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RESEARCH ARTICLE

Mechanical impacts of climbing on cliff vegetation: Contrasting management concepts

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Abstract

1. Climbing a boulder for the first time often means entering a previously inaccessible ecosystem, many of which are inhabited by rare species. Little is known about the impacts of first ascents on cliff vegetation, especially with respect to different rock types. Our study builds on this knowledge gap and investigates how climbing activities affect undisturbed rock ecosystems.
2. We experimentally climbed three previously unclimbed boulders (sandstone, limestone and granite) 500 times. Although limited to a single boulder per rock type, our experiment provides preliminary insight into how vegetation cover responds to climbing activities in different lithologies. The loss of vegetation was analysed using a time series of images of hand and footholds. For one site, vegetation recovery was quantified 3 years after climbing treatment. In addition, Raman spectroscopy was used to analyse possible microplastic abrasion of climbing shoes.
3. The vegetation cover on climbing holds decreased by 0%–15%, with the first ascents being particularly decisive. Vegetation loss varies between rock types, with soft sandstone showing the highest loss due to abrasion of the rock surface.
4. A partial recovery of the cover of the microbial community was observed over 3 years after climbing treatment on the sandstone boulder.
5. Raman spectroscopy identified black particles found on climbing footholds as microplastic abrasion from climbing shoes.
6. The mechanical stress caused by boulderers damages rock vegetation locally on climbing holds and is one of the impacts induced by climbing. Even moderate frequency and no prior cleaning of routes can lead to longer lasting damage to cliff vegetation. In sensitive areas, appropriate management actions should be developed by climbing associations, experts and nature conservation organizations. The strong effect on vegetation caused by first ascents suggests that climbing management should favour closing entire rocks while leaving others open

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(zonation concepts), promoting spatial concentration of impacts. Further studies on microplastics caused by climbing are recommended.

KEYWORDS
bryophytes, cliff ecology, climbing impact, conservation, lichen, management strategies, microplastics, vegetation cover

1 | INTRODUCTION

Climbing is increasing in popularity around the world. It is one of the outdoor sports that has experienced the greatest growth in active athletes, as well as an expansion of climbed rock sites since the middle of the 20th century (McMillan et al., 2003; Rusterholz et al., 2004; Vogler & Reisch, 2011). As the number of climbers increases, the question of their impact and influence on the environment becomes more crucial. Cliffs are priority ecosystems with high conservation value, underscoring the need for stronger protection to mitigate biodiversity loss by 2030 (Morales-Armijo & March-Salas, 2024). These fragile cliff ecosystems have historically been regarded among the most intact ecosystems with minimal human disturbance (Kelly & Larson, 1997; Lorite et al., 2017). However, the extensive inaccessibility of cliffs has led to a lack of research on cliff ecosystems and their responses to disturbances (Herter, 1996; Lorite et al., 2017; Newsome et al., 2012). The rapid rise of sport activities, particularly in ecologically sensitive areas such as cliffs, has drawn increasing attention to their environmental impact, making it a growing focus of study. It is known that climbers affect the cliff ecosystem by (1) removing plants from the rock face, including deliberate 'route cleaning' by brushing off plants, soil and seeds; (2) trampling vegetation at the base of the rock; (3) disturbance of animals living in the rock; (4) use of climbing chalk, leading to rock degradation; and (5) introduction of alien species (Morales-Armijo & March-Salas, 2024). Furthermore, climbing routes often traverse sensitive habitats, where they can conflict with rare vegetation that grows in crevices, cracks, pockets or ledges which climbers use for hand and footholds as they ascend the rocks. Most studies report a change in vegetation communities at climbed sites (Adams & Zaniewski, 2012; Boggess et al., 2021; Camp & Knight, 1998; Clark & Hessl, 2015; Matthes et al., 2000; McMillan & Larson, 2002; Nuzzo, 1996; Rusterholz et al., 2004), while in other studies, climbing activities show no effect on the natural vegetation composition of the rock (Baur et al., 2017; Boggess et al., 2021; Kuntz & Larson, 2006). Studies also suggest that the impact of climbing varies between taxa, with a significant effect observed only on lichens (Adams & Zaniewski, 2012; Boggess et al., 2021; Clark & Hessl, 2015; Nuzzo, 1996), bryophytes (Boggess et al., 2021; Kuntz & Larson, 2006; McMillan & Larson, 2002; Tessler & Clark, 2016) or vascular plants (Lorite et al., 2017). Possible causes of these mixed results are differences in microtopography between unclimbed and climbed rocks (Holzschuh, 2016), site-specific variations in cliff vegetation and species-specific sensitivity to human disturbance (Rusterholz et al., 2004), or the respective study design (Boggess et al., 2021).

Management recommendations from some research findings suggest that low-frequency climbing has no significant impact on the cliff ecosystem (Tessler & Clark, 2016). However, studies revealed the strongest negative effects on cliff dwelling plants when densely vegetated routes are newly developed (Morales-Armijo & March-Salas, 2024) or during the first use of climbing sites (Schweizer et al., 2021). Option one (from now on the 'low-frequency concept') would limit the overall number of climbers to a—yet-to-be defined—carrying capacity. Low-frequency climbing could be enforced by permits and restricted information flow, that is, prohibiting publication of bouldering areas (Lorite et al., 2017; Tessler & Clark, 2016). Option two (from now on 'zonation concept'), on the other hand, would restrict climbing activities to selected cliffs, leaving cliffs with a high conservation value untouched and addressing the concerns of new route development. This concept could be enforced by banning climbing in sensitive cliff habitats.

