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Research article

Effects of mountain biking versus hiking on trails under different environmental conditions

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ABSTRACT

Recreational use of nature areas is increasing worldwide. All trail-based activities have a certain degradation effect on vegetation and soil, and conflicts between conservation values and recreation may occur. Controversy still exists regarding the relative impact of mountain bikers compared to hikers on trails. In this study, we manipulated the use intensity from hikers and mountain bikers on existing, natural-surfaced trails, and investigated effects of increased use and the relative importance of mountain biking on trail degradation. In two study sites, two trails were selected, one designated for hiking and one for biking. Passes were counted with TRAFx counters. The proportion of mountain bikers on the designated biking trails was on average 47%, and on the hiking trails 13%. Trail width and depth were recorded at permanently marked transects repeatedly throughout the growing season, and analyzed with linear mixed models as a function of number of passes, proportion of bikers and environmental conditions along the trail. Trail width, both the core trail without vegetation and the total area influenced by trampling and biking, showed on average small, but highly variable increases with enhanced use. Trail widening occurred particularly in moist parts, and trail width increased more when a larger proportion of the passes was mountain bikers. Trail depth did not change much throughout the study period, suggesting that the soils along the trails were already compacted and to a limited degree prone to soil movement and subsequent soil loss. Our study shows that on-trail use by hikers and mountain bikers have relatively limited overall effects in terms of trail widening and deepening, but that effects depend highly on environmental conditions; enhanced use of trails in wet areas is likely to result in greater trail degradation, and more so if a large proportion of the users are mountain bikers. Management and maintenance of trails, in terms of re-routing or trail surface hardening, could thus be necessary to avoid negative impacts of increased use. For such management actions to be successful, they need to be targeted towards the actual user groups and the natural conditions in the area.

1. Introduction

Nature areas, including national parks and nature reserves, are subject to increasing levels of outdoor recreation and tourist pressure (Balmford et al., 2009; Bell et al., 2007; Leung et al., 2018). At the same time, the activities are growing more diverse and cover larger areas through longer seasons. Most land-based outdoor recreation and nature-based tourism activities are concentrated along various kinds of linear infrastructure in natural areas, such as trails (Monz et al., 2013). The various types of activities, how the activities are performed and consequently their effect on nature, vary, however, with for instance recreational/tourism trends, level of specialization, types of trail facilitation and technological development. The spectrum of specialized (mountain) bikes that have entered the market during the last decades illustrates this variation (Monz and Kulmatiski, 2016).

All trail-based activities have a certain effect on vegetation and soils. These effects have been well documented in the literature including reduction in vegetation cover (Barros et al., 2013; Cole, 1995; Roovers

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et al., 2004), a decline in species richness (Barros et al., 2013), increased cover of bare soil and enhanced soil compaction (Marion and Wimpey, 2007), and increasing risk of erosion, particularly in steep terrain (Goeft and Alder, 2001; Leung and Marion, 1996; Marion and Wimpey, 2007).

The relationship between human use and effects on vegetation and soils is normally assumed to be curvilinear (Hammitt et al., 2015; Monz et al., 2013). Thus the effect increases with increasing use, but only up to a certain level where the curve flattens and additional use causes proportionately smaller effects. The curvilinear disturbance-impact curve predicts that in areas with little or no existing use, even a small increase in use intensity will cause rapid effects, whereas in areas with high use intensity, an increase in use will only have small effects. On existing trails with a long history of use, no large effects should thus be expected if the use intensity increases. However, the model assumes that recreational use is strongly limited to the eroded core zone of the trail (Monz et al., 2013; Wimpey and Marion, 2010). This is indeed mainly the case for on-trail recreation activities (Cole, 1995; Monz et al., 2013), but with some exceptions. Where trail degradation leads to exposure of roots and rocks, deepening of trails or development of muddy sections, avoidance behavior often leads to trail widening and development of parallel trails. As a consequence, the influenced area increases (Dixon et al., 2004; Olive and Marion, 2009).

Environmental conditions could potentially modify the shape of the response curve (Monz et al., 2013) as the effects of use intensity on trail degradation is strongly modified by on-site environmental factors (Leung and Marion, 1996); for instance climate and geology act on topography, soil and vegetation to determine sensitivity to recreational disturbance. Thus, previous studies have shown that a certain amount of use has larger impacts on trail degradation (soil loss in particular) in steep slopes compared to flat terrain (Chiu and Kriwoken, 2003), particularly where trails are aligned across rather than along the slope (Marion and Wimpey, 2017; Meadema et al., 2020; White et al., 2006). Further, substrate properties affect soil erodibility; fine-grained and homogenous substrate is more easily eroded, whereas substrate of mixed sizes (e.g. both silt and gravel) can reduce the speed of runoff and thus reduce erosion risk (Marion and Wimpey, 2017; Olive and Marion, 2009). Muddy sections of the trail, facilitating trail widening, commonly occur in sections of the trail with high soil moisture and poor drainage (Marion and Wimpey, 2007; Meadema et al., 2020).

