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Ecological impacts of (electrically assisted) mountain biking

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ABSTRACT

Mountain biking (MTBing) has become one of the most popular recreational activities and this trend is further amplified with the enhanced use of electrically assisted mountain bikes (eMTBing). While increasing user frequencies are intensifying social and environmental conflicts, the consequences of MTBing in and for the environment are insufficiently understood. The aim of this review is to outline the ecological impacts of conventional mountain biking and to highlight potential differences and consequences arising with the use of eMTBs.

The results systematically summarise how MTBing can lead to immediate responses of animals, changes in habitat use and diurnal activity patterns of wildlife, a reduced reproductive success, seed dispersal, trampling damage on flora, vegetation changes in areas adjacent to trails, as well as soil compaction, exposure and erosion. The increasing use of eMTBs will cause a larger frequency and spatial cover by bikers and therefore a rising number of trails. Wildlife will be more affected when off-trail riding increases or when the use of so far less frequented areas or times will intensify. Vegetation and soil will be more affected, when new trails are created. Both aspects are more likely with the switch to eMTBing as steep slopes are climbed faster and more frequently. However, these direct effects of MTBing may not be associated with negative long-term consequences for ecosystems as those depend on the specific species or subjects of protection, the environmental context and possible interactions with other human activities. Overall, long-term consequences for plants and animals are difficult to assess and thus general patterns of how the direct effects of (e)MTBing translate into consequences for population dynamics are yet missing. It is essential to improve the knowledge regarding long-term effects of (e)MTBing on the population and ecosystem level and societal debates regarding (e)MTBing need to differentiate effects relevant for animal welfare from implications for nature conservation.

1. Introduction

Using electrically assisted mountain bikes (eMTB) is an increasing trend in outdoor recreational activities (Pröbstl-Haider et al., 2018, Schlemmer et al., 2019, Mitterwallner et al., 2021, Moesch et al., 2022). Both MTBs and eMTBs can impact ecological systems, but due to the differences from conventional MTBs and its huge growth rate, eMTBs have a higher potential for ecological impacts on soil, vegetation and wildlife.

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After the development of e-bikes in the early 1980 s in Japan (Parker, 2006), the fastest increase in popularity occurred in the second decade of the 21st century and the e-bike became a substantial part of the bicycle market of many countries. A considerable share of these pedelecs is used for commuting, but growing interest for electrical assistance in leisure activities such as mountain biking is accelerating this trend additionally (Fig. 1). Electrical assistance is additionally opening mountain biking for a wider and more numerous user group (Moesch et al., 2022). From 2015–2021 the sales numbers of eMTBs increased 15.4 times in France, 6.8 times in Switzerland and 15.9 times in Germany (Fig. 1).

The eMTB boom can be observed not just by increasing sales numbers, but also in the media and the tourism industry. In November 2021, more than 453 000 pictures on instagram have been tagged with the hashtag „#emtb", demonstrating the dimension of the community. Print media such as the „E-MOUNTAINBIKE Magazin" (since 2012), or the „EMTB" (since 2016), as well as „The most beautiful e-MTB tours in the Alps" (3rd edition, translated from German; Herb and Simon, 2020) mirror this trend. The tourism industry has recognized the huge economic potential of electrically assisted mountain biking and is promoting this activity by providing an infrastructure for eMTBs (Klöpfer, 2020) as well as advertising the excellent conditions for this sport in the alpine region (e.g.

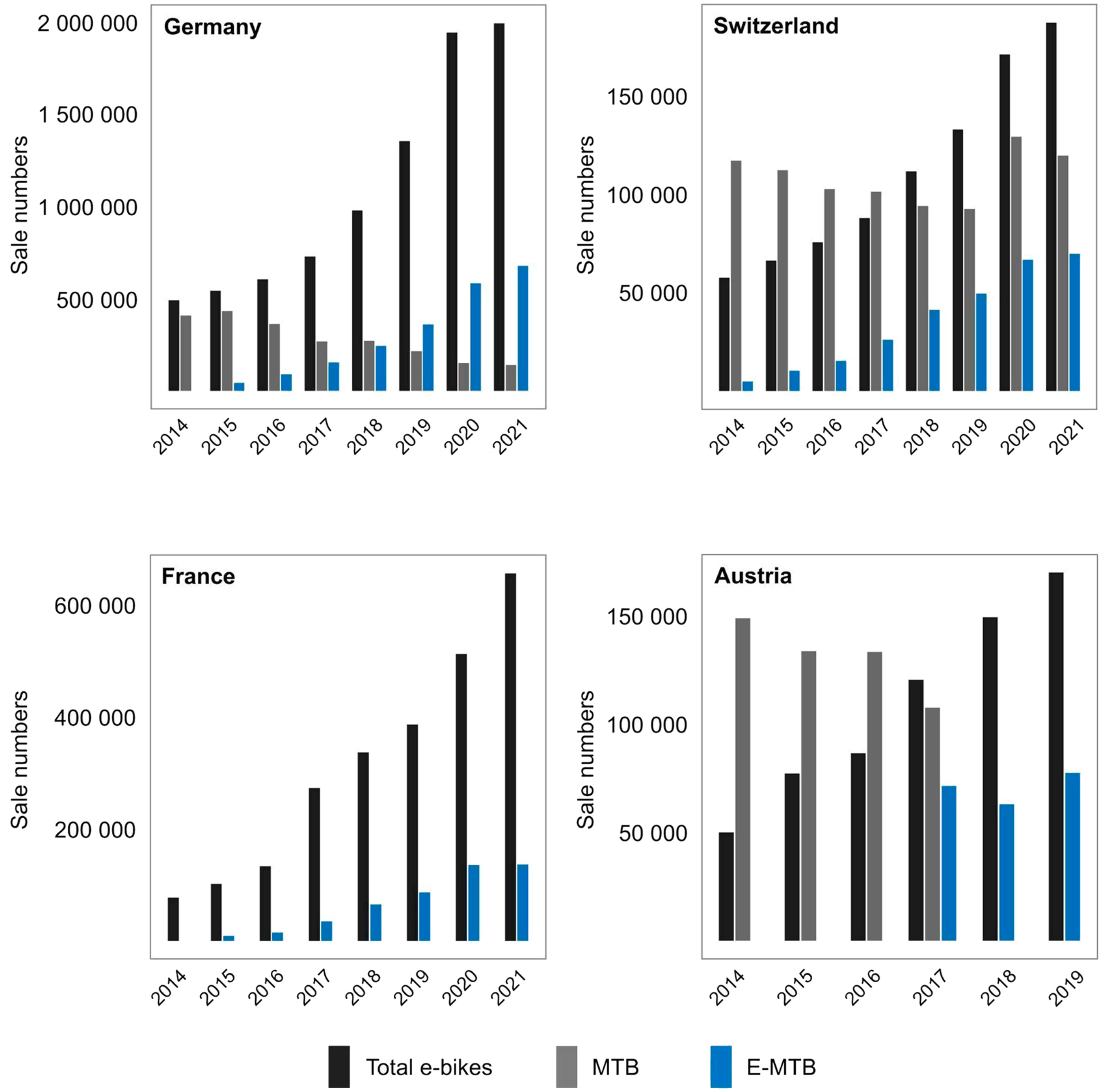

Fig. 1. Sales numbers of e-bikes in total, eMTBs and conventional MTBs in different European countries from 2014 to 2021. Sales numbers of e-bikes in total and eMTBs increased in every country (for Austria numbers for 2020 and 2021 are not available and numbers for eMTBs are available from 2017), whereas sales numbers of conventional MTBs decreased (numbers for MTBs in France are not available; VSSÖ Verband der Sportartikelerzeuger und Sportausrüster Österreichs, 2014, 2015, 2016, 2017, 2018, 2019, UNIVELO, FPS, 2015, 2016, UNIVELO, Union Sport and Cycle, 2017, 2018, "Union Sport and Cycle", 2019, 2020, 2021, 2022, ZIV Zweirad-Industrie-Verband, 2016a, 2016b, 2017a, 2017b, 2018a, 2018b, 2019, 2020, 2021, 2022, ZFVE Schweizer Fachstelle für Velo und E-Bike, 2016, 2017, 2018, 2019, 2020, 2021, 2022a, 2022b).

Surselva Tourismus AG, 2020). In a trend report from 2018, the eMTB is seen as a new possibility to considerably expand MTB tourism in Austria (Oberösterreich Tourismus, 2018).

Mountain biking is particularly attractive in landscapes with high topographical diversity, but hence, resulting in direct disturbances of ecologically valuable ecosystems. As technology in the outdoor sport industry advances (e.g. better clothing, lighter gear, cheaper and faster transportation, easier orientation and navigation), areas that used to be protected by their inaccessibility, are increasingly reached (Turner, 2002; Shultis, 2015; Stinson, 2017) and electrical assistance in MTBs further enhances this potential. At the same time, however, people seek naturalness and natural beauty for recreation (Gobster, 1995; Goossen and Langers, 2000), which is particularly the case in ecosystems that are comparably less affected by anthropogenic use. Hence, it is crucial to understand the environmental impacts of eMTBing, but so far, research on environmental impacts of mountain biking is focusing on conventional MTBs (see e.g. Cessford, 1995a, Lathrop, 2003, Marion and Wimpey, 2007, Newsome, 2010, Quinn and Chernoff, 2010, Hardiman and Burgin, 2013, Grapentin et al., 2018). Effects are often differentiated into impacts on soil, vegetation and wildlife.