Implementing an efficient management strategy requires discussing the underlying research controversy: Is the cliff vegetation disproportionally affected by the first rock climbers ascending the cliff (even without prior cleaning of hand and footholds) or can the cliff vegetation withstand and recover from low-frequency disturbance? The diversity in previous research findings indicates that the answer may be context-dependent and therefore varies with cliff type and species community.

2 | MATERIALS AND METHODS

Addressing this research question, the study design aims to assess possible non-linear relationships between climbing frequency and vegetation damage: (1) During the climbing of previously untouched rocks, the impact on the rock vegetation of sandstone, limestone and granite crags was recorded photographically and saxicolous bryophytes were determined. We chose one boulder per rock type due to limited resources and acknowledge a resulting reduced inferential power, as well as limited generalizability of the outcomes. (2) The sandstone boulder was reexamined and evaluated 2 and 3 years after the experiment of Schweizer et al. (2021) to explore the recovery of vegetation. (3) Additionally, a limestone swab was analysed for microplastic particles that became visible during the ascents.

Our assumptions were that (1) climbing leads to a rapid decline in rock vegetation during the first couple of ascents and (2) that

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vegetation cover does not fully recover within 3 years. The knowledge gained from this study can contribute to the development of sustainable climbing concepts.

2.1 | Impact of bouldering on rock vegetation and management concepts

Our study area in southeastern Germany provides popular sites for outdoor climbing and bouldering on granite in the Fichtelgebirge, sandstone near Bayreuth and limestone in the Frankenjura. The local climbing concepts reflect the two contrasting management options. Rock climbing with ropes on sport climbing cliffs is regulated following the zonation concept, which comprises the division of climbing crags into three zones: closed for climbing (zone 1), zones where climbers can ascent existing routes but not develop new ones (zone 2) and zones where climbing is allowed and the establishment of new routes can be agreed with the responsible organizations (zone 3; IG Klettern, 2021a). For bouldering, a climbing subdiscipline, in which small boulders (mostly <3.5 m) are climbed without a rope, a low frequency concept is implemented. The 'Boulderappell', a self-commitment for boulderers, includes 12 recommendations that allow bouldering with little restrictions but confines overall user frequency by prohibiting publication of bouldering areas (IG Klettern, 2021b). Both concepts effectively regulate climbing activities. While the zonation concept restricts rock climbing to selected large cliffs, the low-frequency concept decreases the overall number of active boulderers by limiting information on available sites. This does not specify the areas where bouldering is environmentally and socially acceptable. Due to the few studies on the effects of climbing, it is still difficult to assess whether this regulation adequately protects the rock ecosystem (Schwartz et al., 2019).

2.1.1 | Methods for assessing vegetation development (%) during ascents

A standard technique used to measure the effects of trampling on vegetation by Cole and Bayfield (1993) has been adapted to measure the effect of bouldering on the vegetation cover of a rock. To compare the impact of climbing on different types of rock with distinct characteristics regarding their surface properties, mineral composition and vegetation composition, this study applied the method to sandstone, limestone and granite crags (Figure 1; Appendix S1).

Before the experiments, the selected rocks showed no signs of climbing (chalk, removed vegetation, trampled ground, etc.) and exhibited the typical characteristics of attractive boulders from a climber's perspective (e.g. sufficient hand and footholds on the cliff with moderate to low vegetation cover, save landing zone). We neither used chalk nor cleaned the cliff faces from vegetation prior to climbing to exclude additional chemical and intentional mechanical impact on species. Additionally, all holds were natural and were neither altered nor sculptured for climbing. The selected rocks were covered with lichen and partially bryophytes. Vascular plants were absent from our climbed routes. Necessary permits from relevant authorities and forest owners were obtained to carry out the fieldwork in the selected areas. Further, all climbers were informed about the aim, procedure and purpose of the study and voluntarily agreed to participate.

The climbing session on each rock lasted between 2 and 8 days in a period of 2 days to 2 weeks. While the sandstone was climbed in June and July 2020 (cf. Schweizer et al., 2021), the interventions on limestone and granite were completed in October 2023. We conducted our 500 ascents in a relatively short time frame to observe the direct impact on vegetation without allowing significant recovery. This approach simulates a higher climbing frequency, compared