Both hiking and mountain biking cause trail degradation (Chiu and Kriwoken, 2003; Pickering and Growcock, 2009; Pickering et al., 2010, 2011; Roovers et al., 2004). Existing studies mainly fall into two categories: experimental and observational (Pickering and Norman, 2017). Controlled experimental studies compare the effects of bikers and hikers in undisturbed vegetation on variables such as vegetation cover and composition and cover of bare soil (Pickering et al., 2011; Thurston and Reader, 2001). A few experimental studies have also been carried out on existing trails (Chiu and Kriwoken, 2003; Wilson and Seney, 1994). These studies show little evidence for different or stronger impacts of biking than of hiking, but are mainly carried out on small spatial scales (short experimental lanes or trail segments) and over short time-periods (all experimental hiking/biking carried out within a few days). Further, the experimental protocol used affects user behavior (e.g. no side-by-side walking), although Chiu and Kriwoken (2003) showed that biking style, e.g. skidding, could impact the severity of trail degradation. Existing studies cover only a limited section of the disturbance curve (cf. Hammitt et al., 2015), and thus, their relevance for assessing trail degradation in real-life situations may be limited. Observational studies investigate impacts on existing trails, selecting trails with different dominant use, e.g. hiking vs. biking trails (Olive and Marion, 2009), or use intensity (Bjorkman, 1998; White et al., 2006). Bjorkman (1998) and White et al. (2006) found that on mountain bike trails, increased use lead to increased trail degradation, but Olive and Marion (2009) did not find any difference in soil loss between trails predominantly used for mountain biking compared to hiking trails. Thus, Monz & Kulmatiski (2016) stated: “From an ecological perspective, mountain biking trails have similar impacts (e.g. soil loss) as hiking trails.” However, studies that compare effects of biking and hiking on existing trails, quantifying use intensity by different user groups while covering a wider range of the disturbance-impact curve, are lacking.

In Norway, mountain biking is allowed on existing, multiuse trails outside of protected areas, but within protected areas, such as national parks, restrictions vary, whereas hiking is allowed. A governmental proposal suggests to allow for mountain biking in protected areas in line with hiking, but restrictions can be introduced if effects from biking are more severe than from hiking and in conflict with conservation values. For managers, knowledge about the effect of opening trails for new user groups in national parks is highly needed: will mountain biking cause other and more severe impacts on trails, and thus provoke higher and other trail maintenance needs, or are impacts similar to that of hikers? In this study we investigate the relative effect of mountain biking compared to hiking on trail degradation, recorded as trail width and depth. We used existing, natural-surfaced trails and recorded trail degradation repeatedly throughout a summer season. We manipulated the use by increasing the use of mountain biking on some trails and of hiking on other trails. This design allowed us to capture effects of ordinary user behavior normally not well captured in small-scale experimental setups, including e.g. fast riding and walking side by side. All passes by hikers and bikers were counted, thus allowing us to estimate effects of amount of use quantitatively. Specifically, we ask:

- How does mountain biking affect trail degradation compared to hiking at different use intensities?
- Are the effects modified by environmental factors?

Based on the literature, as summarized above, we predict the trail degradation effects to increase with use intensity, but with a similar relative impact from biking and hiking. We further predict larger degradation with increasing use intensity in steep terrain, in trail sections with fine-grained, homogenous substrate, and in sections with high soil moisture.

2. Methods

2.1. Study sites

To investigate trail degradation from increased use of trails from hikers and mountain bikers under different climatic conditions, the study was carried out in two study sites; one located in an oceanic climate zone and the other in a continental zone (Fig. 1). In each site, two trails were selected, one to be predominantly used by hikers and one by mountain bikers. The oceanic study site is located in Western Norway (Fig. 1), and the climate is characterized by high annual rainfall (2250 mm) and relatively high mean annual temperatures (7.6 °C, data from the period 1961–1990 from the city of Bergen; https://www.yr.no/nb/). The topography is steep with fjords and mountains ranging up to approximately 700 m a.s.l, and the study sites cover sub-alpine and forested areas. The continental study site is located in Eastern Norway (Fig. 1). The climate is characterized by low annual precipitation (660 mm) and lower mean annual temperatures (2.9 °C, data from the period 1961–1990 from the city of Lillehammer; https://www.yr.no/nb/). The eastern site is in a sub-alpine relatively flat area at approximately 900 m a.s.l., with surrounding mountain peaks approaching 1100 m a.s.l. We used interpolated data on a 1 × 1 km spatial resolution downloaded from the SeNorge data portal (senorge.no) to acquire information on temperature and precipitation during the study period (Lussana et al., 2018). The mean daily temperature during the study period was approximately 3 °C warmer in the oceanic than the continental study site (Table 1). The number of days with precipitation in the period May–; September 2019 was somewhat higher in the oceanic site, but the total amount of precipitation was substantially higher in the oceanic site (Table 1, Fig S1).