Although eMTBs are known to differ in technological features as well as in riding motives and behaviour of the users (cf. Mitterwallner et al., 2021), to date, research on the ecological impacts of eMTBing is lacking. In 1996 Deborah Chavez wrote „*what we learn about mountain bike use may assist us in preparing for future technological advances*" ((Chavez, 1996), p. 10). In this study, we follow this idea and outline how conventional MTBs and MTBing are affecting ecological systems, comparing conventional and electrically assisted MTBs (equipment, the latter with additional weight and torque) and MTBing (persons and their use behaviour) and thus assessing potential differences of both types of MTBing in regard to their environmental impact. By this, we want to provide a robust base for decision-making in policy and other stakeholders as well as reveal knowledge gaps, where further research is needed.

2. Materials and methods

In order to compile existing knowledge on the effect of MTBing on ecological systems, a systematic literature review was conducted (Fig. 2). Research papers in the English language were obtained by searching electronic databases (Web of Science, Google Scholar and Science Direct) from February until July 2020. Key terms used were "mountain bik* " or "mountain bik* + impact" as well as "e-mountain bik* ", "e-mountain bik* + impact". In Web of Science the results were further categorised in "environmental sciences", "environmental studies", "geosciences multidisciplinary", "geography", "ecology", "forestry", "ornithology", "green sustainable

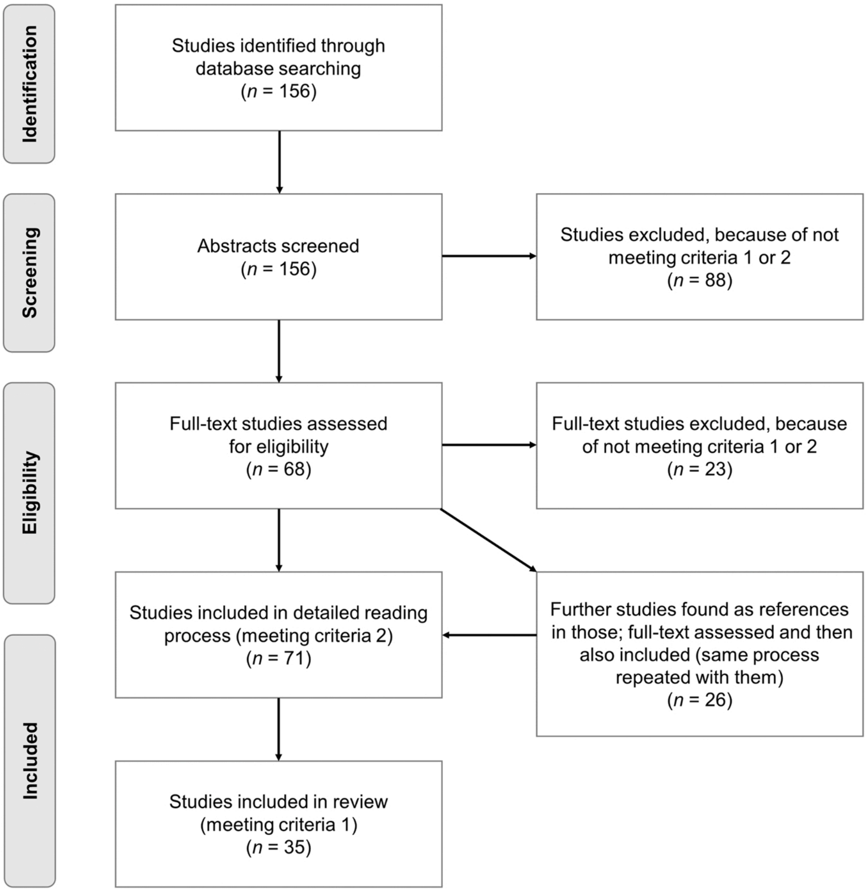

Fig. 2. Flow chart showing the systematic search and review process.

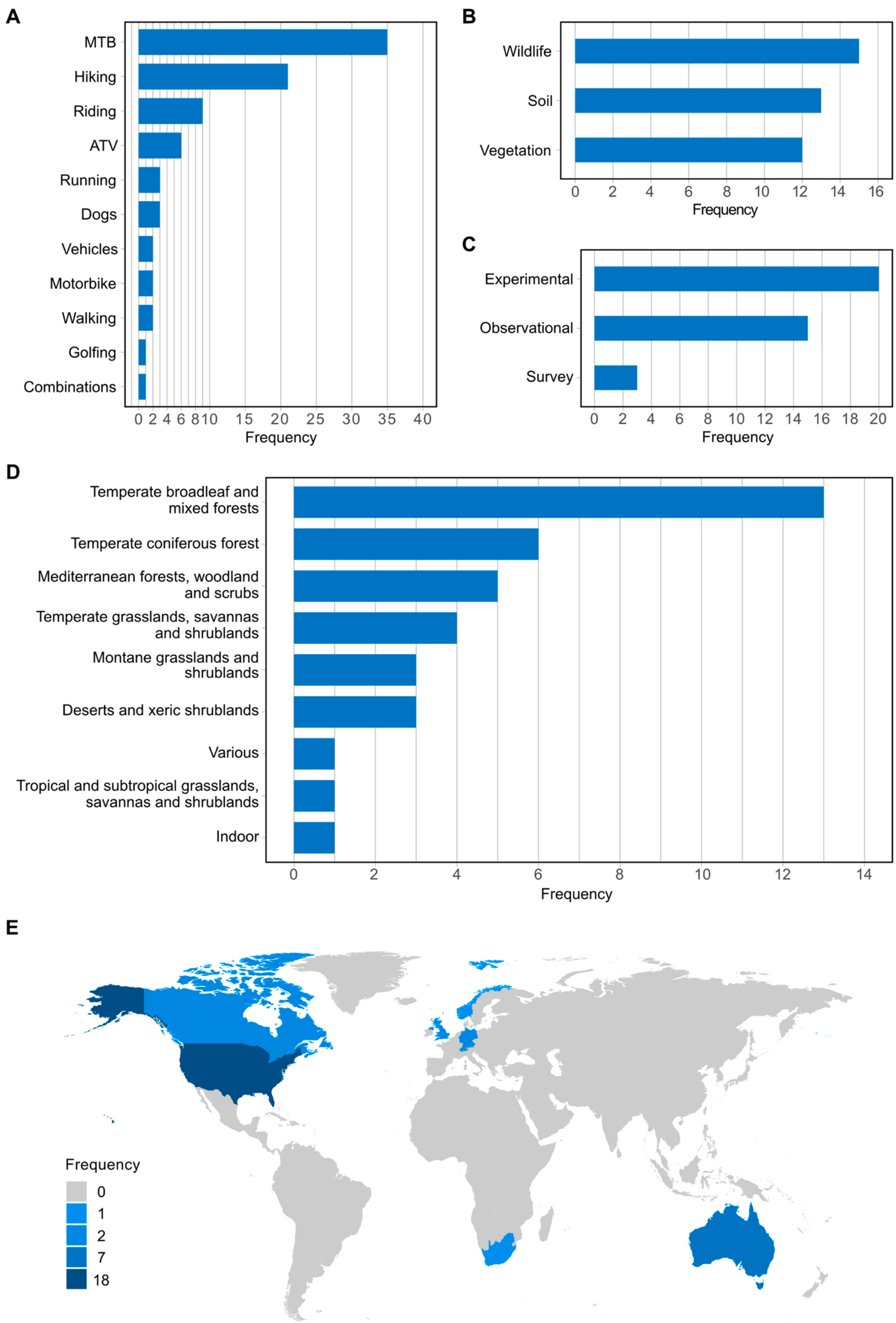

Fig. 3. Data overview over the quantitative synthesis. A) Frequency of the activities studied. „Combination“ means that a combination of activities taking place at the same time was studied; B) Frequency of the ecosystem agents studied; C) Frequency of the methodological approach used; D) Frequency of the habitat types the study site was located in (after the World Wide Fund for Nature 2020 (World Wildlife Fund, 2001), with the category „Indoor“ added by the authors); E) World map showing the frequency of study sites located in the country.

science technology", "geography physical", "biology", "biophysics", "engineering environmental", "imaging science photographic technology", "biodiversity conservation" or "zoology". In Google Scholar search results have been included until page 100 (= 1000 results).

Search records were screened and those not meeting one of the following criteria were excluded, using the title first, followed by the abstract: (1) The impact of (**e**)MTBing on the environment was part of the focal study and considered separately from other activities. (2) The study helps to critically examine the effect of (e)MTBing on the environment, or to develop a future perspective. All those that meet criterion 1 also meet criterion 2. Thus, criterion 1 is a subset of criterion 2 (Fig. 2; see Table A1 in Supplementary material for a list of all included and excluded studies). Studies that met just criterion 2, but not criterion 1 for example were literature reviews, some studies on the preferences and behaviour of mountain bikers or studies on the general effects of recreationists. Due to the vast number of studies, only those promising to fulfil criterion 2 to a high degree were included. The subsequent detailed reading process included studies that met criterion 1 and 2, while only studies that met criterion 1 were included in the review. Suitable references that were found in the studies during the detailed reading process were integrated in the process. Grey literature (i.e. conference proceedings, study reports) that was regarded as suitable was generally included (n(grey total) = 13, n(grey criterion 1) = 4), as it provides important insights in this applied research field and is often cited in peer-reviewed papers.

This approach only partly follows the standard PRISMA protocol because our goal was to represent the scientific literature as complete as possible, both quantitatively (1) and qualitatively (2). Whether studies meet criterion 1 (MTBing and environment part of the study) can be answered unequivocally. This part of the review is thus reproducible. However, the evaluation of criterion 2 (study helps to understand the effect of MTBing on the environment) depends on current knowledge. Including these studies allowed us to gain a much more comprehensive understanding of the topic. We are convinced that this approach yielded the best possible result for our work and thus for the scientific community, especially because this is such a multidisciplinary field.