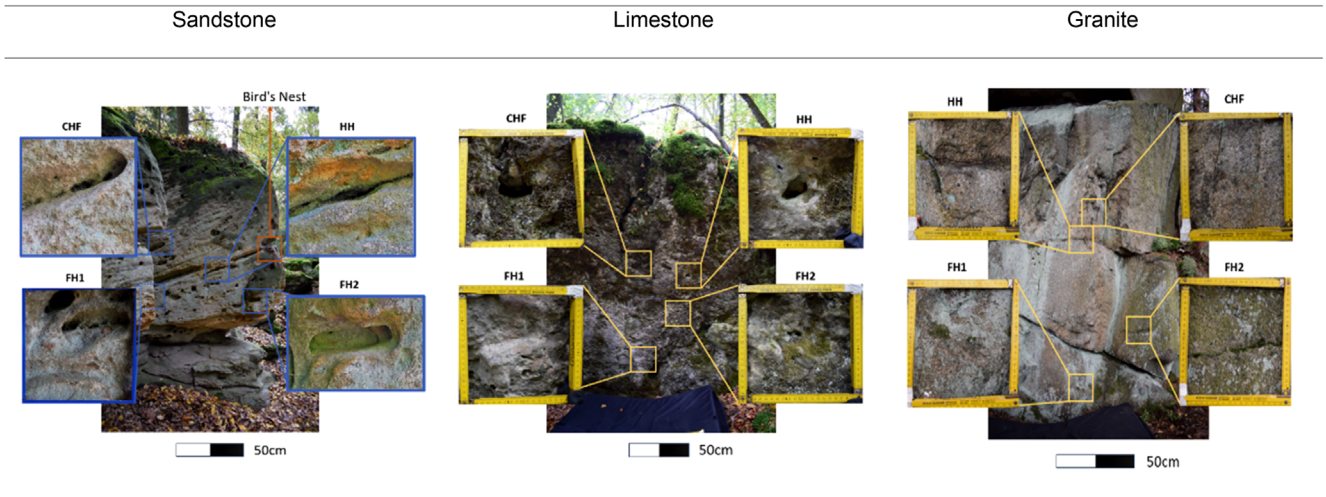


FIGURE 1 The rocks examined with the selected natural hand and footholds. The influence of climbing on rock vegetation was investigated on sandstone (49.91758, 11.50744), limestone (49.77895, 11.38902) and granite rocks (49.99328, 11.99903) near Bayreuth. A handhold (HH), two footholds (FH1, FH2) and a combined hand and foothold (CHF) were defined on the selected rocks and used at each ascent to determine the change in vegetation cover (%) at these locations. An abandoned bird's nest was found on the sandstone rock during a subsequent visit in 2023.

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to the maximum 30 ascents of a route climbing experiment by Morales-Armijo et al. (2024). To determine the percentage decrease in vegetation, the bryophyte and lichen cover of each boulder was visually assessed and documented before treatment, as well as after 10, 20, 30, 50, 75, 100, 150, 200, 250, 300, 350, 400, 450 and 500 ascents. One handhold (HH), two footholds (FH1 and FH2) and one combined hand and foothold (CHF), which were used for each ascent, were photographed in the mentioned interval steps.

The contrast and brightness of the images were increased by software. Automatic image analysis, such as ImageJ, was tested, and several different approaches were considered. However, a quantitative image-based method could not detect and distinguish the specific colours of the bryophytes and lichens, which were in some cases nearly identical to the substrate colour (e.g. for limestone) and was deficient due to variable lighting conditions. Therefore, the total loss of vegetation was manually evaluated and is based on visual estimation by humans. To ensure consistency and transparency in our estimates, we first established clear assessment criteria. As part of this process, we re-evaluated the sandstone images of Schweizer et al. (2021) using these criteria. Initial evaluations were conducted by two observers, who jointly discussed and refined the criteria. Subsequently, the images were individually evaluated in randomized order. Cross-checking was performed to align interpretations and resolve discrepancies. For the cover estimation, a 20 × 20 cm frame with a 5 × 5 layover grid was used (Figure 1). The mean cover of all cells (each cell 4 × 4 cm) combined is the relative bryophyte and lichen cover of the selected hold at the respective number of ascents. Data analysis and visualization were carried out in R version 2021.09.0 with packages 'segmented' and 'AICcmodavg' (R Core Team, 2021).

2.1.2 | Species communities of the study sites

Lichens deserve high priority in monitoring species affected by climbing, as they occupy the same niches as climbers (Clark & Hessl, 2015). Although lichens were not systematically classified and determined, bryophytes were represented by 12 widespread species on the limestone and granite rocks (Appendix S2, Düll & Düll-Wunder, 2023; Euro+Med PlantBase, n.d.; Meinunger & Schröder, 2007). On the sandstone rock, no bryophyte species were detected.

2.2 | Vegetation recovery on bouldering routes

To evaluate the long-term effects of climbing on the rock ecosystem, the rehabilitation ratio of the sandstone has been examined. The ratio was determined by assessing microbial recolonization on hand and footholds over a 2–3-year recovery period. Therefore, images of the hand and footholds were taken after climbing in 2020 (see Section 2.1) as well as in 2022 and 2023. Images were mixed randomly to avoid bias, and the percentage of cover of the microbial community (consisting of algae, fungi and bacteria) was visually estimated. The comparison of the vegetation cover on sandstone from 2020, 2022 and 2023 aims to reveal the extent to which the rock ecosystem can recover from disturbances caused by climbing. We consulted a lichenologist to critically evaluate our hypothesis and obtain an expert opinion. The other two types of rock (granite and limestone) were not included in the recovery analysis since the climbing experiment was only conducted in 2023, and the vegetation had not yet had time to recover.

2.3 | Microplastic rub-off from climbing shoes

With a growing number of ascents, the increasingly black coloration of some footholds suggested abrasion of the shoe soles. Black material samples were analysed in the laboratory using a WITec alpha300 RA+ Raman imaging system, employing a 50× objective with a numerical aperture of NA = 0.55 (Zeiss LD EC Epiplan-Neofluar Dic 50×/0.55). Spectra were acquired with an excitation wavelength of $l = 532$ nm using an integration time of 0.5 s (50 accumulations) and a laser intensity of 1 mW. Two particles, one from the cliff sample and another from the climbing shoe sole, were analysed on their chemistry and morphology to determine whether the particles originated from the same material.

