramat Hanadiv:

- **Ensure that mountain bikers stay on trail**. Environmental degradation can be substantially reduced when bikers stay on formal trails. To minimise the environmental impacts of formal trails, ensure that they are located on side-hills to minimize erosion, and away from sensitive or critical wildlife habitats. To motivate bikers to stay on formal designated trails, ensure good sign-posting, good maintenance of the trail, provide education for mountain bikers, and perhaps most importantly, design the trails so as to provide them with the experiences they are seeking.
    - (a) Monitor mountain-bike trail use, to get objective data on intensity of use, patterns of use (e.g. seasonality) and frequency of off-trail use.
    - (b) Ensure good trail maintenance and design
    - (c) Survey of mountain bikers: needs, environmental concerns
    - (d) Mapping of trail network vs. elevation, distribution of rare species or sensitive habitats
- **Monitor target habitats and species.** In order to ensure no declines in habitats or species of concern, and to help fill knowledge gaps, monitor a small set of species likely to be impacted by mountain biking, e.g. ground beetles, amphibians, reptiles or small birds.
    - (a) Integrate this within existing population monitoring protocols at the scale of the whole nature reserve, to get a before/after comparison, or a trail/no trail comparison.

- **Early detection of invasive or ruderal plant species dispersal.** As a precautionary measure, monitor the trailside vegetation yearly to detect the arrival of new plant species, in particular invasive alien species or ruderal species, that might have been spread by the trail users.
    (a) In case of detection of new invasive alien/ruderal plant species, take action against them, develop measures to limit the risk of spread (e.g. cleaning shoes and bikes before/after ride), and develop a monitoring program to assess whether mountain bikes act as vectors of seed dispersal and how.

4. References

Ansong, M. & Pickering, C. (2014) Weed seeds on clothing: A global review. Journal of Environmental Management, 144, 203–211.

Anthony, R. G., Steidl, R. J., & McGarigal, K. (1995). Recreation and bald eagles in the Pacific Northwest. Wildlife and Recreationists: Coexistence Through Management and Research. Island Press, Washington, 223-241.

Arroyo, B. & Razin, M. (2006) Effect of human activities on bearded vulture behaviour and breeding success in the French Pyrenees. Biological Conservation, 128, 276–284.

Ballantyne, M., Gudes, O., & 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.

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

Ballantyne, M. & Pickering, C.M. (2015b) The impacts of trail infrastructure on vegetation and soils: Current literature and future directions. Journal of Environmental Management, 164, 53–64.

Bar (Kutiel), P. (2017) Visitor trampling impacts on soil and vegetation: the case study of Ramat Hanadiv Park, Israel. Israel Journal of Plant Sciences, 1–17.

Bélanger, L. & Bédard, J. (1990) Energetic Cost of Man-Induced Disturbance to Staging Snow Geese. The Journal of Wildlife Management, 54, 36–41.

Bjorkman AW (1996) Off-Road Bicycle and Hiking Trail User Interactions: A Report to the Wisconsin Natural Resources Board. Wisconsin Department of Natural Resources, Bureau of Research.

Burgin, S. & Hardiman, N. (2012) Is the evolving sport of mountain biking compatible with fauna conservation in national parks? Australian Zoologist, 36, 201–208.

Cessford, G., New Zealand, & Department of Conservation (1995) Off-road impacts of mountain bikes: a review and discussion. Head Office, Dept. of Conservation, Wellington, N.Z.

Cole, D.N. (1987) Effects of three seasons of experimental trampling on five montane forest communities and a grassland in Western Montana, USA. Biological Conservation, 40, 219–244.

Crisfield, V.E., Macdonald, S.E., & Gould, A.J. (2012) Effects of Recreational Traffic on Alpine Plant Communities in the Northern Canadian Rockies. Arctic, Antarctic, and Alpine Research, 44, 277–287.

Davies, C. & Newsome, D. (2009) Mountain bike activity in natural areas: impacts, assessment and implications for management: a case study from John Forrest National Park, Western Australia. CRC for Sustainable Tourism,

Davis, C.A., Leslie, D.M., Walter, W.D., & Graber, A.E. (2010) Mountain Biking Trail Use Affects Reproductive Success of Nesting Golden-Cheeked Warblers. The Wilson Journal of Ornithology, 122, 465–474.

Davis, C.A., Leslie Jr, D.M., & Hayden, T. (2008) Effects of mountain biking activity on foraging and nesting behavior of Golden-cheeked Warblers. Final Report, Project Number MIPR, .

Gander, H. & Ingold, P. (1997) Reactions of male alpine chamois Rupicapra r. rupicapra to hikers, joggers and mountainbikers. Biological Conservation, 79, 107–109.