While screening the search results of the electronic databases, 156 studies were classified as relevant based on their title. Of these, 88 were excluded after reading the abstracts because of not meeting criteria 1 or 2. The remaining 68 studies were full-text assessed for eligibility and 23 were excluded because of not meeting the criteria. During the detailed reading process of the remaining papers, 26 further studies that were found as references in those were judged as relevant after full-text assessing. As a result, 71 studies were included in the detailed reading process (meeting criteria 1 and/or 2) and of those, the 35 that only met the criterion 1 were included in the review (Supplementary material, Table A2). In this search process, only two studies were identified dealing with eMTBs (Pröbstl-Haider et al., 2017; Schlemmer et al., 2019), but not specifically with their environmental impacts.

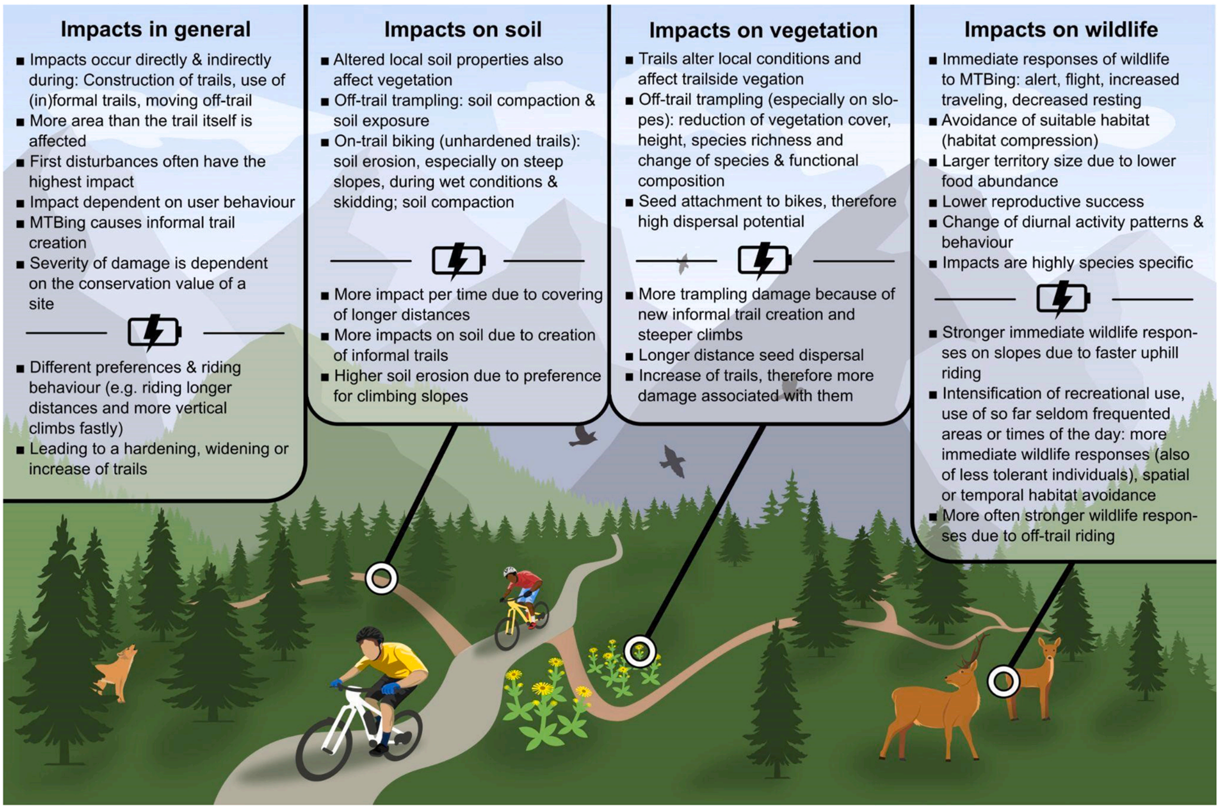

Fig. 4. Impacts of conventional mountain biking on ecosystems and the potential consequences of electrically assisted mountain biking. The upper part of each box summarises the findings of the literature review, whereas the lower part beneath the battery summarises **potentially** arising consequences of the e-assisted riding, which were discussed in this review.

Fig. 3 shows a quantitative synthesis of the studies included in the review. The literature review revealed an existing research bias towards studies in North America (n = 20), Australia (n = 7) and Europe (n = 7). Most studies not only target MTBing but also other recreational activities (e.g. hiking) and compared their ecological impact.

3. Overview and structure

Interactions of mountain biking and the environment are manifold. In order to emphasise the main study fields, we provide an literature-based overview on the main findings regarding MTB effects on environmental factors. As literature on eMTBing is currently limited, we will highlight the most important differences between traditional MTBing and eMTBing and draw conclusions through analogy. Our further goal was to identify research gaps regarding common and differing environmental impacts of both (e)MTBing types.

Terrestrial outdoor activities such as mountain biking are interacting with the lithosphere, the biosphere and the atmosphere. Direct or indirect effects of mountain biking can thus be observed on either soil, vegetation or wildlife (Hammitt et al., 2015; Huddart, Stott, 2019). Prominent findings include vegetation removal on trails and altered species composition, species richness and vegetation cover along trails as well as the potential of MTBs to contribute to seed dispersal (Bjorkman, 1998; Thurston and Reader, 2001; Pickering et al., 2011; Havlick et al., 2016; Pickering et al., 2016; Weiss et al., 2016; Hardiman et al., 2017). Soil properties are changing towards higher compaction and higher erosion on trails (Wilson and Seney, 1994; Bjorkman, 1998, Goeft and Alder, 2001, Thurston and Reader, 2001, Chiu and Kriwoken, 2003, Lei, 2004, White et al., 2006, Martin et al., 2018). A direct impact on wildlife is a higher alert and flight response, whereas indirect responses result in spatiotemporal avoidance of trails with potentially reduced habitat size or habitat suitability and towards nocturnality shifted activity patterns (Gander and Ingold, 1997; Papouchis et al., 2001; Taylor and Knight, 2003; Wisdom et al., 2004; George and Crooks, 2006; Naylor et al., 2009; Wyttenbach et al., 2016; Coppes et al., 2017; Lowrey and Longshore, 2017; Scholten et al., 2018; Wisdom et al., 2018; Fig. 4). The most general impact is how trail networks are used and by this, potentially extended. However, most effects are resulting not solely from mountain biking as trails are mostly constructed for and used by also other recreational activities. More severe consequences therefore occur through off-trail trampling or riding and the formation of informal trails, which are further fragmenting habitats and increasing the area used by recreational activities (Newsome and Davies, 2009; Ballantyne and Pickering, 2015a). Moreover, findings show that responses of wildlife species are highly species-specific and so far, studies are biased towards carnivorous, mesocarnivorous and herbivorous mammals (i.e. no study on invertebrates or reptiles; Burgin and Hardiman, 2012). While individuals are obviously disturbed, there is so far only scarce evidence for lower reproductive success or declining populations as a result of mountain biking activity.

In general, the severity of the impacts of mountain biking highly depends on the behaviour and trail preferences (e.g. staying on trails) of bikers, which is formed by intrinsic (e.g. athletic ambition) and extrinsic (e.g. Instagram photos) motives, but also technical possibilities. Whereas there are no major differences in motivational patterns of eMTBers and conventional MTBers, they differ in their sociodemographic backgrounds and their physical activity levels (Schlemmer et al., 2019; Moesch et al., 2022). Mountain bikers using electrical assistance „*showed a higher mean age, [.] a lower general level of education, a higher percentage of retirees, and a lower level of physical activity*“ (Schlemmer et al., 2019, p. 3) compared to conventional mountain bikers, what might have an impact on where and how they can go by bike. Concerning trail preferences, MTBers generally desire vertical climbs and singletrails (Cessford, 1995b; Symmonds et al., 2000; Goeft and Alder, 2001; Ramthun and Armistead, 2001; Morey et al., 2002). However, riders choose short trails, when it is steep and longer trails, when it is flatter (Morey et al., 2002) and less experienced and/or older riders prefer gradual and less steep uphills (Cessford, 1995b; Symmonds et al., 2000). Although this seems to indicate less preference of steep and long trails for the group of eMTBers due to their often higher age and lower experience, mountain bikers tended to prefer steeper and longer trails with electrical assistance as opposed to conventional MTBs (Mitterwallner et al., 2021). Likewise, this trend is supported by an example from the eMTB industry, which aims to enhance the flow experience while riding uphill instead of downhill (Bosch, 2017). In addition, trail length is considered as something positive by conventional MTBers, but just up to a certain point and it is closely connected to the vertical climb and the individual limits (Morey et al., 2002; Koemle and Morawetz, 2016). As those limits are shifted when using electrical assistance this might similarly indicate a preference for longer distances. The behaviour and the trail preference of eMTB users will hence, highly depend on the sociodemographic background as well as on the intrinsic motives, but have the potential to shift riding behaviour towards longer distances and steeper climbs.

In the following we thus report the findings of research on how MTBing is affecting soil, vegetation and wildlife followed by a discussion of potential changes regarding the impacts with the switch towards eMTBing. Henceforth, **eMTBing** is highlighted in order to facilitate the discrimination between MTBing and **eMTBing.**

4. General impact of trails

Environmental damage starts with the initial trail construction, which can have a more significant impact than the subsequent use of trails (Hennings, 2017). This accounts not only for officially constructed trails, but similarly, for informal trails, which are formed via trampling activities and are often less destructive (Havlick et al., 2016). At established trails, direct impacts on the trail are accompanied by indirect effects such as littering near the trail (McDougall and Wright, 2004; Potito and Beatty, 2005; Hamberg et al., 2008; Ballantyne and Pickering, 2015b).