3 | RESULTS

3.1 | Reduction of vegetation coverage during bouldering activities

During the ascents, a decline in bryophyte and lichen cover became apparent on each boulder (Figure 2). Using the Akaike Information Criterion (AIC) and R^2, the segmented regression model was identified as the most appropriate model to describe the course of vegetation decline, largely outperforming both the linear regression model and the null model with zero slope (Appendix S3).

The loss of vegetation cover on the holds varied between 0.0% and 14.6% points. It was lower on the handholds (0.0%–2.0% points) than on the combined hand and footholds (1.8%–9.4% points) and footholds (0.0%–14.6% points). Consequently, the holds that experienced a decline in vegetation cover (>0% points) showed the most significant reduction during the initial ascents, with breakpoints ranging from 10 to 287 ascents, and an average breakpoint at 129 ascents (Appendix S3). On several holds, a further decline in vegetation cover was observed after the breakpoint.

The removal of lichens and bryophytes was concentrated around the immediate surroundings of the hand and footholds. Thus, the percentual decrease would be higher if the units of measurement were limited to the scope directly used for climbing or significantly lower if compared to the whole cliff.

The rock types show varying degrees of decline in the percentual vegetation cover over the course of the ascents (Figure 2; Appendices S3 and S4). The lichen cover of the sandstone decreased by 2.0%–14.6% points to a relative cover of 85.2%–93.6%.

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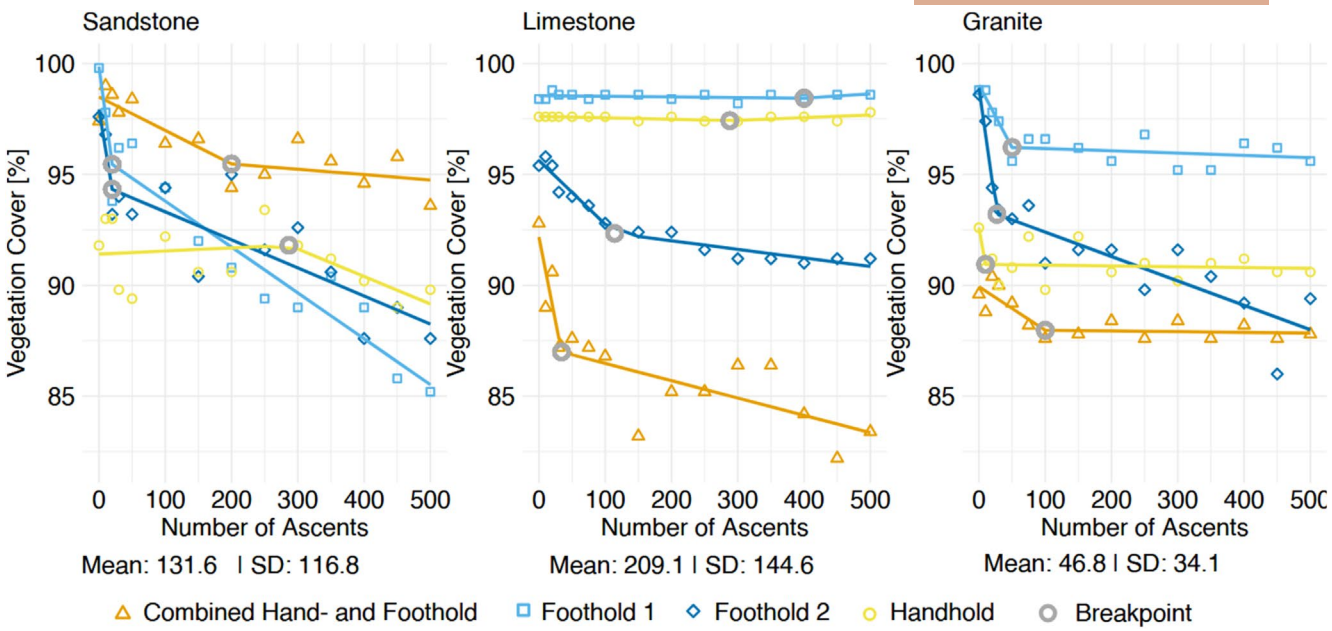


FIGURE 2 Development of vegetation cover on selected climbing holds over the course of 500 ascents, modelled using segmented regression. For most of the holds, the strongest decline in vegetation cover occurs during the first ascents. Many continue to show a decline after the breakpoint, without stabilizing within the 500 ascents observed. Below the graph, the means and standard deviations (SD) of the breakpoint values of all holds combined are presented for each rock type.

