Origin of the impact of rock climbing on cliff ecosystems: A guide to evidence-based conservation management to regulate climbing

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ABSTRACT

1. Cliff ecosystems provide refuge to 35-66% of the world's endemic plants. However, they face growing threats from climbing. Evidence suggests that untouched cliffs harbor approximately twice the plant richness compared to climbed cliffs, with increasing impact as climbing intensity increases. Unfortunately, the origin and extent of the climbing impact has not been assessed so far.
2. We recorded cliff vascular plants and lichens at the protected natural area of El Potrero Chico (Mexico) before and after the establishment of new climbing routes. Subsequently, we re-recorded the routes at various time-points after openings while controlling the number of ascents. Additionally, we examined whether original cliff vegetation abundance influences the extent of climbing impact, and whether the surroundings of the new routes were also affected.
3. We found that the establishment of new climbing routes exerted the strongest negative effects on cliff plants, reducing species richness by 38%, while subsequent climbers' ascents generated a minimal impact on richness. Worryingly, route opening affected not only species richness in the route itself, but also the surroundings of the climbing routes. Cliff plant abundance decreased by 60.6% within the bolted climbing routes, whereas it rapidly decreased by 42.3% in the surrounding area. However, this impact depended on the original vegetation abundance of the untouched cliffs. Lichen cover showed a gradual decrease, indicating that cliff-dwelling lichens are affected not only by the opening of the route but also by subsequent climbers' ascents.
4. *Synthesis and applications:* Given the almost non-existent regulation of outdoor climbing activities in most countries, we urge the implementation of a conservation management protocol that defines clear strategies to regulate climbing activities and preserve pristine cliffs. On untouched cliffs with narrow endemic, rare, or threatened

species, we propose banning the establishment of new climbing areas. On cliffs lacking protected or unique species, dynamic management actions should be implemented, setting a maximum number of climbing routes that can be established, and defining Limits of Acceptable Change as climbing intensity increases. The proposed conservation management should help to halt the loss of unique cliff biodiversity and safeguard pristine cliff ecosystems.

Keywords: Cliff ecology; Climbing regulation; Conservation management; Endangered species; Lichens; Limits of Acceptable Change; Monitoring strategy; Pristine ecosystems.

INTRODUCTION

Cliffs are unique and biodiverse ecosystems that face growing pressures worldwide due to rock climbing and other recreational activities such as rappelling and highline (Larson et al., 2000; Chang & Xu, 2020). They harbor a great diversity of plants comprising species that are highly specialized on cliff environments, many of them being endemic and endangered species, as well as ecologically more widespread species (Larson et al., 2000; March-Salas et al., 2023a). Given the uniqueness and high conservation value of cliff biodiversity, understanding the threats of rock-climbing and developing approaches for an effective conservation management is imperative (deCastro-Arrazola et al., 2021). There is consistent evidence that rock-climbing negatively impacts species richness and abundance in cliff habitats, also catalysing a significant decline of rare plants (e.g., Tessler and Clarck, 2016; Lorite et al., 2017; March-Salas et al., 2018; Schmera et al., 2018; March-Salas et al., 2023b). These detrimental effects of rock-climbing mainly arise from direct trampling, the erosion of cliffs due to repetitive climbers' ascents, or plant removal by trampling, pulling or uprooting by climbers (Holzschuh 2016; Harrison et al., 2022). Moreover, as recently shown, the use of climbing chalk (magnesium carbonate) can also affect the germination and survival of rupicolous plants as it triggers changes in soil nutrients and pH (Hepenstrick et al., 2020). Furthermore, the opening of new climbing routes involves removing plants, mosses, and lichens along the planned route transect to ensure safe climbing, which likely causes a substantial part of their overall damage. However, no studies investigated which aspect of climbing activity exerts the greatest impact on cliff biodiversity.

Climbing is undergoing an exponential and unplanned growth, with hundreds of new routes in previously untouched areas, leading to a significant decline in pristine cliffs and its biodiversity (Vogler and Reisch, 2011). Notably, nowadays there are more than 640,000 climbing routes in Europe and over 210,000 in North America (The Crag, 2022). Regrettably, the opening of new routes remains unregulated, with little to no legal restrictions (Hanemann, 2000). Opening a climbing route involves the installation of safety anchors using a drill (*i.e.*, bolting), as well as the removal of unstable rocks that could endanger climbers. Additionally, 'route cleaning' is a common practice during route opening that typically involves removing the individual plants that may obstruct the climber's ascent, soil that accumulates in cliff crevices, and even the use of metal brushes to eliminate mosses and lichens that could be bothersome or slippery for climbers. Whether the people responsible for establishing and adding the bolts to the climbing routes (*i.e.*, outfitters) lack sufficient botanical and biological knowledge, this action may impact endemic, ecologically-relevant, and even endangered cliff-dwelling flora. Besides route opening, the paradigm suggests that the increased climbing intensity may lead to more pronounced impacts on cliff plant communities (Clark and Hessl, 2015; Lorite et al., 2017). However, there are intrinsic variations in the rock-climbing impact, probably related to differences in species composition and site characteristics (Harrison et al., 2022). Thus, the relevance of increased climbing intensity for cliff biodiversity remains inconclusive, as similar impacts have been observed in both low- and high-intensity climbing areas (Schmera et al., 2018; March-Salas et al., 2023). Understanding the dominant drivers of the overall impact of rock-climbing activities would be crucial for comprehensive and efficient management of this popular recreational activity and for a better protection of cliff biodiversity.