Existing MTB trail networks often increase with the development of new, partly informal, trails (Ballantyne and Pickering, 2015a; Havlick et al., 2016; Korpilo et al., 2018). The resulting large and complex trail networks have cumulative impacts (Ballantyne and Pickering, 2015a). There are three possible ways of **eMTBs** causing an increase of existing MTB trail networks: 1) New formal trails are built for **eMTBers**. 2) New formal trails are built also for other recreationists, because **eMTBers** increase the total number of visitors and therefore create a higher demand for trails. 3) **eMTBers** increase the number of informal trails (directly or indirectly). In fact, reports from Austria show that the **eMTB**-boom of the last years already resulted in the construction of new trails in order to increase touristic offers in these areas (personal information from tourism agencies for the European Alps).

5. Impacts on soil

5.1. General impacts of recreational activities on soil

Soil gets compacted during trail construction, but the hardening process will decrease soil loss during the subsequent trail use (Wimpey and Marion, 2010; Ballantyne and Pickering, 2015a). When formal trails are hardened, the impacts on soil depend on the methods and materials used for hardening (i.e. tarmac, gravel, boardwalk). Informal trails, however, are initially formed by trampling, which is a well studied process and known to progressively cause consecutive impacts (Hennings, 2017; Martin and Butler, 2017; Pickering and Norman, 2017). Soil is compacted (Bjorkman, 1998; Thurston and Reader, 2001; Lei, 2004; Martin et al., 2018), litter removed (Thurston and Reader, 2001) and the vegetation cover decreases (Bjorkman, 1998; Thurston and Reader, 2001; Pickering et al., 2011; Havlick et al., 2016).

Protective layers of soil will be lost as a consequence of regular trampling (Thurston and Reader, 2001), and thus a typical long-term effect of unhardened trails is soil erosion (Newsome and Davies, 2009; Ballantyne and Pickering, 2015a; Salesa and Cerdà, 2020) and incision, especially on steeper slopes (Marion and Olive, 2006). Other common long-term effects are trail widening (Goeft and Alder, 2001; Wimpey and Marion, 2010), the change of soil pH and the reduction of microbial biomass (Malmivaara-Lämsä et al., 2008). The latter has been shown to occur even up to a distance of 20 m from the trail (Malmivaara-Lämsä et al., 2008).

Importantly, as vegetation loss impacts the soil (Dadkhah and Gifford, 1980), damaged soil inversely results in hampering the recovery of vegetation (Keesstra et al., 2016). Soil compaction changes the soil structure and hydrology in several ways, for example through a lower soil porosity, aeration and infiltration (Dadkhah and Gifford, 1980; Kozlowski, 1999). These changes in turn, lead to a reduced vegetation growth and reproductive success, due to physiological dysfunctions (Kozlowski, 1999) such as reduced nutrient and water absorption and reduced root growth (Cambi et al., 2017; Correa et al., 2019).

Table 1
Overview of studies on the impacts of MTBing on soil. Decrease (↓), increase (↑), unaffected (→); effect greater (>) smaller (<), or equal (≙).

Study	Activities studied	Type of study	Study topics (among others)	Main results regarding MTBing (or comparison with other activities)
Bjorkman (1998)	MTB	Obs.	Initial trampling effects on soil; effects of on-trail MTBing on soil	Soil compaction especially high during the first thousands passes (90 000 in total); similar pattern for soil erosion on slopes (no soil erosion on flat sections)
Chiu and Kriwoken (2003)	MTB, hiking	Exp.	Effects of on-trail activities on soils	Soil erosion : MTB ≙ hiking; especially strong effects on slopes & during wet conditions; skidding as MTB-specific damage strongest of all effects
Goeft and Alder (2001)	MTB	Obs.	Effects of on-trail MTBing on soils	Higher soil erosion on new trail sections (except uphills), downhill slopes & curves; higher soil compaction on old trail features; no trail widening during one year
Lei (2004)	MTB, hiking, vehicles, motorcycling	Exp.	Initial trampling effects on soil	All activities: soil compaction (↑), bulk density (↑), percent pore space (↓); vehicles > MTB ≙ motorcycles > hiking
Martin et al. (2018)	MTB, cyclocross biking, hiking	Exp.	Initial trampling effects on soil	(Soil compaction after 400 passes: MTB ≙ CX, biking ≙ hiking)
Newsome and Davies (2009)	MTB	Obs.	Effects of on-trail MTBing on soils	Tyre ruts & skid marks on informal trails
Olive and Marion (2009)	MTB, hiking, riding, ATV, mixed use	Obs.	Effects of on-trail activities on soils	Soil erosion : ATV > riding ≙ mixed use > hiking ≙ MTB; trail grade (among other factors) determined amount of impact
Thurston and Reader (2001)	MTB, hiking	Exp.	Initial trampling effects on soil	Soil exposure at high use intensities (500 passes): MTB > hiking; at low use intensities similar
White et al. (2006)	MTB	Obs.	Effects of on-trail MTBing on soils	Highest soil erosion on steep slopes and in an ecoregion with erodable soils and less vegetation; greatest trail width also in this ecoregion
Wilson and Seney (1994)	MTB, hiking, riding, motorcycling	Exp.	Effects of on-trail activities on soils	Soil erosion/compaction: riding > hiking > motorcycling > MTB; especially prone to erosion: steep slopes, clay or sandy clay soils, wet conditions

5.2. Impacts of MTBing and eMTBing on soil properties

The following section summarises the existing evidence for impacts of mountain biking on soil properties (Table 2). Studies targeted the effects of MTBing on soil erosion, compaction and exposure in the initial construction of formal and informal trails as well as on already existing trails. Generally, knowledge on water runoff resulting from MTBing activities on trails and its consequences for soils is lacking (Cooke and Xia, 2020). In addition, no studies examined differences of effects on soils between MTB and **eMTB** and hence, the following discussion is based on differences in riding preferences and technical properties of both bike types.

5.2.1. Initial trampling effects

Initial trampling effects of MTBing on soil was investigated regarding soil compaction (Lei, 2004; Martin et al., 2018) and soil exposure (Thurston and Reader, 2001; Table 1) following a standard experimental procedure, where predefined lanes without recreation history are exposed to different MTBing intensities (0, 25, 75, 200, 500 passes; Cole and Bayfield, 1993). Study results agree that MTBing causes soil compaction (Bjorkman, 1998; Lei, 2004; Martin et al., 2018) and that the effect occurs faster than it does due to hiking (Lei, 2004; Martin et al., 2018). Whether soil compaction by **eMTBs** is more intense as a result of higher weight and hence, a higher contact pressure compared to MTBs is unclear. Although compaction by motorcycling was found to be similar to MTBing (Lei, 2004), wider tyres might have counteracted the higher weight of motorbikes, compared to MTBs. Cyclocross (CX) bikes with narrower tires and thus a higher contact pressure, are compacting soil slightly more than MTBs (Martin et al., 2018). As **eMTBs** tend to use slightly wider tyres, future research needs to assess whether **eMTBing** on untrampled sites leads to a higher soil compaction than MTBing and should consider differences in biking behaviour and follow a standard experimental procedure to ensure comparability (Cole and Bayfield, 1993). Apart from the direct effect of soil compaction, it is similarly important to understand the risk of the formation of new trails by **eMTBing**. As soil on existing trails is already compacted, new trails might pose a greater threat for ecosystems.

The only study observing the increase of soil exposure following MTBing revealed a higher impact occurring from MTBing compared to hiking at high use intensities (Thurston and Reader, 2001). The experimental trails did not include steep slopes and passages of braking, or skidding, which potentially cause even higher amounts of soil exposure compared to flat sections. Assuming that **eMTBers** climb steep slopes more often compared to conventional MTBers, they likely cause a higher risk for impacts on soil exposure and initial soil erosion (Bjorkman, 1998).

5.2.2. On-trail effects on soil erosion and compaction

MTBing is causing soil erosion, and especially steep slopes increase the erosion rate (Wilson and Seney, 1994; Bjorkman, 1998; Goeft and Alder, 2001; Chiu and Kriwoken, 2003; White et al., 2006; Newsome and Davies, 2009; Olive and Marion, 2009). An **electrical** engine might change trail preferences of bikers in a way that steeper trails are preferred and therefore, soil erosion is potentially higher. However, uphill **eMTBing** might differ from conventional MTBing and so far, it is unclear how such a difference translates into effects on soil erosion. It is likely that the increased power on the back-wheel and the resulting stronger torque might lead to a higher risk of wheel spinning and therefore a higher impact on soil erosion. Nonetheless, also the opposite is possible, since the torque might be more constant compared to the fluctuations from human-powered uphill riding.

Compared to other recreational activities, MTBing has less impact on soil erosion (Wilson and Seney, 1994; Olive and Marion, 2009) or similar impacts as hiking as long as skidding and wet conditions are avoided, which highly affect soil erosion (Wilson and Seney, 1994; Chiu and Kriwoken, 2003). Whether **eMTBers** skid more often while riding than conventional MTBers is unknown. Technical riding skills reduce soil erosion (Cessford, 1995a; Goeft and Alder, 2001; Chiu and Kriwoken, 2003), but to date there are no studies on **eMTBers**' technical abilities. As **eMTBers** may partly be less experienced, many possibly lack technical riding skills which enable them to avoid skidding. It is similarly unknown whether **eMTBer** are riding more often under wet conditions. It seems possible that the generally older and less physically fit user group (Schlemmer et al., 2019) avoids wet conditions, because of enhanced difficulties during riding. This needs to be verified by scientific data.