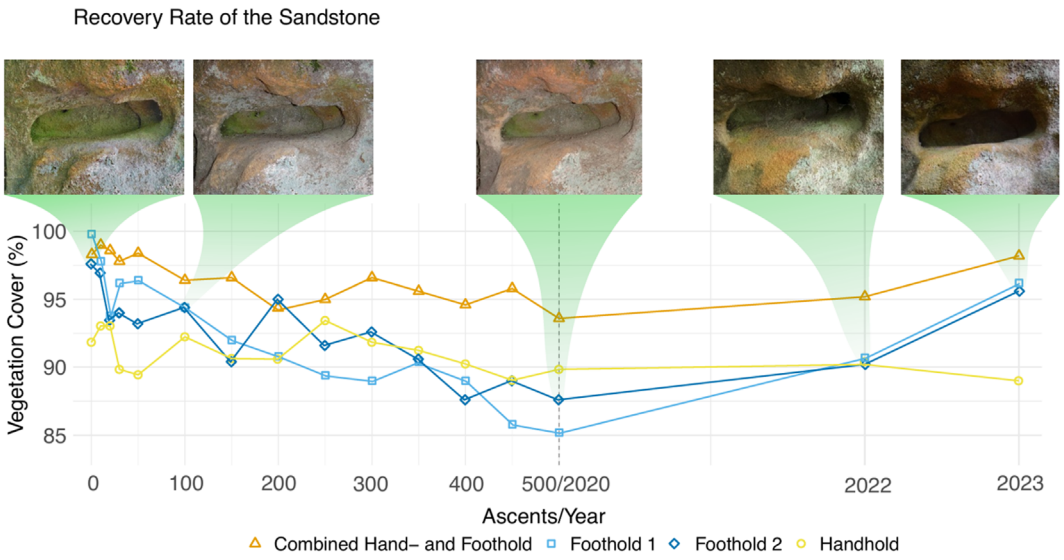


FIGURE 3 Decrease and recovery of the cover of the lichen and microbial community on the sandstone rock during the study period. The percentage of colonized cover of the holds has decreased by 2.0%–14.6% points during the 500 ascents in 2020. In the three subsequent years, a microbial community recolonized 0.0%–11.0% points. The decline and recovery are visible in the images of foothold 2.

An abrasion of the lichen cover with parts of the rock surface was visibly noticed (Schweizer et al., 2021). The combined hand and foothold as well as the handhold showed a slight decrease in lichen cover of 2.0%–3.8% points. For footholds 1 and 2, the loss in lichen cover was higher with 10.0%–14.6% points (Figures 2 and 3).

For the limestone boulder, the percentual vegetation cover did not change for foothold 1 nor for the handhold. The combined hand and foothold, as well as foothold 2, showed a decrease in vegetation cover of 4.2%–9.4% points to a relative cover of 83.4%–91.2% (Figure 2). The combined hand and foothold was a crevice. During the climbing session, the soil, as well as the lichen and bryophyte cover in and around it, were visibly removed.

The relative cover of lichen and bryophytes on the unclimbed granite was 89.6%–98.8%. During the 500 ascents, it was reduced by 1.8%–9.2% points to a total cover of 87.8%–95.6%. The combined hand and foothold, foothold 1 and the handhold, showed a decline in their lichen and bryophyte cover by 1.8%–3.2% points, while foothold 2 showed a stronger decline of 9.2% points (Figure 2).

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3.2 | Recovery of vegetation cover after a selected period of time

The cover of the microbial community (consisting of algae, fungi and bacteria) on the sandstone showed signs of recovery after a period of 3 years. During the recovery period, the cover on the footholds increased by 8.0%–11.0% points, while 2.0%–3.6% points of the initial cover did not recover (Figure 3; Appendix S4). Notable was the partial change in colour of foothold 1 from predominantly grey lichen (2020) to a greenish-yellow biofilm (2023). The colonized area of the combined hand and foothold experienced a full recovery (3.8% loss in 2020), while no regrowth was visible on the handhold.

3.3 | Microplastics released from climbing shoes

The material responsible for the black discoloration of foothold 1 of the sampled limestone represents black rubber abraded from the climbing shoes (Figure 4).

Raman spectra with nearly identical peaks at around 1342 and 1577 cm^{-1} imply that the particle samples taken from the limestone rock and the climbing shoe sole were derived from the same material. Interestingly, it was mainly the high carbon black content that was identifiable from the sole. This finding is consistent with the statement of the climbing magazine Lacrux (Lacrux, 2022), which says the material of climbing shoe soles is industrial rubber, which is 97% petroleum-based and further contains, among other ingredients, carbon black.

4 | DISCUSSION

4.1 | Disturbances of the cliff ecosystem caused by climbing

The objective of this study was to evaluate the impact of bouldering on the vegetation cover of previously unclimbed rocks in relation to an increasing number of ascents without prior route cleaning. In contrast to Baur and Fröberg (2007), Clark and Hessl (2015) and Kuntz and Larson (2006), we also determined an impact of climbing on bryophytes and not exclusively on lichens. The results confirm that bouldering leads to a decrease in the percentage of rock vegetation cover. For most holds, we found the strongest decline during the first ascents. After the breakpoint, the loss rate decreases but continues for the majority of holds.

The overall decline in vegetation cover due to climbing activities differed between rock types. Sandstone showed the highest decrease in vegetation cover with 10.0%–14.6% points on the footholds and 2.0%–3.8% points on the combined hand and foothold and handhold. The effect of bouldering may be strongest on sandstone due to its characteristics as the rock with the highest porosity and the lowest abrasion resistance compared to limestone and granite (Kılıç et al., 2008; Schweizer et al., 2021). During the ascents, the surface of the sandstone substrate was partially abraded, and presumably, the lichen cover was also removed along with the substrate (Adams & Zaniewski, 2012; Schweizer et al., 2021). Therefore, we assume that the different rate of vegetation loss depends on the characteristic microtopography of the rock. Limestone has a lower erosion rate than sandstone and, furthermore, a higher porosity as well as a lower resistance force than granite. This probably makes the limestone's lichen and bryophyte community more resistant to disturbance. These findings align with management recommendations that suggest adapted climbing practices if the rock substrate is less solid. This includes the prior cleaning of shoes before climbing (Fontainebleau Rules, 2024), no climbing in wet conditions, etc. (Friedrich, 2002).