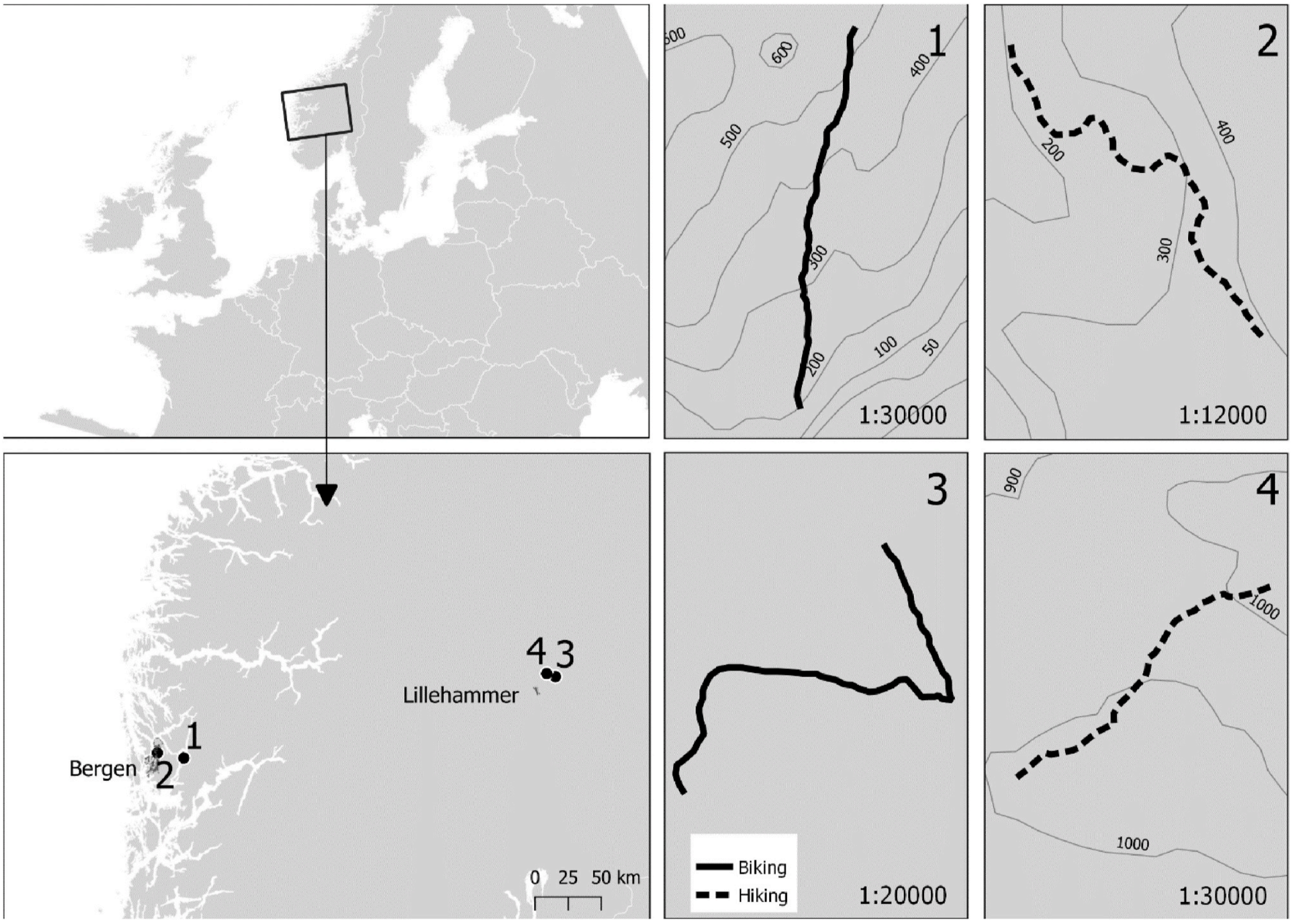

Fig. 1. Overview of study sites and trails in Norway. The oceanic site is located close to the city of Bergen, and the continental site close to the city of Lillehammer. Dotted lines show trails designated for hiking, whole lines trails designated for biking.

Table 1
Overview of study trails, with elevational range, length, dominant vegetation and bedrock, and number of segments. Weather data for the study period May–September 2019 are interpolated data with a 1 × 1 km spatial resolution, averaged over trail starting and end point. Daily temperature shows mean ± SD for the study period.

Study site	Designated use	Elevation (m a.s.l.)	Length (km)	Vegetation	Bedrock	No. of segments	Precipitation (mm)	No. of days with rain	Max. daily precipitation (mm)	Daily temperature (°C)
Oceanic	Biking	200–520	2.7	Open forest and heath, with some mire/bogs.	Amphibolite, mica shists	23	1569	104	99	11.1 ± 4.6
Oceanic	Hiking	200–400	1.3	Forest-dominated, with some heath and mire/bogs.	Quartzite	20	1135	105	67	11.3 ± 4.5
Continental	Biking	920–990	2.6	Sub-alpine heath, with some mire/bogs.	Sand-stone, thick moraines	22	546	90	35	8.5 ± 5.0
Continental	Hiking	960–1030	2.3	Sub-alpine heath, with some mire/bogs.	Sand-stone, thick moraines	22	543	82	34	8.3 ± 5.0

In each site we used existing topographic maps, maps of mountain bike routes (http://www.trailguide.net), Strava heatmaps (https://www.strava.com/heatmap) and established contact with local users to identify potential trails for the field study. A suitable trail had to meet the following criteria: It should be minimum 2 km long (without other trails crossing), with natural surface (i.e. not gravel or other fixed surface), occurring in natural vegetation (i.e. no urban or agricultural areas, no plantation forests.), have a variation in topography and plant communities, have low to medium existing use (based on local knowledge and visually assessed pre-study degradation), and preferably use dominated by one user group (either mountain bikers or hikers), with low to no impact from horseback riding. In addition, permission to perform the study had to be given by the land owner.

A number of potential trails were visited, and four trails were selected (Table 1), two in each study site, of which one was designated for mountain biking and one for hiking. The trails are hereafter referred to as biking and hiking trails. The oceanic hiking trail did not meet the length criterium (Table 1), but was chosen due to low availability of existing trails with low to medium use in the area.

2.2. Control of use

We contacted local groups through different channels (personal contact, e-mails, announcements on Facebook groups) and encouraged use of the study trails throughout the summer of 2019. Mountain bikers were informed of the designated biking trails only, and we created Strava segments that were distributed to bikers. The oceanic biking trail was used for a local Enduro race from May–August, whereas the continental biking trail was used as part of a mountain bike race with approximately 300 participants in end-August 2019.

Hikers were informed only of the designated hiking trails. We mounted signs in each end of the hiking trails informing about the study, calling on people to take a 'detour'. We also established a mail box with a book for self-registration and awarded small prizes to a random selection of hikers each month, to encourage hiking on the trails.

To count the number of users on each trail, and to get an estimate of the use intensity by different user groups (hikers vs. bikers), we placed four TRAFx counters (TRAFx Research Ltd., Canmore, Alberta, Canada) along each trail at the time the study started; two vehicle counters counting bikes and two infrared (IR) trail counters counting all passes. The IR-counters sense and detect the infrared wavelength that people emit, and the vehicle counters use a magnetometer to detect bikes. Two counters of each type were used to make sure all passes along the whole trail were counted, and to have a backup in case of malfunction. The counters were placed close to the trail 'start' (i.e. where most people would start their trip) and towards the trail 'end'. The vehicle counters were buried 15 cm underground just beside the trail where the drainage was good. All counters were placed in narrow parts of the trail so that only one person at the time passed the counter. The IR counter sensors were placed approximately 1 m aboveground in trees or cairns to avoid counting animals such as sheep or dogs, and thus did not count the smallest children. It was made sure that nothing, like branches or leaves, got between the sensor and the trail, and direct exposure to sunlight was avoided. All equipment (sensor, counter, battery) was hidden to avoid people tampering with it. Counters were collected at the end of the study period.