Direct soil compaction measurements revealed that compaction occurs on MTB trails (Bjorkman, 1998, Goeft and Alder, 2001) and old trail sections are generally more compacted (Goeft and Alder, 2001). Moreover, soil compaction follows a curvilinear asymptotic trend (Bjorkman, 1998). Therefore, on already established and used trails **eMTBing** will most probably not relevantly increase the compaction.

Future research needs to clarify the ways in which on-trail **eMTBing** is associated with soil erosion. Studies should include the impact on slopes as well as of skidding and during wet conditions on untrampled sites and already established trails. In order to evaluate the actual impact on soils, enhanced knowledge on the riding behaviour and trail preferences of **eMTBers** is needed.

5.2.3. Trail width and widening effects

MTBing is unlikely to contribute to trail widening (Bjorkman, 1998; Goeft and Alder, 2001; White et al., 2006). Steep slopes were associated with wider trails (Bjorkman, 1998), whereas in the southwestern U.S. no such relation between slope and MTB trail width was found (White et al., 2006). MTB trails were shown to be narrower than trails for hiking, horse riding or ATV driving (Marion and Olive, 2006), but this might be an effect of the frequency of the respective sports. Trail width differs between ecological regions (being widest in areas with sparse vegetation; White et al., 2006). However, trail widening did not occur after a trail was established (Bjorkman, 1998). Nevertheless, if steep slopes are related to wider MTBing trails (Bjorkman, 1998), **eMTBing** could increase the trail width in recreational areas, since they might climb steep slopes more often than conventional MTBers and since they may have less technical skills, due to their lower physical fitness and less experience (Schlemmer et al., 2019). In addition, **electrical** assistance highly supports overcoming obstacles, such as vegetation adjacent to trails, which could lead to a greater trail widening with time. However, to what extent **eMTBers** are widening trails needs to be the object of future studies.

6. Impacts on vegetation

6.1. General impacts of recreational activities on vegetation

Recreational impact on vegetation can be classified into two categories. Firstly, there are the impacts of trails on the flora during trail establishment as well as subsequently on the adjacent vegetation (Ballantyne and Pickering, 2015a; b; Pickering and Norman, 2017). During trail construction, plants are damaged and removed (Pickering and Hill, 2007). An established trail can change the microclimate and the light intensity (Cole, 1987, Yan et al., 2014, Kostrakiewicz-Gierałt et al., 2021). In addition, while the compaction or sealing of soil may alter drainage patterns, the missing vegetation cover can alter hydrological processes and trail users may serve as seed dispersers (Cole, 1987; Young and Mitchell, 1994; Ballantyne and Pickering, 2015a; b). All these processes also affect the adjacent vegetation in the way that, „*there can be changes [in] vegetation cover, plant height, abundance and composition along with the introduction and spread of weeds*“ (Pickering and Norman, 2017, p. 271).

Secondly, there are the direct impacts of trampling, when recreationists go off-trail (a process potentially causing informal trails; Bernhardt-Römermann et al., 2011, Pescott and Stewart, 2014, Martin and Butler, 2017). Off-trail trampling directly affects vegetation by damaging plant tissues, and indirectly through mostly soil compaction and its consequences, such as reduced water and nutrient availability (Kozlowski, 1999; Kissling et al., 2009). Eventually, the amount of damage depends on plants' resistance and resilience under the local environmental conditions as well as on process characteristics such as type, frequency or season (Bernhardt-Römermann et al., 2011; Pescott and Stewart, 2014). Similar to trampling effects on soil, the damage of vegetation is most severe at first trampling events and thereafter increases only marginally (Weaver and Dale, 1978; Bjorkman, 1998; Cole, 2004; Wimpey and Marion, 2010; Monz et al., 2013). However, the actual relevance of damage is highly dependent on the conservation value of the present species (Pickering, 2010) and small scale heterogeneity in disturbances may support the coexistence of different species and hence, species diversity.

6.2. Impacts of MTBing and eMTBing on vegetation

Similar as for other recreational activities, conventional MTBing affects vegetation by off-trail activities and by trail constructions

Table 2
Overview of studies on the impacts of MTBing on vegetation. Decrease (↓), increase (↑), unaffected (→).

Study	Activities studied	Type of study	Study topics (among others)	Main results regarding MTBing
Bjorkman (1998)	MTB	Obs.	Long-term trampling, off-trail trampling, trail widening	Devegetation on-trail; no significant veg. cover changes adjacent to trail; trampled trail width increased with slope & shade
Bouchard et al. (2015)	MTB, hiking, dog walking	Obs.	Seed dispersal potential	Seeds were carried by visitors
Goeft and Alder (2001)	MTB	Obs.	Off-trail trampling; trail widening	No vegetation changes within 2 m of trails during one year; no trail widening during one year
Hardiman et al. (2017)	MTB, hiking	Exp.	Seed dispersal potential	Seeds from the ground got attached and were transported
Havlick et al. (2016)	MTB, hiking, jogging	Exp.	Off-trail trampling	Veg. cover (↓), especially uphill
Marion and Olive (2006)	MTB, hiking, riding, ATV	Obs.	Trail width	MTB trails the narrowest among all types
Martin et al. (2018)	MTB, cyclocross biking, hiking	Exp.	Off-trail trampling	Veg. condition worsened (aerial imagery veg. assessment)
Pickering and Barros (2015)*	MTB, hiking	Exp.	Off-trail trampling	Community trait weighted means for: leaf area (↑), specific leaf area (↑), leaf dry matter content (↓), height (→)
Pickering et al. (2011)*	MTB, hiking	Exp.	Off-trail trampling	Veg. height (↓) & cover (↓); overlapping herb (↓), shrub (↓) & graminoid (→) cover; species richness (↓) & composition (affected)
Pickering et al. (2016)	MTB, riding	Exp.	Seed dispersal potential	Seeds in a pasture got attached and were transported
Thurston and Reader (2001)	MTB, hiking	Exp.	Off-trail trampling	Plant stem densitiy (↓), species richness (↓)
Weiss et al. (2016)	MTB	Exp.	Seed dispersal potential	Seeds from the ground got attached and were transported
White et al. (2006)	MTB	Obs.	Trail width	No relationship between slope & MTB trail width; greatest width in an ecoregion with erodable soils and less vegetation

*Studies based on the same experiment

(Table 2). The damage of plants together with altered soil properties (see 5.2) results in e.g. loss of vegetation cover, species richness and altered species composition (Bjorkman, 1998; Goeft and Alder, 2001; Thurston and Reader, 2001; Pickering et al., 2011; Pickering and Barros, 2015; Havlick et al., 2016; Martin et al., 2018). As a consequence of off-trail MTBing, informal trails emerge, which are known to affect species composition less than formal trails (Pickering and Norman, 2017). In some areas, informal trails may cover large areas and thus cause higher vegetation loss than formal trails (Ballantyne and Pickering, 2015a), but the removal of dominant plant species may be beneficial for other disturbance or light adapted species. Vegetation alongside the trail is additionally impacted by the dispersal of seeds transported via MTB tyres (Bouchard et al., 2015; Pickering et al., 2016; Weiss et al., 2016; Hardiman et al., 2017). However, the tyres of MTBs were shown to capture less seeds than walking shoes (Hardiman et al., 2017). The potential of MTBing for widening trails, is rather small (Bjorkman, 1998; Goeft and Alder, 2001; Marion and Olive, 2006; White et al., 2006). In the following, these effects are outlined more precisely and potential alterations for **electric assistance** are discussed.

6.2.1. *Direct off-trail trampling effects*

MTBing leads to significant impacts on vegetation (Bjorkman, 1998; Thurston and Reader, 2001; Pickering et al., 2011; Pickering and Barros, 2015; Havlick et al., 2016; Martin et al., 2018). Specifically, MTBing can lead to vegetation loss (Bjorkman, 1998; Thurston and Reader, 2001; Pickering et al., 2011; Pickering and Barros, 2015; Havlick et al., 2016), reduced vegetation height, altered species composition (Pickering et al., 2011), an affected Community Trait Weighted Means (CTWM) for leaf area and reduced relative cover of specific herb species (Pickering and Barros, 2015). Heterogeneous disturbances of dominant vegetation may allow the coexistence of more species, but studies also report loss in species richness (Thurston and Reader, 2001; Pickering et al., 2011). MTBing has a comparable trampling damage as other activities (Thurston and Reader, 2001; Havlick et al., 2016), but trampling experiments with spatially separated activities showed that MTBing at high use levels has a higher impact compared to hiking (Pickering et al., 2011; Pickering and Barros, 2015; also partly Havlick et al., 2016). The first MTB passes cause the greatest changes in vegetation cover, whereas an extremely high number of passes does not further increase the amount of damage. Trampling on vegetation adjacent to MTB trails is of minor concern (Bjorkman, 1998; Goeft and Alder, 2001).

All the outlined impacts scale up with biking frequency. Thus, since a mountain biker covers a longer distance in the same amount of time compared to a hiker, biking will overall result in a higher spatial impact. The electrical assistance allows **eMTBer** to ride even longer distances (Mitterwallner et al., 2021). Additionally, an **electrical** engine might change trail preferences of bikers in a way that steeper sections are preferred. As a result, impacts on vegetation would increase with **electrical** assistance of MTBs as the most concise trampling impacts of mountain biking occur on uphill sections (Pickering et al., 2011; Havlick et al., 2016). An increase in trampling impacts associated with higher weight (Pickering et al., 2010) is probably negligible as the weight difference between MTBs (circa 10–15 kg) and **eMTBs** (circa 20–30 kg) is relatively small. Thus, future research needs to compare the impacts of **eMTBing** and other activities (e.g. indicator-based assessment, cf. Leote et al., 2022). Studies on trampling impacts rarely differentiate between plant species and ignore other ground-living organisms like insects, for instance. Differentiating observable disturbances and vegetation removal from long-term effects on population dynamics and species composition is crucial as MTB impacts increase spatial heterogeneity and allow the coexistence of differently adapted species. Understanding such context dependent positive effects of MTB related disturbances while identifying species and ecosystems that are particularly susceptible is thus crucial for differentiated management of MTB activities.