The variable impact of bouldering on cliff ecosystems of various rock types also raises the question of whether different levels of protection are required. Lower species richness of lichen is found on granite (Armstrong, 2024; Brodo, 1973). Furthermore, the endangerment or loss of lichen species on granite and sandstone is more severe (39%) than on calcareous rock (17%; Litterski et al., 2019). Although when it comes to bryophytes, Cleavitt et al. (2009) state that rare moss species are found more frequently on calcareous rock, such as limestone. The richness of liverwort species, on the other hand, increases on non-calcareous

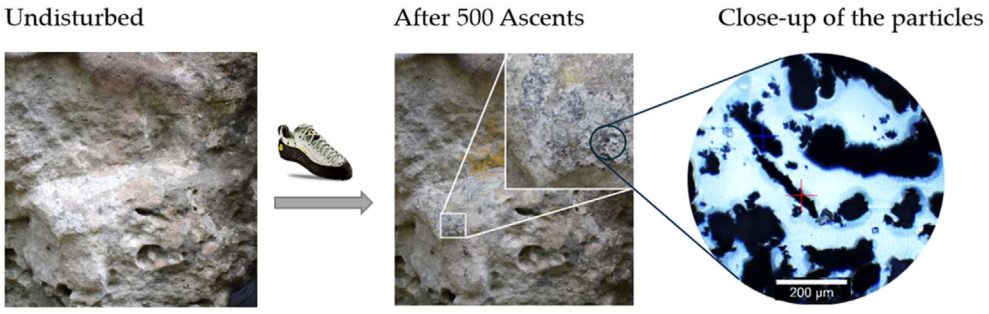


FIGURE 4 Detection of microplastic input through climbing activities. After 500 ascents, foothold 1 of the limestone showed black discoloration. Under the microscope, elongated particles were observed that show the typical structure of rubber abrasions, which is not common for naturally occurring materials. Raman spectroscopy was used to compare particles from the rock and the climbing shoes. Since the characteristic peaks in both samples are nearly identical, they have the same chemical composition and structure, indicating that they are made of the same material.

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rock (Cleavitt et al., 2009). Several rare, also red-listed bryophyte and lichen species on sandstone cliffs in Germany (Thiel & Spribille, 2007), indicate that each rock type remains an ecosystem of its own with a unique plant community requiring individual assessment and protection.

All in all, the reduction in vegetation cover was lower on the handholds (0.0%–2.0% points) than on the combined hand and footholds (1.8%–9.4% points) and the footholds (0.0%–14.6% points). A possible reason for this is the 33% higher reaction force on footholds compared to handholds on a vertical rock surface (Noé et al., 2001; Schweizer et al., 2021). Also, while the skin of the fingers is elastic and adapts to the rock surface, the climbing shoe sole is more stable with a higher friction. As a result, the load exerted by the hand is lower due to its even extension on a larger surface area (Schweizer et al., 2021). Furthermore, climbers slip more frequently with their feet than with their hands due to reduced sensation, with more effect on the rock due to higher friction of the sole (Schweizer et al., 2021). Our findings underscore that the first ascents and the development of the route affect cliff plants the most (Morales-Armijo et al., 2024; Schweizer et al., 2021), but we could show a considerably lower impact on the vegetation of the cliffs in our study, where prior cleaning and active removal of vegetation were excluded. This highlights the potential to minimize vegetation removal during the development of the route as a key lever for conservation.

4.2 | Recovery

The sandstone was not climbed during the recovery period of 3 years due to its inaccessible location. Furthermore, the neighbouring crags also showed no signs of climbing. In general, the recolonized area of the sandstone rock increased substantially during the recovery period of 3 years. However, the relatively long period was still too short for a full recovery of the initial lichen community of all holds. In addition, we assume the presence of early stage colonizers, that is, microbial communities with algae, fungi and bacteria, which might endured the past disturbances as endolithic community (Hallmann et al., 2015) and/or also have been dispersed via free air. The sheltered and presumably rather humid conditions on sandstone could provide a favourable environment for fast microbial colonization. The slow growth rate of lichens depends on the climatic conditions (Beschel, 1958) and the pH-value of the substrate (Hepenstrick et al., 2020; Steinbauer et al., 2013; Weber & Büdel, 2001). However, we acknowledge that our recovery analysis is restricted to one sandstone boulder and cannot be generalized, that is, for other rock types. Replicated studies on different rock types and a multitude of species (lichens, bryophytes and vascular plants) are needed to evaluate the recovery rate of climbing rocks. On foothold 1 of the sandstone, a change in species composition was visible, from a grey lichen cover to a greenish biofilm (presumably consisting of algal and fungal microorganism and bacteria; Hallmann et al., 2015). Possible explanations are a change in climatic conditions, substrate weathering, allogenic processes, species competition or disturbances of the rock surface, for example, through the bouldering session in 2020 (Armstrong, 2024). We assume a first colonization predominately by algae and bacteria, followed and accompanied gradually by fungi and lichen growth. Some argue that rock climbing may contribute or is a reason for changes in the composition of the lichen community (Adams & Zaniewski, 2012). On the contrary, research on recolonization of lichen communities after artificial removal does not indicate a substantial shift in community composition. However, nutrient-tolerant species appear to benefit more than others (Favero-Longo et al., 2023). Firm conclusions require precise species determination.