After collecting the data counters, the information was reviewed manually and examined to check daily and seasonal variations. Any anomalies were considered more closely with respect to factors such as time in the season, weekday, time of day, weather conditions, and compared with the other counters on the same trail. With the exception of the vehicle counters on the continental hiking trail, all counters worked properly during the study. To estimate the number of bikers on this trail, we used Strava-metro data for the two continental trails (San Francisco, CA, USA) and the relationship between Strava bike registrants and the number of counted bike passes on the continental biking trail during the study period. For the rest of the trails, we used data from the counters placed at the trail start to estimate number of passes. More details are found in **Supplemental Material**.

2.3. Field sampling

We used a stratified sampling method following Leung and Marion (1999), placing sampling segments every 100 m along the trail, including a total of 87 segments. A sampling segment was a 15 m long part of the trail with homogenous vegetation and terrain. The sampling segments were placed semi-randomly, i.e. we used the 100 m distance as a first criterium, but adjusted placement to ensure homogenous vegetation at the sampling segment and the inclusion of plant communities occurring infrequently along the trails. The oceanic hiking trail was shorter than the others, and for this trail 80 m was used as distance between sampling segments.

For each segment, we recorded plant community type according to the classification system "Nature types in Norway" (NiN; Halvorsen et al., 2020), and trail slope alignment was recorded as the difference between trail exposition and terrain slope exposition, both measured with a hand-held magnetic compass.

At each sampling segment, three transects were placed perpendicular to the trail, at 2.5, 7.5 and 12.5 m from the segment starting point. The transect end points were located in intact, undisturbed vegetation and permanently marked with plastic sticks and 90 mm nails, and the position was taken with a hand-held GPS. For each transect, we used a measuring tape to record core trail width in cm. Trail degradation state was noted, in three classes: total (no vegetation), high (vegetation partly present, but with visible holes in the vegetation cover due to trampling), and moderate (visible signs of trampling, but vegetation cover intact. We recorded the width of the transition zones (cm), defined as the zones between the core trail and the intact vegetation, where degradation was lower than the core trail, but with visible signs of trampling, and degradation state was noted as either high or moderate. Trail depth (cm) was recorded as the longest distance between the ground and a horizontal line drawn between the two edges of the core trail. We recorded substrate type as the visually estimated percentage cover of three classes: (i) stone and bedrock, (ii) gravel, and (iii) sand, silt and clay. Further, we visually estimated the percent cover of (iv) soil organic matter and (v) peat. Finally, we recorded the trail slope with a clinometer (Plaincode™ Clinometer + bubble level app for Android), in degrees. All transects were photographed, with the measuring tape in place.

Sampling segments and transects were established early in the growing season (after snow-melt), which differed between the study areas: 6/May 7, 2019 in the oceanic site, and on 4/5 June in the continental site. The study trails were visited approximately every fourth week, and the study was ended on 9/10 and 25/26 September in the oceanic and continental site, respectively, with a total of five sampling times for each trail (Fig. S1). At each sampling time, measurements of core trail width and degradation state, transition zone width and degradation state, and trail depth were repeated, and transects were photographed.

2.4. Statistical analyses

In total, our dataset included 1305 observations of 261 transects on 87 segments (Table 1). Trail degradation (response variables) was represented by trail width, total trail width and trail depth, and by change in these three variables from sampling time 1 to sampling time *t*. Total trail width was calculated as the sum of the core trail width and the width of the transition zones. To allow for investigations of effects of use intensity and of varying use intensity by different user groups, we included two explanatory variables: total use intensity (i.e. the total number of passes from the start of the study to sampling time *t*), and the proportion of bikers of total use intensity. Environmental conditions (explanatory variables) were represented by trail slope, trail slope alignment, percentage cover of peat, percentage cover organic matter, of sand and silt, of gravel, and of stone and bedrock, and by soil moisture.

The first field sampling was carried out early in the growing season, when vegetation cover was sometimes sparse and the width of transition zones could be difficult to determine. We carried out a manual check of photos comparing different sampling times during data preparation to determine the width of transition zones and adjusted the width for eight transects at sampling time 1. For some transects, permanent markers were removed between sampling times. Photos were used for relocations in the field, but for two transects, relocations were inaccurate. A total of 17 observations were therefore removed from the dataset.

From the counters, we acquired data on the total number of passes and number of bikers between each sampling time for each trail (Table S2) and calculated the accumulated use for each sampling time. From these numbers we derived the variables number of passes and proportion of bikers.

Based on the plant community types determined at the segment level and their distribution along a gradient in soil moisture (Halvorsen et al., 2020), we derived an ordinal variable on soil moisture, from 1 (dry) to 4 (mire/bog with peat formation).

To limit the number of explanatory variables, we investigated the correlation between the soil/substrate variables (soil moisture, percentage cover of peat, organic matter, sand and silt, gravel, and stone and bedrock). Pearson's correlation tests revealed several significant correlations (Table S1). In particular, soil moisture was positively correlated with amount of peat and organic matter, and negatively with the amount of stone and bedrock. Sand and silt correlated negatively with amount of peat and organic content (Table S1). The organic content was particularly high in one trail (oceanic hiking trail), whereas the amount of sand and silt was variable in all four trails. Consequently, we used soil moisture and amount of sand and silt to represent soil and substrate conditions. In addition, we used trail slope alignment and trail slope as explanatory variables.