6.2.2. *Seed dispersal and pathogen spread potential*

In experiments, plant seeds attached to MTB tyres (Pickering et al., 2016; Weiss et al., 2016; Hardiman et al., 2017) showed a higher attachment rate under semi-wet (Weiss et al., 2016) or wet (Hardiman et al., 2017) conditions. In a national park, however, MTBing was having the lowest seed dispersal potential compared to other activities (Bouchard et al., 2015, $n = 10$). Furthermore, similarly to other recreational activities, MTBing bears the potential to spread plant pathogens, such as the fungus *Phytophthora ramorum*, which causes the Sudden Oak Death (Cushman et al., 2007; Cushman and Meentemeyer, 2008).

A difference in seed transportation capacity between MTBing and **eMTBing** is unlikely since constructional differences are only marginal and riding under wet conditions presumably plays a minor role for both MTBer (Symmonds et al., 2000) and **eMTBer**. However, a high amount of seeds also attached to mountain bikes under dry conditions, when the bike was moved through seeding weeds on a pasture (Pickering et al., 2016), although this simulated activity is less common. Since **eMTBing** covers a greater distance in the same amount of time compared to conventional MTBing (Mitterwallner et al., 2021), **eMTBing** bears a higher chance to pick up seeds and disperse them over a larger area. Even a few seeds that are dispersed over long distances may severely affect ecosystems (Cain et al., 2000), with both positive and negative effects. Similar assumptions account for the spread of plant pathogens in soil on tyres (Cushman et al., 2007).

Future experimental research needs to investigate the difference in seed dispersal potential of conventional MTBing and **eMTBing** under several conditions (dry, wet, on-trail, off-trail; attachment and detachment rate). Cyclist surveys may further clarify how often **(e)MTBers** ride under wet conditions and how often and where they clean their bikes. Previous studies have highlighted the need for large sample sizes when quantifying attached seeds as well as the need for differentiating possible attachment sites (equipment, clothing, etc.). Seed transportation is particularly problematic if it helps potential invasive species to overcome natural barriers, when e.g. bikes are transported over large distances with cars.

6.2.3. *Impacts of formal and informal trails on vegetation*

As a consequence of reduced nurse shrub density and abundance on trails, the forest succession might be impacted negatively (Ballantyne and Pickering, 2015a), potentially resulting in a greater forest loss due to informal trails. Nevertheless, bare earth trails

Table 3
Overview of studies on the impacts of MTBing on wildlife. Decrease (↓), increase (↑), unaffected (→); effect greater (>) smaller (<), or equal (≙).

				Effect of MTBing on:		
Study	**Activities studied**	**Type of study**	**Species**	**Immediate responses (to activities in comparison)**	**Habitat use**	**Diurnal activity, behaviour & further**
Ciuti et al. (2012)	MTB, hiking, riding, ATV	Obs.	Elk (*Cervus elaphus*)			No general effect on: animal scan frequency; time of scanning, grooming, travelling
Coppes et al. (2017)	MTB, hiking	Obs.	Western capercaillie *(Tetrao urogallus)*		Avoidance of area close to trails; no effect on home range selection	
Davis et al. (2010)	MTB	Obs.	Golden-cheeked Warblers (*Dendroica chrysoparia*)		Larger territory size	Nest success (↓), nest abandonment (↑), nest predation (↑), no effect on diurnal behaviour
Gander and Ingold (1997)	MTB, hiking, jogging	Exp.	Chamois (*Rupicapra r. rupicapra*)	Distance moved: MTB ≙ jogging > hiking; alert & escape distance similar	Lower number of animals after disturbance	
George and Crooks (2006)	MTB, hiking, riding, vehicles	Obs.	Bobcat (*Lynx rufus*), coyote (*Canis latrans*), mule deer (*Odocoileus hemionus*).		Bobcats & coyotes avoidance of areas with MTB activity	Bobcats, diurnal activity shifts
Lowney (2011)	MTB	Obs.	Red squirrel (*Sciurus vulgaris*)		Avoidance of MTB areas due to lower abundance of preferred trees	
Lowrey and Longshore (2017)	MTB, golfing	Obs.	Desert bighorn sheep (*Ovis canadensis nelson*)		Avoidance of formely used area since introduction of MTB trail-system	
Naylor et al. (2009)*	MTB, hiking, riding, ATV	Exp.	Elk (*Cervus elaphus*)	Travel time increase: ATV > MTB > hiking ≙ riding; resting time decrease (in one of the years): MTB ≙ hiking; feeding time decrease: ATV		Altered diurnal behaviour (travel time increase, resting time decrease) only during disturbance and shortly after, not during times in between disturbance
Papouchis et al. (2001)	MTB, off-trail hiking, ATV	Exp.	Desert bighorn sheep (*Ovis canadensis nelson*)	% fled: off-trail hiking > ATV > MTB	Individuals from low-use areas avoid high-use areas (use here includes also other activities)	

(*continued on next page*)

Table 3 (*continued*)

					Effect of MTBing on:	
Reilly et al. (2017)	MTB, hiking, riding, dogs	Obs.	Bobcat (*Lynx rufus*), coyote (*Canis latrans*), grey fox (*Urocyon cinereoargenteus*), mountain lion (*Puma concolor*), mule deer (*Odocoileus hemionus*), racoon (*Procyon lotor*), striped skunk (*Mephitis mephitis*), two rabbit species combined (*Sylvilagus* spp.), virginia opossum (*Didelphis virginiana*), feral pig (*Sus scrofa*)		No effects of MTB activity	Coyote, mule deer, striped skunk: shifts of diurnal activities due to high recreational use (use here also includes other activities)
Scholten et al. (2018)	MTB	Obs.	Red deer (*Cervus elaphus*)		Avoidance of area close to MTB trails	
Taylor and Knight (2003)	MTB, hiking	Exp.	Bison (*Bison bison*), pronghorn antelope (*Antilocapra americana*), mule deer (*Odocoileus hemionus*)	Alert distance, flight distance, distance moved: MTB ≙ hiking; (one exception for flight distance of mule deer: hiking > MTB)		
Wisdom et al. (2004)*	MTB, hiking, riding, ATV	Exp.	Elk (*Cervus elaphus*), Mule deer (*Odocoileus hemionus*)	Flight response (elk): ATV > MTB > riding > hiking; mule deer: no distinct flight responses, only minor increases in movement during non-motorized activities		
Wisdom et al. (2018)*	MTB, hiking, riding, ATV	Exp.	Elk (*Cervus elaphus*)		Greater distance to trails kept during MTBing period	
Wyttenbach et al. (2016)	MTB, off-trail hunting, off-trail orienteering	Exp.	Roe deer (*Capreolus capreolus*)	Distance moved: off-trail use > MTB	Completed distances returned to normal after disturbance	

*Studies based on the same experiment

(nearly all informal trails are that kind) generally change species composition adjacent to trails less than gravel or tarmac trails (Pickering and Norman, 2017).

For assessing potential effects of **eMTBing** on the vegetation by using and creating trails, it needs a better understanding of the use and potential extension of trails by **eMTBing** as well as how **eMTB** and MTB trails differ in their characteristics. The characteristics of informally created trails align with the typical trail preferences of **eMTBers**. Informal trails establish fast on uphill sections, due to the increased trampling damage (Pickering et al., 2011; Havlick et al., 2016) and a similar vegetation damage as through conventional MTBing is likely (Ballantyne and Pickering, 2015a). However, across different formal and informal trails, solely formal wide tarmac and gravel trails affected the adjacent species composition under a mixed use (with MTBing being a main activity; Pickering and Norman, 2017). Unless **eMTBing** leads to an increase of hardened trails, which could result in a changing species composition adjacent to trails (Pickering and Norman, 2017), it is unclear whether it will seriously threaten local vegetation populations.

Future research needs to assess under which circumstances **eMTBers,** compared to MTBers, are responsible for an increase of informal or formal trails in recreational areas.

7. Impacts on wildlife

7.1. General impacts of recreational activities on wildlife

Terrestrial recreation in ecological systems is impacting wildlife (Marzano and Dandy, 2012; Larson et al., 2016; Marion et al., 2016; Bateman and Fleming, 2017; Hennings, 2017). Impacts are either immediate and lead to direct behavioural responses like alert and flight (Marzano and Dandy, 2012; Marion et al., 2016 and references therein) or long-term effects, such as habitat degradation or fragmentation by trails (Marzano and Dandy, 2012; Marion et al., 2016). The magnitude of impacts on wildlife depends on several interacting factors. General factors are spatial, temporal and behavioural visitor use characteristics as well as the environmental durability, namely (Hammitt et al., 2015): species, group size, gender ratio, habituation, topography, vegetation density, key locations (breeding & feeding areas, watering holes) and season (Knight and Cole, 1991; Hammitt et al., 2015; Marion et al., 2016; Hennings, 2017).