4.3 | Chalk-free ascents and no prior cleaning of hand and footholds

Unlike the usual habit, neither chalk was used nor vegetation was removed on purpose before or during our experiment. Chalk probably would have covered a part of the bryophyte and lichen communities and therefore would have affected the visual assessment of the vegetation cover. Nevertheless, chalk is commonly used by climbers to improve the grip of the handholds. The impact of the chemical compound magnesium carbonate, also known as chalk, on rock vegetation is increased weathering, as well as changes in the site's chemistry due to its basic effect (Fickert, 2014). The study by Hepenstrick et al. (2020) found a negative influence of chalk on germination and survival of mosses and ferns. However, the chemical reactions triggered by the use of chalk may vary depending on the rock type (Hepenstrick et al., 2020).

The cleaning of rocks was also not considered in this study. Before climbing a rock for the first time, vegetation and soil are often removed from potential holds with a brush to increase friction and minimize the risk of slipping (Boggess et al., 2021). Vascular plants and bryophytes are mainly concerned. They mostly colonize ledges, crevices and pockets, which are often used as hand or footholds. Taking into account the cleaning of the rock surface, the highest loss of vegetation could occur immediately at the time opening a route (Morales-Armijo & March-Salas, 2024). Therefore, encouragement for climbers to limit cleaning could have a positive effect on the vegetation community, especially for bryophytes and vascular plants (Adams & Zaniewski, 2012).

4.4 | Management responses

Compared to other outdoor sports such as hiking or paragliding, climbing and bouldering activities are typically concentrated at sites and even at specific routes within cliffs, where climbers spend extended periods of time. This focused use minimizes the need for infrastructure and helps limit disturbance to adjacent habitats. Climbing regulations are particularly necessary when cliffs host 'rare, endemic, endangered or millennial-old species' (Morales-Armijo et al., 2024). Our study has highlighted the effect of bouldering on the species communities on the cliff face.

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As the impact is locally restricted, the coexistence of climbing and nature conservation can be possible. Morales-Armijo et al. (2024) suggest different management strategies depending on, for example, plant abundance and occurrence of singular species. Our results, revealing a disproportionally high disturbance caused by the first few climbers, argue for management via zonation concepts, where parts of the cliffs remain untouched (see Table 1 for a comparison of management approaches), while others are open for unlimited climbing. This would prevent the impacts on the communities of cliff plants that are reported for intense climbing (Clark & Hessl, 2015; Lorite et al., 2017), while it is questionable whether low impact practices of participants or limited climbing frequency may reduce the relevant part of climbing disturbance (Tessler & Clark, 2016).

Mitigation of adverse ecological impacts may be achieved by minimizing the active removal of cliff vegetation during route development, and by integrating such considerations well founded and more emphatically into regulatory frameworks and best-practice guidelines. Results from our recovery analysis additionally point to the potential of temporary closures that can, for example, alleviate impacts of overuse and allow for reestablishment of vegetation.

Climbers can also contribute to the research and management of cliff ecosystems. As monitoring resources are limited and cliff faces often difficult to assess, cooperation between climbers and nature conservation could help the monitoring process, for example, through the use of an app (Clark & Hessl, 2015; Gross et al., 2023; March-Salas et al., 2018). The unique bryophyte and lichen communities of the rock ecosystem are crucial for the conservation of biodiversity (Spitale & Nascimbene, 2012). Monitoring taxa, species composition and the number of individuals provides new insights into the reactions of flora and fauna to disturbances. In addition, climbers can participate in citizen science programmes (Gross et al., 2023). In US national parks, there are already collaborations between climbers and scientists that contribute to the conservation of bat species or the peregrine falcon (Gross et al., 2023; Shafer, 2022), in the Frankenjura climbers cooperate with nature conservation authorities by notifying them about breading birds to temporarily close the cliff.

4.5 | Effects of microplastics on the environment

The soles of climbing shoes are designed to provide good grip on holds through friction (Sherman et al., 2025). The abrasion of the sole was noticeable and high concentrations of rubber additives from climbing shoe abrasion were detected, especially on the limestone cliff after the experiment. Similar outcomes were observed for aerosol particulate matter and settled dust in indoor climbing facilities, highlighting the urgent need for further investigations (Sherman et al., 2025). Outdoors, the uptake of abrased sole particles by humans is expected to be lower than indoors, as they get dispersed by atmospheric movements. However, abraded microplastics and rubber-derived compounds are released directly into sensitive ecosystems. In the environment, rubber particles have the potential to modify soil pH and soil nitrification potential (Smolders & Degryse, 2002), which may affect the availability of plant nutrients (Forster et al., 2020) and cause shifts in microbial communities such as mycorrhiza and nitrogen-fixing organisms (Rillig et al., 2019). The sole particles contain a variety of polycyclic aromatic hydrocarbons (PAH) (Fořt et al., 2022) and are therefore a potential source of carcinogens, mutagen or acute irritants (Brandsma et al., 2019; Perkins et al., 2019; Watterson, 2017). Rubber crumbs pose a threat to the human body and the natural environment. Ecotoxicity testing of Fořt et al. (2022) has also shown that rubber potentially affects the community composition of soil and water ecosystems. By analysing the sample of one climbing site (limestone) in the laboratory, we could verify the rubber abrasion impact, indicated by a dark surface

TABLE 1 Comparison of the two management strategies 'low frequency concept' and 'zonation concept' regarding ecological impacts, trade-offs and challenges.