All explanatory variables were centered and scaled prior to analysis (Nakagawa and Cuthill, 2007; Schielzeth, 2010). We standardized the variables by one standard deviation, as recommended by Schielzeth (2010). Standardized coefficients refer to how many standard deviations the response variable will change per a standard deviation increase in the predictor variable and allows the interpretation of the relative importance of the explanatory variables in the final models as well as between studies (Schielzeth 2010).

First, to investigate use patterns and whether we achieved a higher biking use on the designated biking trails, we used analysis of variance (ANOVA) to test whether use intensity and proportion of bikers varied with designated use (hiking, biking), site (oceanic, continental), and sampling time (excluding sampling time 1, where use was zero), including interactions between the explanatory variables. Backward model selection was carried out, and models were compared with Akaike's Information Criterion (AIC). Only the most parsimonious models were used.

Further, to reveal initial differences between trails at the start of the study, we examined how core trail width, total trail width, and trail depth at sampling time 1 varied with site, designated use and their interaction, as well as with environmental variables (soil moisture, amount of sand and silt, trail slope, and trail slope alignment). Response variables were log-transformed to achieve normal distribution of errors and reduce heteroscedasticity. We ran linear mixed-effect models with Satterthwaite's method to obtain p-values. We tested different random effects structures (no random factor, segment, segment nested in trail, and segment nested in trail nested in site) with the beyond optimal model, as recommended by Zuur et al. (2009). The nested models were run with maximum likelihood (ML) estimation and compared using AIC (Zuur et al., 2009). The best fitting model for initial trail conditions included segment as random factor.

Finally, we wanted to examine how use intensity and use type affected trail degradation. As the initial trail conditions varied (see **Results**), we calculated change in core trail width, total trail width and trail depth between sampling time 1 and sampling time *t*. Change in core trail width, total trail width and trail depth were investigated as a function of use intensity, proportion of bikers, and environmental conditions. We fitted complex models including two-way interactions between use intensity and proportion of bikers, and between use intensity, proportion of bikers and all environmental variables. To find the best random effects structure, we tested different alternatives for the beyond optimal model (transect, segment/transect, trail/segment/transect, and site/trail/segment/transect), as described above. For core and total trail width change, the best fitting model included transect nested in segment nested in trail, whereas for trail depth change, best model included transect nested in segment.

All full mixed effects models (initial trail conditions, change in trail conditions) were simplified by removing non-significant terms sequentially, comparing resulting AIC-values. ML estimation was used for model simplification, whereas final models were fitted with restricted maximum likelihood estimation (REML; cf. Zuur et al., 2009). Only the most parsimonious models are presented.

All analyses were performed in R version 3.6.2 (R Core Team, 2019) using the packages lme4 (Bates et al., 2015) and lmerTest (Kuznetsova et al., 2017).

3. Results

3.1. Use during the study period

The use intensity increased through the season, but varied between the four study trails (Fig. S2a). The continental hiking trail had the highest total use intensity (3310 passes), whereas the continental biking trail had the lowest use (1504 passes). Designated use, site and sampling time together explained 86% of the variation in use intensity ($F_{4,11} = 24.51$, $p < 0.001$). The use increased significantly with time ($p < 0.001$) and was on average higher in the continental site ($p = 0.008$), but with no main effect of hiking and biking trails (hiking vs. biking; $p = 0.742$; Table S2). However, there was a significant site × designated use interaction, with the hiking trail having more users than the biking trail in the continental site, but with the opposite pattern in the oceanic site ($p = 0.001$).

The study design was successful in directing bikers to the designated biking trails (Fig. S2b). On the biking trails, the proportion of bikers averaged 47.3% (±8.6 SD), whereas on the hiking trails, the proportion of bikers was substantially lower (13.2 ± 2.4). The proportion of hikers was correspondingly high on the hiking trails, but also substantial on the biking trails (52.7 ± 8.0). Designated use and sampling time together explained 93% of the variation in proportion of bikers on the trails ($F_{2,13} = 101.3$, $p < 0.001$), and with no difference between the oceanic and continental study sites (Table S2).

3.2. Initial trail conditions

Both core trail width, total trail width and trail depth varied between the trails at the start of the study (Table 2, Fig. S3). Significant effects of site and use showed that on average, trails were wider and deeper in the oceanic site and on biking trails. However, the significant site × use interaction revealed that the differences between hiking and biking trails were only present in the oceanic site (Table 2, Fig. S3).

Initial trail conditions also varied according to environmental conditions. Both core and total trail width were somewhat smaller in trail sections with higher cover of sand and silt (small, negative estimate; Table 2a,b). Total trail width increased with soil moisture and was generally smaller in flat compared to steep terrain (small, negative

Table 2
Model coefficients from the most parsimonious linear mixed-effect models explaining core (A) and total (B) trail width as well as trail depth (C) at the start of the study. Estimates for the random factor (segment) are not shown.

A) Core trail width	Estimate	Standard error	t-value	p-value
Intercept	4.549	0.061	74.063	<0.001
Site (continental vs. oceanic)	–0.589	0.091	–6.387	<0.001
Use (hiking vs. biking)	–0.792	0.093	–8.531	<0.001
Sand and silt	–0.109	0.033	–3.291	0.001
Site × use	0.929	0.129	7.210	<0.001
B) Total trail width				
Intercept	5.176	0.076	68.548	<0.001
Site (continental vs. oceanic)	–0.544	0.113	–4.814	<0.001
Use (hiking vs. biking)	–0.868	0.115	–7.579	<0.001
Soil moisture	0.142	0.042	3.415	0.001
Trail slope	–0.077	0.027	–2.852	0.004
Sand and silt	–0.085	0.030	–2.823	0.005
Site × use	1.042	0.161	6.462	<0.001
C) Trail depth				
Intercept	2.183	0.128	17.037	<0.001
Site (continental vs. oceanic)	–0.337	0.186	–1.817	0.073
Use (hiking vs. biking)	–0.972	0.194	–5.017	<0.001
Trail slope	0.168	0.057	2.947	0.004
Site × use	1.116	0.271	4.120	<0001

estimate; Table 2b). Trails were, however, deeper in steep terrain (positive estimate; Table 2c).