7.2. Impacts of MTBing and eMTBing on wildlife

Human disturbance in the case of mountain biking was shown to cause diverse responses of wildlife species with mammals being the most focused group of species, followed by birds (Table 3). Direct encounters of MTBers and animals result in immediate responses such as alert and flight accompanied with reduced feeding and resting time and hence, negative effects on stress levels and energy budgets of individuals (Gander and Ingold, 1997; Papouchis et al., 2001; Taylor and Knight, 2003; Wisdom et al., 2004; Naylor et al., 2009; Wyttenbach et al., 2016). In order to spatially or temporally avoid direct encounter, animals evidently change their habitat use and diurnal activity patterns (Gander and Ingold, 1997; Papouchis et al., 2001; George and Crooks, 2006; Naylor et al., 2009; Davis et al., 2010; Lowney, 2011; Ciuti et al., 2012; Wyttenbach et al., 2016; Coppes et al., 2017; Lowrey and Longshore, 2017; Reilly et al., 2017; Scholten et al., 2018; Wisdom et al., 2018,). This enforced reaction leads to habitat reduction, potentially accompanied with territory extension and habitat loss with associated consequences in species interactions and foraging behaviour. Although it is important to evaluate how mountain biking affects population dynamics, only the risk of MTBing for the reproductive success of a bird species has yet been investigated (Davis et al., 2010). So far, research on this issue is lacking and in general, the findings of this literature review highlight the need for further work as study results are too incomplete and often inconsistent to propose general management solutions. Details on the review results concerning impacts of MTBing and potential differences for **eMTBing** are following.

7.2.1. Immediate responses of animals

The immediate response of animals is here defined as the reaction following an unexpected disturbance, which was mostly measured as alert distance, flight distance and difference in feeding and resting time. Most of the studies examining the immediate responses of animals on mountain biking found that it provokes direct flight responses of wildlife accompanied with reduced resting and feeding time (Gander and Ingold, 1997; Papouchis et al., 2001; Taylor and Knight, 2003; Wisdom et al., 2004; Naylor et al., 2009; Wyttenbach et al., 2016).

On-trail MTBing initiates immediate responses of animals to a similar (Gander and Ingold, 1997; Taylor and Knight, 2003) or higher (Wisdom et al., 2004; Naylor et al., 2009) degree than other non-motorized on-trail activities and to a lesser degree than off-trail activities (Papouchis et al., 2001, Wyttenbach et al., 2016). ATVs have a greater impact than all other forms of recreation due to their higher speed and greater noise (Wisdom et al., 2018). As **eMTB** use is evidently associated with higher speed in uphill and flat sections compared to conventional mountain biking (Mitterwallner et al., 2021) it is likely that wildlife species will respond more sensitive to approaching **eMTBs**, although the duration of disturbance is probably shorter.

Evidence on the immediate responses of wildlife to mountain biking shows that off-trail recreational activities have a higher impact than on-trail activities (Papouchis et al., 2001; Wyttenbach et al., 2016). Conventional mountain bikers tend to create informal trails (Newsome and Davies, 2009; Ballantyne and Pickering, 2015a; Köck and Brenner, 2015; Korpilo et al., 2017). With **electrical** assistance off-trail riding gets easier and hence, the process might become more frequent. On-trail, there is a chance that species habituate to recreational use (e.g. Riley et al., 2003). In this sense, only tolerant individuals might use the habitat close to trails, while less tolerant individuals keep greater distances (Papouchis et al., 2001; Bejder et al., 2009). Therefore, the responses of animals closest to trails might not be exceptionally stronger to **eMTBing** than to other activities (Taylor and Knight, 2003). Nevertheless, disturbance of the less tolerant animals might occur, when **eMTBers** use low frequency areas, or ride at times of the day, which so far have not been frequented by other user groups.

Further studies need to target differences in spatio-temporal use patterns of both groups to evaluate the risk of higher use of informal trails and riding at disturbance-sensitive times like dawn, dusk or at night. A promising approach for future research could be the tracking of individual animals in several areas of different use intensities. Ideally, also the physiological stress response of animals should be investigated simultaneously, since observed behavioural responses do not necessarily indicate the extent or type of disturbance effects (Müllner et al., 2004). Many investigated animals are intensely hunted or have been so in the past. Flight reactions to humans may be strongly influenced by hunting activities (Ciuti et al., 2012; Thurfjell et al., 2013). Studies comparing outdoor sports' disturbance effects in hunted with non hunted populations are currently missing.

7.2.2. Effects on habitat use

The effects of mountain biking on the habitat use of wildlife species is investigated by quantifying species' occurrence with camera traps, GPS-loggers, experiments or counts of animal marks such as pellet groups or hairs. Most studies targeted either avoidance of MTB trails or avoidance of generally highly used areas as response of animals to mountain biking and interpreted both as a form of habitat reduction since the majority of study species were mobile species with large habitat sizes. As a response to mountain biking several mammal species and one bird species were found to avoid trails (chamois (Gander and Ingold, 1997), bobcat & coyote (George and Crooks, 2006), roe deer (Wyttenbach et al., 2016), western capercaillie (Coppes et al., 2017), bighorn sheep (Lowry & Longshore 2017), red deer (Scholten et al., 2018)) or areas frequently used for mountain biking (bighorn sheep (Papouchis et al., 2001), mule deer (George and Crooks, 2006), red deer (Scholten et al., 2018)). No negative effect of mountain biking was found for 10 mammal species (bobcat, coyote, grey fox, mountain lion, mule deer, racoon, striped skunk, two rabbit species combined, Virginia opossum, feral pig (Reilly et al., 2017) and for the red squirrel (Lowney, 2011)). Another negative impact of habitat fragmentation through MTB trails may be lower food abundance as shown for golden-cheeked warblers by having larger territory sizes (Davis et al., 2010).

Generally, **eMTBing** is unlikely to cause an increased spatial avoidance as long as the same trails are used as by conventional MTBs. However, in case **eMTBers** increase off-trail riding and the use of formerly unreachable areas, this will increase the chance for habitat loss or reductions as a result of spatial avoidance responses by wildlife species (Gander and Ingold, 1997; Papouchis et al., 2001; George and Crooks, 2006; Davis et al., 2010; Wyttenbach et al., 2016; Coppes et al., 2017; Lowrey and Longshore, 2017; Scholten et al., 2018; Wisdom et al., 2018). Another important aspect is the general increase of activity and frequency, which is accelerated as **electrical** assistance opens mountain biking for a wider user group (Schlemmer et al., 2019). High use intensities may lead to the avoidance of whole areas by individuals (Papouchis et al., 2001) or entire populations (Lowrey and Longshore, 2017).

The task of future research is to characterise the current habitat use of different species in many areas with recreational use in order to enable comparisons and identify the effect of habituation on the species and population level. Concerning the impacts of **eMTBing**, researchers should now focus on areas where so far no, or only some activities have taken place, but where chances are high that **eMTBing** (or also other activities) will be frequent in the future.

7.2.3. Effects on the diurnal activity and behaviour

Apart from a spatial avoidance as response to mountain biking, wildlife species also react to disturbances by shifting their temporal activity patterns. For mountain biking, opposing results were found in this literature review. Golden-cheeked warblers did neither change diurnal activity nor nesting behaviour when MTBing occurred in the area (Davis et al., 2010) and similarly, no relationship between MTB intensity and changes in temporal behaviour patterns of elks was observed (Ciuti et al., 2012). For elks, however, another study concerning the effects of mountain biking on temporal patterns found a reduced resting time as well as increased travel time of the animals as a response to MTB disturbances (Naylor et al., 2009).

Generally, results on the effects of MTBing on diurnal activity patterns differ between study designs and are highly species-specific. A camera trap study on 10 different species observed negative effects only for coyote and mule deer as they shifted activity towards the night and striped skunks by increasing activity in the morning (Reilly et al., 2017). In accordance, George and Crooks (2006) revealed that bobcats and - although weaker - coyotes activity patterns shift towards nocturnal activity in areas with high biker activity.

These contrasting results show that at this state of research, it is impossible to generalise effects of mountain biking on the diurnal behaviour of wild animal species. Nevertheless, behavioural changes can occur as long as the MTBing disturbance lasts (Naylor et al., 2009). Thus, if **eMTBing** increases the frequency of disturbance it might increase these behavioural changes. In order to estimate this effect, further studies on the riding behaviour of **eMTBers** and the resulting changes in animal activity patterns are necessary. However, it is likely that responses and habituation capacity are highly context- and species-specific and therefore not generalisable.

7.2.4. Effects on the reproductive success

Evidence on the effect of mountain biking on reproductive success of animals is highly incomplete and consists exclusively of a study investigating the effect for golden-cheeked warblers (Davis et al., 2010). Overall nest success was halved in biking sites, nest abandonment was three times higher and nest predation more than doubled as opposed to non-biking sites.

The authors argue that these negative effects are a result of the alteration and fragmentation of nesting habitats (Davis et al., 2010). As already noted, **eMTBing** could have similar effects, since it depends on the maintenance of trail systems and possibly even leads to an expansion of those. However, further research is needed and must include other species and representatives of other classes. In general, studies rarely evaluate if observed short-term disturbances affect reproductive success and thus long-term population development of focal species.

8. Discussion

This review systematically collected research evidence for ecological consequences of conventional mountain biking and discussed how a switch to **electrically** assisted mountain biking can intensify these effects. While contrasting findings for wildlife make it impossible to evaluate a general effect on wildlife, evidence for the effects of MTBing on soil and vegetation is consistent, but depends on species and context. Effects of (**e**)MTBing on ecological systems will intensify with a larger frequency and spatial cover by mountain bikers and therefore a rising number of trails, resulting in a substantially greater overall impact on ecosystems (Fig. 1). In the following, the relevance of studies on ecological impacts of (**e**)MTBing, weaknesses of current studies as well as remaining research gaps are summarised and discussed.