Garber, S.D. & Burger, J. (1995) A 20-Yr Study Documenting the Relationship Between Turtle Decline and Human Recreation. Ecological Applications, 5, 1151–1162.

George, S.L. & Crooks, K.R. (2006) Recreation and large mammal activity in an urban nature reserve. Biological Conservation, 133, 107–117.

Goeft, U. (1999) Managing mountain bike impacts in the south west of Western Australia: Combining biophysical impact studies with rider preferences for better trail design. .

Goeft, U. & Alder, J. (2001) Sustainable mountain biking: a case study from the southwest of Western Australia. Journal of sustainable tourism, 9, 193–211.

Gutzwiller, K. J. (1995). Recreational disturbance and wildlife communities. Wildlife and recreationists: Coexistence through management and research, 169-181.

Hagen, S. & Boyes, M. (2016) Affective ride experiences on mountain bike terrain. Journal of Outdoor Recreation and Tourism, 15, 89–98.

Hardiman, N., Dietz, K.C., Bride, I., & Passfield, L. (2017) Pilot Testing of a Sampling Methodology for Assessing Seed Attachment Propensity and Transport Rate in a Soil Matrix Carried on Boot Soles and Bike Tires. Environmental Management, 59, 68–76.

Hockin, D., Ounsted, M., Gorman, M., Hill, D., Keller, V., & Barker, M.A. (1992) Examination of the effects of disturbance on birds with reference to its importance in ecological assessments. Journal of Environmental Management, 36, 253–286.

Jordan, M. (2000) Ecological impacts of recreational use of trails: a literature review. The Nature Conservancy, New York, .

Kelly, C.L., Pickering, C.M., & Buckley, R.C. (2003) Impacts of tourism on threatened plant taxa and communities in Australia. Ecological Management & Restoration, 4, 37–44.

Kerlinger, P., Burger, J., Cordell, H. K., Decker, D. J., Cole, D. N., Landres, P., ... & Temple, S. (2013). Wildlife and recreationists: coexistence through management and research. Island Press.

Koemle, D.B.A. & Morawetz, U.B. (2016) Improving mountain bike trails in Austria: An assessment of trail preferences and benefits from trail features using choice experiments. Journal of Outdoor Recreation and Tourism, 15, 55–65.

Kueffer, C., Pyšek, P., & Richardson, D.M. (2013) Integrative invasion science: model systems, multi-site studies, focused meta-analysis and invasion syndromes. New Phytologist, 200, 615–633.

Kutiel, P., Eden, Z., & Zhevelev, H. (2001) The impact of motorcycle traffic on soil and vegetation of stabilized coastal dunes, Israel. Journal of Coastal Conservation, 7, 81–90.

Lathrop, J. (2003) Ecological impacts of mountain biking: a critical literature review. Wildlands CPR Report. 11pp, .

Liddle, M.J. Recreation Ecology. Chapman and Hall, London (1997)

Lonsdale, W.M. (1999) Global Patterns of Plant Invasions and the Concept of Invasibility. Ecology, 80, 1522–1536.

Marion, J.L. & Wimpey, J. (2007) Environmental impacts of mountain biking: science review and best practices. Managing Mountain Biking, IMBA's Guide to Providing Great Riding. International Mountain Bicycling Association (IMBA) Boulder, 94–111.

Miller, J.R. & Hobbs, N.T. (2000) Recreational trails, human activity, and nest predation in lowland riparian areas. Landscape and Urban Planning, 50, 227–236.

Miller, S.G., Knight, R.L., & Miller, C.K. (1998) Influence of Recreational Trails on Breeding Bird Communities. Ecological Applications, 8, 162–169.

Nathan, R. (2006) Long-Distance Dispersal of Plants. Science, 313, 786–788.

Naylor, L.M., J. Wisdom, M., & G. Anthony, R. (2009) Behavioral Responses of North American Elk to Recreational Activity. Journal of Wildlife Management, 73, 328–338.

Olive, N.D. & 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.

Papouchis, C. M., Singer, F. J., & Sloan, W. B. (2001). Responses of desert bighorn sheep to increased human recreation. The Journal of wildlife management, 573-582.

Pescott, O.L. & Stewart, G.B. (2014) Assessing the impact of human trampling on vegetation: a systematic review and meta-analysis of experimental evidence. PeerJ, 2, e360.

Pickering, C., Ansong, M., & Wallace, E. (2016) Experimental assessment of weed seed attaching to a mountain bike and horse under dry conditions. Journal of Outdoor Recreation and Tourism, 15, 66–70.