3.3. *Effects of use intensity and proportion of bikers on trail degradation*

Core trail width varied throughout the season. Due to increased vegetation growth as the growing season proceeded, core trail width deceased over time in some transects, particularly between sampling time 1 (the start of the growing season) and 2 (ca. four weeks after). Change in core trail width thus ranged between −98 and 559 cm over the study period, with a mean overall change of 8.9 cm (±43.0 SD), i.e. a small overall increase, but with large variation (Fig. 2a). As a result, change in core trail width over time was on average not significantly different from zero (model intercept 7.967, $p = 0.320$; Table 3a). The most parsimonious model explaining change in core trail width (Table 3a) showed an increase in core trail width with increasing use, and a significant positive interaction between use intensity and proportion of bikers; core trail width increased more with high use when the proportion of bikers was high. Soil moisture was, however, the most important predictor for increase in core trail width (large positive estimate): core trail width increased more in wet parts of the trail. Significant two-way interactions between soil moisture and both the proportion of bikers and use intensity revealed that core trail width increased particularly in wet parts of the trail when a high proportion of users were bikers (Table 3a).

The change in total trail width over time ranged between −88 and 638 cm (15.4 ± 38.6 cm). As for core trail width, total trail width was reduced in some transects, particularly between sampling time 1 and 2 in the continental site (Fig. 2b). The most parsimonious model for total trail width change (Table 3b) showed a significant increase in total trail width with use intensity, and a significant interaction between use intensity and proportion of bikers revealing that total trail width increased more with a combination of high use and many bikers. There was no significant main effects of environmental conditions (soil moisture; $p = 0.084$, sand and silt; $p = 0216$). However, significant two-way interactions between the number of passes and each of these two environmental variables showed that as use intensity increased, total trail width increased particularly in wet parts of the trail and in parts with high content of sand and silt. There was one outlier in the dataset, where total trail width increased with 638 cm from the first to the last sampling time (oceanic biking trail). Excluding the outlier did not affect the final model.

Trail depth varied between 0 and 65 cm, and the change in trail depth from sampling time 1 ranged between −13.5 and 57 cm (0.84 ± 4.0 cm). Generally, effects of both use and environmental variables on trail depth change were small (small coefficient estimates compared to Table 3a and b). The main effects of use intensity and proportion of bikers were not statistically significant (Table 3c), but a small increase in trail depth related to soil moisture was evident. Further, the use intensity × proportion of bikers interaction revealed a small, but statistically significant increase in trail depth with a combination of high use and many bikers (Table 3c, Fig. 2c). Soil or terrain properties (sand and silt, trail slope, or trail slope alignment) had no effect on deepening of trails.