8.1. *Relevance for understanding interactions of (e)MTBing with ecosystems*

Understanding the interaction of (**e**)MTBing and ecological systems including long-term impacts on local and regional population dynamics is crucial to allow a reflected normative evaluation by society. Current debates among stakeholders are often based on single observable effects, while this review has identified a lack of understanding how single effects of (**e**)MTBing on soil, vegetation or wildlife extrapolate from individuals to the species, population or ecosystem level. Societal debates also need to differentiate effects relevant for land use like farming, forestry or hunting from implications for nature conservation. While, for instance, increased flight behaviour of deer is often used as an argument in public debates, even the loss of multiple individuals would be irrelevant from a nature conservation perspective if population dynamics are mainly regulated by hunting to allow forest growth. In fact, flight behaviour of deer would likely change considerably if those species would not be hunted and could habituate to human presence without fear (De Boer et al., 2004). On the other hand, population dynamics of remnant rare protected species may be very reactive to disturbances, particularly in sensitive time periods. Similarly, while the disturbance of vegetation along (**e**)MTB trails in meadows may cause financial loss to landowners, it enhances spatial heterogeneity with a possible net benefit for diversity (cf. Steinbauer et al., 2018). Debates among involved stakeholders thus need to acknowledge the complexity of ecological consequences as well as to differentiate and finally to balance societal aims. In addition, ecological effects of (**e**)MTBing are largely not discussed in relation to the influence of other user groups or other far-reaching anthropogenic factors (e.g. agriculture, forestry, soil sealing).

8.2. *Identifying weaknesses of existing studies and knowledge gaps*

The basis for a reflected discussion of (**e**)MTBing within a specific societal and environmental context is a profound understanding of its effects. While this review has summarised multiple single ecological effects, it also highlighted our lack of understanding of more complex relationships as well as a strong inconsistency between findings. This is particularly true for the effect of (**e**)MTBing on wildlife. A major reason for contrasting findings is a lack of standardised methodological approaches for studies investigating wildlife responses to MTBing. Methodologies range from experimental approaches like actively disturbing populations (e.g. Taylor and Knight, 2003) to GPS-telemetry (e.g. Wisdom et al., 2018) and camera trap studies (e.g. Reilly et al., 2017). Whereas disturbance experiments reveal direct alert or flight responses, GPS-telemetry identifies large-scale movement patterns (spatial avoidance) and camera traps with large-scale and long-term design assess spatial and temporal avoidance of disturbed sites. However, all methods used for investigating these complex effects on wildlife are limited. A general problem of current studies on wildlife interactions with MTBing is that habituation or tolerance effects as well as species-specific behaviour are ignored. Most data were collected in areas where MTBing was an ongoing activity and hence, all results are skewed towards individuals of a species population, which presumably already tolerate MTB disturbances to a certain degree or got habituated to it. In addition, studies mostly investigated short-term and site- as well as species-specific effects. Just one of the studies on wildlife did distinguish between individuals (Papouchis et al., 2001), although there is evidence that individuals of the same species have personalities and hence might react differently to disturbances (Bejder et al., 2009). Therefore, if exclusively tolerant individuals of a population are observed that stay closest to MTB-trails (or the opposite), there is a great potential for a study bias leading to wrong generalisations. An experiment where individual elk were tracked revealed that 50% of the animals were located beyond the maximum viewing distance from trails during mountain biking disturbance (Wisdom et al., 2018), pointing out the importance of this phenomenon for overall research conclusions. A further aspect is that **e-mountain bikers** often ride longer distances than conventional mountain bikers (Mitterwallner et al., 2021), thus potentially entering refuge areas for wildlife more frequently. However, data on the effect of MTBing on non-habituated animals are missing and therefore it is difficult to predict the effect **e-MTBing** has on wildlife in remote areas. Depending on other environmental factors such as habitat attributes, predator density or food availability, the absence or extent of direct responses like flight or alert behaviour are not necessarily a good indicator for the effects an activity has on wildlife (e.g. when individuals tolerate the recreational disturbance as the lesser of two evils). On the other hand, the ability of individuals and species to habituate to such disturbances has to be included in the interpretation of results. Nevertheless, it is difficult to distinguish between tolerance and true habituation of wildlife (Bejder et al., 2009; Hennings, 2017). Investigations with camera traps are suitable for assessing long-term behavioural adaptation such as spatial or temporal avoidance, but target species are limited to medium- or large-sized mammals and individuals are mostly not distinguished. The movement patterns of individuals are investigated in studies with GPS-telemetry, however, these studies are limited to a small number of individuals of one species and general responses for whole populations or ecosystems are impossible. Besides the limitations of all approaches, the differences in study design and methodologies have the disadvantage of hampering meta-analysis, which would be highly beneficial for assessing general patterns.

Studies targeting MTBing effects on vegetation rarely differentiate between species (Thurston and Reader, 2001; Pickering et al., 2011; Pickering and Barros, 2015; Bouchard et al., 2015), although long-term monitoring of species compositions adjacent to trails are vital in order to quantify the effect of mountain biking on vegetation. Hence, research gaps include specifically long-term studies on plant species compositions in different distances to MTB trails with a focus on invasive species (Bouchard et al., 2015). Moreover, the potential of MTBing to spread pathogens like certain fungus needs to be studied.

Concerning the conservation of specific species, it is important to assess whether only small-scale damage occurs or local populations are threatened. From a nature conservation perspective, the potential threat by mountain biking needs to be considered especially for ecosystems with high endemism like alpine mountains and islands. For example, there is evidence that human pathways like roads or trails act as main introducers of alien plant species (e.g. (Tyser and Worley, 1992)). Moreover, comparable and long-term study designs targeting the effects of mountain biking on the individual level of wildlife species need more attention in future research. Further taxonomic groups should be targeted in studies on physiological stress, reproductive success, species richness and community composition. Effects need to be investigated under consideration of mountain bike frequencies. Especially long-term monitoring studies with designs that cover trailsides and offside trails (e.g. with camera traps) are promising. But also new methodological approaches like the quantification of sound signals of, for instance, birds or insects (Pijanowski et al., 2011) provide promising tools to increase understanding of taxonomic groups beyond medium- and large-sized mammals.

8.3. Suggestions for future research

Generally, this review reveals the comprehensive lack of research on the environmental effects of MTBing and particularly **eMTBing**. As technical properties, riding behaviour (Mitterwallner et al., 2021) as well as user group and user preferences (Schlemmer et al., 2019) of **eMTBing** differ from conventional mountain biking there is an urgent need to fill these knowledge gaps. In experiments, higher pass frequencies, which represent the increase in MTBing activity due to **eMTBs**, should be tested. Additionally, soil degradation effects of **eMTBs** are likely to vary compared to conventional MTBs. Hence, off- and on-trail soil compaction and erosion needs to be investigated at different site characteristics (slopes, substrates and weather conditions) with a focus on riders' skills and behaviours (starting, braking and skidding), for both **eMTBs** and MTBs. For this, the use of the standard experimental procedure introduced by Cole and Bayfield (1993) could be a suitable standardised experimental approach that would guarantee comparability between studies.

As pointed out in this review, off-trail riding represents the biggest not controllable threat to vegetation, soil and wildlife by initially damaging vegetation, removing and compacting soil (e.g. Thurston and Reader, 2001) and disturbing wildlife (Papouchis et al., 2001, Wyttenbach et al., 2016). However, the potential of off-trail mountain biking is unknown and difficult to assess. So far, a survey amongst bikers revealed that 70% leave legal trails (International Mountain Bicycling Association, 2015). Apart from repeating such surveys particularly for **eMTBers**, quantifying the supply and demand of trails that meet the preferences of MTBers and **eMTBers** in order to evaluate the potential risk of off-trail riding might be a suitable approach. This approach however, is highly site-specific and therefore not generalisable.

9. Conclusion

We conclude that in the current situation, the exploration of new areas has the strongest effects on ecological systems - be it through the use of previously unused trails, or the impetuous construction of new trails. The underlying reason for this is that the proportionally highest damage occurs at the beginning of a new disturbance (positive curvilinear asymptotic trend). Therefore, it needs to be well considered where and when new trails are constructed, although it may be similarly an effective measure of visitor management, in order to nudge people away from areas of high conservation value. This is especially relevant in view of the technical innovations yet to come, which again will allow a more intense use of natural areas.

Difficulties in generalising results and rules will remain even with a standardisation of methodological approaches. As this review outlined, study results, particularly in regard to wildlife effects, are highly species- and site-specific and approaches to assess effects on the levels of individuals as well as communities of all species and sites are a difficult task. The complexity and dynamics of ecosystems used by humans for recreational activities requires large amounts of data and adequate analyses for the identification of underlying patterns. And yet, habituation effects of wildlife will only be captured by before vs after disturbance comparisons. Areas without human influence however, are scarce. Most of the forest and mountain systems are largely influenced by diverse human activities since centuries, particularly in Europe, making it impossible to exclude other influential factors on wildlife activity patterns such as hunting, forestry, agriculture or infrastructure. In addition, every debate regarding the interactions between **(e)**MTBiking and the environment needs to differentiate between observable impacts and their evaluation, which could be positive and negative and likely differs between stakeholders. Understanding interactions of human activities and environmental factors and recognising the values natural systems have for humans, is essential for any reflected debate. Outdoor sport activities such as mountain biking also have the potential to substantially contribute to the recognition and appreciation of the value of ecosystem services. Hence, the sustainable use of natural systems needs to be ensured for mountain biking and other recreational activities by combining research, nature conservation, management and political solutions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2023.e02475.

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