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

Pickering, C. & Mount, A. (2010) Do tourists disperse weed seed? A global review of unintentional human-mediated terrestrial seed dispersal on clothing, vehicles and horses. Journal of Sustainable Tourism, 18, 239–256.

Pickering, C.M., Castley, J.G., & Richardt, K. (2012) Informal trails fragmenting endangered remnant vegetation in Australia. 362–363.

Pickering, C.M., Hill, W., Newsome, D., & Leung, Y.-F. (2010b) Comparing hiking, mountain biking and horse riding impacts on vegetation and soils in Australia and the United States of America. Journal of Environmental Management, 91, 551–562.

Pickering, C.M., Rossi, S., & Barros, A. (2011) Assessing the impacts of mountain biking and hiking on subalpine grassland in Australia using an experimental protocol. Journal of Environmental Management, 92, 3049–3057.

Potito, A.P. & Beatty, S.W. (2005) Impacts of Recreation Trails on Exotic and Ruderal Species Distribution in Grassland Areas Along the Colorado Front Range. Environmental Management, 36, 230–236.

Spahr, R. (1990) Factors Affecting the Distribution of Bald Eagles and Effects of Human Activity on Bald Eagles Wintering Along the Boise River. Boise State University Theses and Dissertations, .

Stake, M. M. (2000) Impacts of mountain biking activity on golden cheeked warblers at Fort Hood, Texas." Endangered species monitoring and management at Fort Hood Texas: 2000 Annual Report (2000).

Steven, R., Pickering, C., & Guy Castley, J. (2011) A review of the impacts of nature based recreation on birds. Journal of Environmental Management, 92, 2287–2294.

Symmonds, M.C., Hammitt, W.E., & Quisenberry, V.L. (2000) Managing Recreational Trail Environments for Mountain Bike User Preferences. Environmental Management, 25, 549–564.

Taylor, A.R. & Knight, R.L. (2003) Wildlife responses to recreation and associated visitor perceptions. Ecological Applications, 13, 951–963.

Thurston, E. & Reader, R.J. (2001) Impacts of Experimentally Applied Mountain Biking and Hiking on Vegetation and Soil of a Deciduous Forest. Environmental Management, 27, 397–409.

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.

Weir, D.V. (2000) Impacts of non-motorized trail use. Edmonton, Alberta, Canada, .

Weiss, F., Brummer, T.J., & Pufal, G. (2016) Mountain bikes as seed dispersers and their potential socio-ecological consequences. Journal of Environmental Management, 181, 326–332.

White, D.D., Waskey, M.T., Brodehl, G.P., & Foti, P.E. (2006) A comparative study of impacts to mountain bike trails in five common ecological regions of the Southwestern US. Journal of Park and Recreation Administration, 24, 21–41.

Wilson, J.P. & Seney, J.P. (1994) Erosional Impact of Hikers, Horses, Motorcycles, and Off-Road Bicycles on Mountain Trails in Montana. Mountain Research and Development, 14, 77.

Wöhrstein, T. (1998). Mountainbike and Environment: Ecological Impacts and Use Conflict.

Ziener, K., & Brandenburg, C. (2007). Konfliktbewältigung und Konfliktprävention beim Management landschaftsbezogener Freizeit-und Erholungsaktivitäten. na.

5. Appendixes

Appendix 1 – Database of biophysical impacts of mountain biking on plants, soils and wildlife.

Appendix 1 – Excel database of the biophysical impacts of mountain biking on plants, soil and wildlife. Table adapted from Ballantyne et al. (Ballantyne & Pickering, 2015b) and extended.

Appendix 2 – Summary list of key mountain biking indicators per impact category

Table 2 Key indicators to assess the environmental impacts of mountain biking (adapted from Davies and Newsome, 2009)

Category of impact	Impact	Mountain bike indicator
Trail	Trail width	- Tread width
	Trail widening	- Maximum width of trail identified by tyre marks
	Informal trails	- Number, location and condition of trails
	Technical features	- Type, number, location
Soil	Soil compaction	- Penetrometer - Bulk density
	Soil erosion	- Trail incision depth - Soil loss - Soil moisture - Soil organic matter
Vegetation	Trampling	- Vegetation cover (overall or per structural levels) - Species composition (abundance, diversity) - Vegetation height - Plant stem density
	Seed dispersal	- Seed attachment rate - Seed attachment distance
Wildlife	Disturbance	- Activity budgets - Alert response - Reproductive success - Territory size - Predation rate
	Habitat alteration	- Index of fragmentation - Mapping of corridors
	Mortality	- Number of collisions