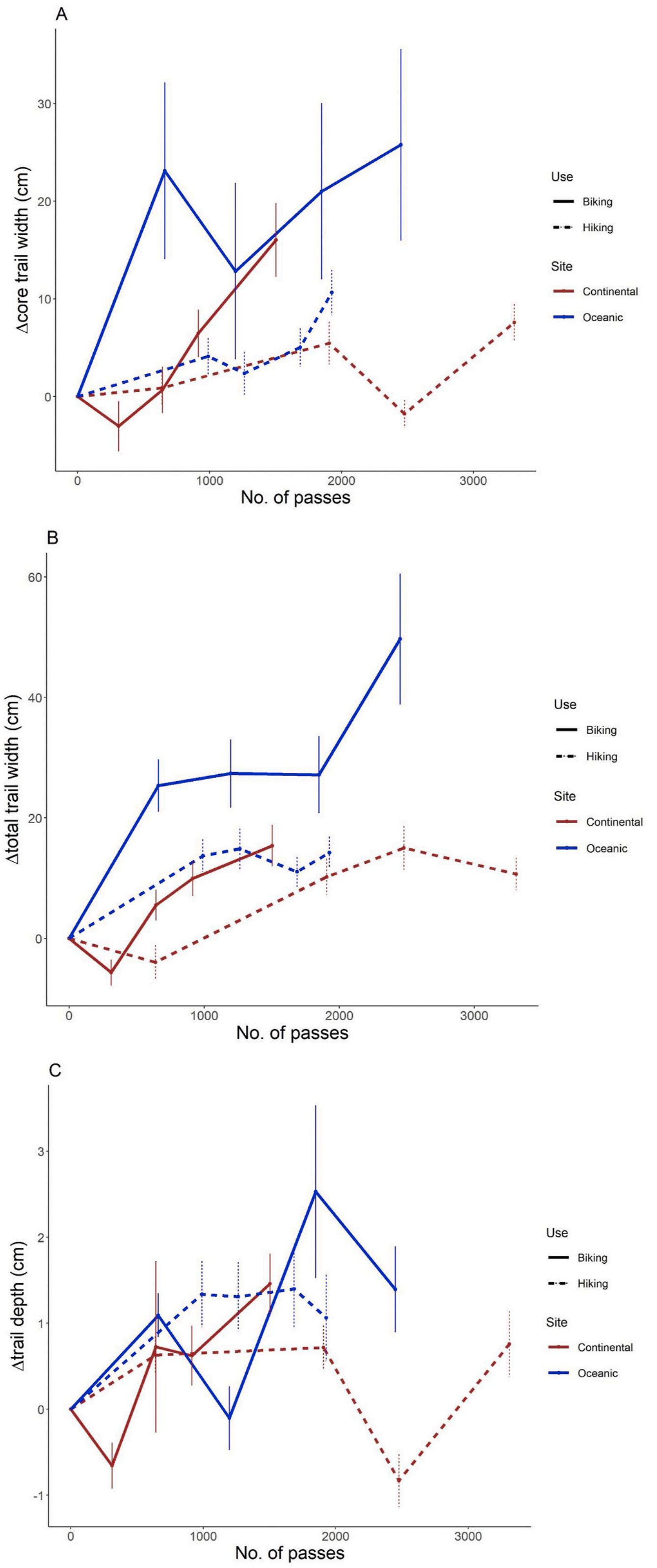

Fig. 2. (A) Change in core trail width, (B) change in total trail width, and (C) change in trail depth (cm) as a function of use intensity, for each trail separately. Blue = oceanic site, brown = continental site, solid lines show trails designated for biking, dotted lines show trails designated for hiking. Error bars show ±1 SE. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4. Discussion

In this study, we manipulated the use intensity by hikers and mountain bikers on existing, natural-surfaced trails, and investigated effects of increased use and the relative importance of mountain biking on trail degradation.

4.1. *Changes in trail width and depth*

At the start of the study, trails were wider in moist and flat compared to dry and steep parts. When use intensified, we found an overall small,

Table 3
Parameter estimates for "best" model of change in A) core trail width, B) total trail width, and C) trail depth as a function of use intensity, proportion of bikers and environmental variables. Estimates of random factors (core and total trail width: trail/segment/transect, trail depth: segment/transect) are not shown.

	Estimate	Standard error	t-value	p-value
A) Change in core trail width				
Intercept	7.967	6.610	1.205	0.320
No. passes	3.730	0.808	4.619	<0.001
Proportion of bikers	1.510	2.129	0.709	0.479
Soil moisture	10.889	3.591	3.033	0.003
No. passes × proportion of bikers	2.916	0.859	3.396	<0.001
Proportion of bikers × soil moisture	5.903	1.858	3.178	0.002
No. passes × soil moisture	1.679	0.832	2.018	0.044
B) Change in total trail width				
Intercept	13.273	6.385	2.079	0.137
No. passes	7.348	1.275	5.764	<0.001
Proportion of bikers	2.479	3.219	0.770	0.445
Soil moisture	4.309	2.466	1.747	0.084
Sand and silt	3.095	2.492	1.242	0.216
No. passes × proportion of bikers	5.285	1.439	3.672	<0.001
No. passes × soil moisture	4.659	1.166	3.995	<0.001
No. passes × sand and silt	3.386	1.080	3.135	0.002
C) Change in trail depth				
Intercept	0.772	0.206	3.755	<0.001
No. passes	0.232	0.142	1.640	0.101
Proportion of bikers	0.188	0.204	0.919	0.360
Soil moisture	0.459	0.197	2.331	0.022
No. passes × proportion of bikers	0.594	0.188	3.157	0.002

average increase in trail width, but the variation between trail parts was large. Soil moisture was the most important environmental predictor for trail width increase, demonstrating the sensitivity of soils with high content of organic material or poor drainage to recreation activities (Meadema et al., 2020; Whinam and Chilcott, 2003). Further, the significant interaction between number of passes and soil moisture revealed that the trail width increased more in moist than in dry parts of the trail with enhanced use. This effect was even greater when a large proportion of the users were mountain bikers. Thus, our results suggest that mountain biking has more negative effects on trails in moist areas, such as mires, bogs or swampy areas, than hiking, in contrast to our expectations. Avoiding moist or muddy core parts of the trail is likely an important cause of trail widening (Dixon et al., 2004; Olive and Marion, 2009), and our results suggest that mountain bikers are more inclined to avoid these core sections of the trails. We found no effect on trail width from topography (trail slope or trail slope alignment), and only a small effect of substrate (increasing total width where the amount of sand and silt was large, when use intensity was high). Trails were wider in flat terrain both in the beginning and the end of the study period, strengthening the impression of users to spread out when the terrain flattens.

As expected, trail depth varied along the trails at the start of the study, being larger in steep parts of the trails (Meadema et al., 2020). However, as use increased, we found only small overall changes in trail depth – and both increases and decreases in depth occurred (Fig. 2c). The small overall changes suggest that the soils along the trails were already compacted and to a limited degree prone to soil movement and subsequent soil loss. The observed depth decreases were small. Soil loosening and movement could potentially lead to soil accumulation (and thus reduced depth) in some transects. Further, in flat, muddy trail sections, the susceptibility to hiking/biking – and hence trail depth – was observed to vary with weather conditions; after rain ruts or footprints were deeper than in dry weather. In addition, some measurement errors could occur, although this is not likely to be an important contributor, as previously recorded measurements were consulted when doing field work. Although changes in trail depth were small, statistically significantly larger effects were found when a greater proportion of the passes was constituted by mountain bikers, suggesting more soil loosening by tires than feet. The effect of soil substrate or topography (trail slope or trail slope alignment) on trail depth increase were negligible, in contrast to expectations (Marion and Wimpey, 2017; Meadema et al., 2020; Olive and Marion, 2009; White et al., 2006), except for an increase in trail depth with increasing soil moisture.

The oceanic and the continental trails had slightly different initial trail conditions, particularly the oceanic biking trail was wider and deeper. We chose the two study sites partly to cover contrasting climatic conditions, especially in terms of precipitation during the summer season (Table 1), as rainfall could accelerate soil erosion after hiking/biking, contributing to increasing trail depth (Leung and Marion 1996). However, our findings do not suggest such an effect in the oceanic site, despite the general steeper topography and larger elevation range included along the trails (Table 1). Although we did not test specifically for effects of study site, results do suggest that high use may exacerbate trail degradation (trail width) in high-rainfall areas (Fig. 2). Nevertheless, all study trails covered variation in moisture, substrate and topography, and the result shows that for management purposes, the environmental conditions along the trail, and not just geographical position, are highly relevant.