Low-frequency concept		Zonation concept
- Climbing frequency or overall number of climbers restricted to a pre-defined limit at each site	How it works	- Sites (or parts of rocks) either free for climbing or protected for nature conservation
- All sites are affected by climbing activities - Reduced critical impact (Tessler & Clark, 2016) - First impacts already harmful (Morales-Armijo et al., 2024; Schweizer et al., 2021)	Ecological impacts	- Impact limited to pre-defined areas without unique—endemic, rare, or threatened—species (Morales-Armijo et al., 2024) - Protection of geosites (Marrosu & Balvis, 2020)
- Requires tools and resources to reduce visitor numbers (permits, limited parking, information retention) - Restricted access to outdoor recreation	Trade-offs	- Required resources for the well-founded zonation process (time, experts, organizations, communication) - Science-based strategy is expected to promote acceptance among involved stakeholders - Some rocks/routes never accessible for climbers
- Defining carrying capacity and a system to keep frequency low - Question of fair limitation (may cause imbalance in discrimination) - Low acceptance among climbers	Challenges	- Collaboration and compromises between climbers and nature conservation - Defining clear criteria for zoning (occurrence of rare species, overall high vegetation cover etc.)

Note: In any case, dynamic process management and recurrent monitoring are recommended for management concepts.

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colouring. Rock types differ in roughness, porosity and mineral composition (Brodo, 1973). Sedimentary rocks, such as limestone, are generally more porous and less compact than igneous rocks like granite (Lee & Parsons, 1999). This higher intergranular porosity not only facilitates biological colonization (Cámara et al., 2008; Tonon et al., 2022) but may also enhance the adhesion of microparticles such as microplastics. In climbing areas, limestone often shows less material loss through abrasion compared to sandstone, while simultaneously developing polished ("greasy") and black surfaces due to repeated contact. These characteristics suggest that limestone may retain surface-bound particles more effectively. The study of microplastic accumulation in outdoor environments requires more attention. However, compared to the large amount of rubber abrasion from motorized vehicle tires (Sommer et al., 2025), the input from climbing shoes is expected to be significantly lower. Further studies on the amount of rubber abrasion and environmental variations are indispensable to adequately assess this issue.

5 | CONCLUSIONS

This study aimed to identify the impact of bouldering on cliff ecosystems. Based on the decline in lichen and bryophyte cover during the ascents and its slow recovery rate, it can be concluded that the development of new routes and especially the first climbing sessions lead to recognizable damage to the cliff vegetation. Rock properties and species composition were found to influence the percentage of vegetation loss. However, only lichens and bryophytes were considered, as no vascular plants were present on the analysed boulders.

We chose to assess one boulder per rock type due to the limited resources in our study design. Although the low degree of replication ($n = 1$ boulder per rock type) reduces the generalizability of the results, this study provides new insight into how the properties of the rock affect the rate of vegetation loss caused by rock climbing. Furthermore, the cliff ecosystem is able to partially recover over 3 years, but studies on species composition are recommended to check for potential shifts. In addition, the recovery capacity for other rock types has not been studied, which reveals another research opportunity for the future.

In this study, the microplastic input of climbing shoes into the environment was determined for the first time. To assess the impact, measurements are required that determine the amount of microplastic abrasion by climbers.

This work is one of the few studies on the ecological consequences of bouldering. The information gained is intended to stimulate communication between stakeholders and climbers. When discussing suitable management strategies, ecologists, representatives of climbing associations, local authorities and other stakeholders must collaborate to find effective solutions, with knowledge of minimum impact practices playing a key role. Further conservation measures must be considered to protect the cliff ecosystem and its unique species community. Whether moderate frequentation or restricted access to sites of high conservation value is the management action of choice, needs to be decided based on the specific situation. It became obvious that the first climbs of a boulder lead to the strongest reduction in vegetation cover. But the percentage of climbed boulders to unclimbed cliff faces is noteworthy for setting the impact of bouldering in relation. However, it is recommended to identify species of high conservation value before opening new routes. Overall, cooperation and compromise are essential to balance recreational activities with nature conservation.

AUTHOR CONTRIBUTIONS

Isabell A. Österle, Sofie Paulus and Manuel J. Steinbauer developed the concept of the research project; Isabell A. Österle, Sofie Paulus and Arne Schwietering performed the fieldwork; the visual assessment of the rock photos and the statistical analysis were carried out by Isabell A. Österle; Isabell A. Österle and Sofie Paulus contributed equally to the evaluation of the results and the writing of the paper, with significant contributions from Arne Schwietering and additional input from Volker Audorff and Manuel J. Steinbauer; all authors were involved in discussing the findings and refining the manuscript.

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CONFLICT OF INTEREST STATEMENT

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 STATEMENT

Photos of rocks and climbing holds taken during the bouldering session and recovery period, as well as the Raman spectra obtained from the limestone rock and climbing shoe sole, are available from the authors upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Appendix S1. Enlarged view of the rocks from Figure 1.

Appendix S2. Bryophyte species detected at the limestone and granite crags.

Appendix S3. Regression analysis of the climbing holds. Estimates for the breakpoint and slopes of each hold are given along with

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their standard errors. The Davies test was used to determine the *p*-value and identify the presence of a significant change, indicated by a breakpoint in the regression. The AIC and R^2 values suggest that the segmented regression provides the best fit for the data of most holds.

Appendix S4. Course of the vegetation coverage (%) of the holds during the climbing session and recovery phase.

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