4.2. Limitations of the study design

This study is an attempt to add another piece to the puzzle on effects of human use on vegetation. The range of potential variables to include in these types of studies, both environmental variation and use types and behaviors (number, equipment, when, where, how) that could be of relevance for management decisions, is infinite. Our study is limited, but with a clear purpose: to investigate the relative importance of hiking vs. mountain biking on trail degradation on existing, natural-surfaced trails. Although the study includes only four trails in two study sites, the defined criteria for including a study trail (see 2.1. Study sites) ensured the inclusion of environmental variation of known importance for predicting trail degradation, such as trail slope and alignment in the terrain and trail substrate (erodibility, moisture) (for a recent literature review, see Meadema et al., 2020). We therefore believe our results to be generalizable. However, environmental extremes, e.g. very dry, very steep or very erodible substrate, were lacking on our trails, and our results may have limited transfer value to such areas.

Following the predictions of the curvilinear response curve (Hammitt et al., 2015; Monz et al., 2013), increased on-trail recreational use on well-established trails should have small effects. We have limited knowledge of use intensity on the study trails in the years prior to the study, thus exactly where along the use intensity spectrum our study started out, is hard to establish. Further, the total accumulated use during the field season was relatively low (see e.g. Gundersen et al., 2019). Nevertheless, we demonstrate that within a growing season, increased use does indeed cause wider trails. The shape of the response curve varies, however, among trails (Fig. 2). Use type seems to account for some of these differences: core trail width in particular increased more (steeper curves) with increased use on the designated biking trails compared to the hiking trails. Further, the results clearly demonstrate differences in the response curves along parts of the trails (Table 3), with a steeper relationship between use and effect in wet than in dry trail segments, this effect also being larger in the designated biking trails. Further, our results show that trail width is not a simple function of use intensity; a complex combination of timing (when in the growing season), weather (heavy rainfall or dry periods) and use intensity results in varying – and sometimes decreasing – trail width throughout a growing season.

4.3. Contributions to the literature

Existing comparative studies of hiking and biking show small to no differences in trail degradation effect (Chiu and Kriwoken, 2003; Pickering et al., 2011; Thurston and Reader, 2001). However, these studies have been conducted within a short time-span and with a low number of total passes, and some were carried out in undisturbed vegetation (Pickering et al., 2011; Thurston and Reader, 2001). Studies on existing trails with a high number of users (Bjorkman, 1998; Meadema et al., 2020; White et al., 2006; Wimpey and Marion, 2010) do not directly compare hikers and bikers. Our study is thus a necessary supplement to existing literature, as the first study to compare the relative effects of mountain biking and hiking on natural-surfaced trails throughout a whole growing season, accounting for the number of passes by each use type.

Our design was successful in enhancing biking on the designated biking trails, thus allowing the investigation of the relative impact of biking. We manipulated use through encouraging, rather than experimentally applying, recreation on the trails. Thus, the study investigates effects on trails of normal behavior, which is important, as controlled experimental studies may underestimate trail degradation effects such as trail widening by using one person to trample or bike back and forth.

The oceanic biking trail was used for a local Enduro race during the study period. While biking calmly uphill, at least some of the mountain bikers raced downhill, which might have affected their biking style compared to recreational biking, e.g. with a higher tendency of skidding or taking short cuts, contributing to increasing trail width. The quantification of different behavior is, however, not possible with our dataset. Nevertheless, our finding of both increased trail depth and width in moist trail segments suggest that behavior patterns vary: while some avoid wet and muddy parts, contributing to trail widening, others pass straight through, leaving deep foot marks or ruts.

The proportion of bikers on designated biking trails in our study (approximately 50%) is likely higher than what is to be expected in general on trails in national parks, where biking is only recently proposed to be allowed. Thus, our results are highly relevant for future management strategies on national park trails.

4.4. Conclusion

Management of increased recreational use of nature in general and protected nature areas in particular, is a global challenge. Knowledge about the users and activity specific degradation effects is of critical importance for establishing appropriate management recommendations. Our study shows that on-trail use by hikers and mountain bikers have relatively limited effects in terms of trail widening and deepening. However, the effects are variable: where trails cross wet areas, such as mires, bogs or other plant communities with poor drainage, more trail degradation is to be expected with increased use from both hikers and mountain bikers. Our study also demonstrates that higher trail degradation can be expected if a large proportion of the users are mountain bikers, particularly in wet trail parts. Management and maintenance of trails, in terms of re-routing or trail surface hardening, could thus be necessary to avoid negative impacts of increased use. For such management actions to be successful, however, they need to be targeted towards the actual user groups and carried out in accordance with hiking and mountain bike trail standards.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2020.111554.

Novelty and relevance statement

This is the first study to compare the relative effects of mountain bikers and hikers on trail degradation on existing, natural-surfaced trails with control over use intensity. The study has relevant implications for management of trails, demonstrating that increased use leads to increased trail width, particularly when moist, and this effect is greater when a large proportion of users were mountain bikers, calling for targeted management and maintenance of trails.

Author contribution

Marianne Evju: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Writing – Reviewing and Editing, Dagmar Hagen: Conceptualization, Methodology, Writing - original draft, Writing – Reviewing and Editing, Mari Jokerud: Conceptualization, Methodology, Investigation, Writing – Reviewing and Editing, Siri Lie Olsen: Conceptualization, Methodology, Investigation, Writing - original draft, Writing – Reviewing and Editing, Sofie Kjendlie Selvaag: Conceptualization, Methodology, Investigation, Writing - original draft, Writing – Reviewing and Editing, Odd Inge Vistad: Conceptualization, Methodology, Writing - original draft, Writing – Reviewing and Editing

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