Concern regarding the climbing impact is heightened particularly whether the new climbing routes are planned to be installed in protected natural areas and/or in very densified cliff areas. For instance, approximately 62% of climbing routes in Spain are situated within protected natural areas (deCastro-Arrazola et al., 2021), posing a worrying threat to their biodiversity. Not surprisingly, there is a growing conflict between climbers and managers of natural areas. So far, measures implemented by nature managers mainly involved restricting access to climbers during the breeding season of cliff-nesting birds. In the world-famous Margalef climbing area (Spain), located in the Sierra de Montsant Natural Park, technical reports also recommend monitoring the carrying capacity of cliff ecosystems and their surroundings, and encourage to limit access when exceeded. More drastic measures have even gone as far as a total ban on rock climbing in certain areas due to the impact on birds or cliff flora of high conservation value (e.g., *Petrocoptis grandiflora*, a narrow endemic plant of Serra da Enciña da Lastra Natural Park, Spain). Where such regulations and management protocols are absent, this may lead to the establishment of new climbing routes on cliffs with abundant vegetation and endemic and/or threatened cliff flora. Therefore, nature managers need guidance on when and how to implement effective conservation actions, as well as the monitoring strategies required to follow up on cliff biodiversity.

Here, we assess for the first time the origin of the impact of climbing activity on cliff ecosystems. To this end, we contacted local outfitters to establish and bolt new climbing routes on pristine cliff ecosystems of the highly popular climbing site and protected natural area of El Potrero Chico (Nuevo Leon, Mexico), and we recorded cliff plants and lichens before and after they established the new routes. The pristine cliffs varied in vegetation density, allowing us to assess whether the abundance of original cliff vegetation influence the impact. Afterwards, climbers climbed the new routes and cliff plants and lichens were subsequently re-recorded. We hypothesized that (1) the opening of new climbing routes affects cliff plants more than subsequent climbers' ascents; and (2) the impacts of the climbing activity are stronger on cliffs with originally dense vegetation. The insights from this study enable us to develop a conservation management protocol to guide the management strategy and regulation of rock climbing, and ultimately aid in the conservation of cliff ecosystems and their unique biodiversity.

MATERIAL AND METHODS

Study site

El Potrero Chico (Nuevo León, Mexico) is located close to Monterrey, in the northern periphery of the 'Sierra El Fraile y San Miguel' protected natural area, part of the Sierra Madre Oriental Mountain range. It covers 23,506 hectares and elevation ranges from 800 to 2,360 m asl. This region is formed by Mesozoic sedimentary rocks, including shale and limestone cliffs that support rich and diverse cliff vegetation (Larson et al. 2000; INECC 2017). El Potrero Chico has a semi-arid climate, featuring hot summers with average monthly maximum temperatures exceeding 40 °C from June to August and moderate winter temperatures ranging between 7 and 16 °C. Precipitation peaks in September and October, averaging between 70 and 130 mm per month. The dominant vegetation types in the study area are submontane vegetation and desert rosetophilous scrub, the latter having been classified as a conservation priority because of its high level of endemism (Estrada-Castillón et al., 2012).

Recognized as one of the most popular climbing destinations worldwide, El Potrero Chico offers around 700 climbing routes in 24 rock faces (Madden, 2022). Approximately 100 of these routes have been opened in the last two years. Rock climbing began there in 1960, but its popularity as a climbing area greatly increased in the late 1980s. The preferred seasons for climbing are late autumn and early spring (between November and March) due to favorable temperatures and low/scarce precipitation. For instance, during the winter seasons of 2022-23 and 2023-24, there were 2312 and 2238 climbers in El Potrero Chico, respectively (information provided by the Tourism Secretary of Hidalgo).

Field monitoring design

We conducted the first assessment on the origin of the climbing effect on cliff plant communities and lichens by evaluating the effect of establishing new climbing routes as well as of subsequent climbers' ascents on pristine cliffs. Specifically, to understand whether cliff communities are more affected either by the opening of the new routes or by climbing activity, we recorded pristine cliffs before (pre-opening) and immediately after (post-opening) the opening of the climbing routes in October 2022. Then, we recorded the cliff plants and lichens after 10, 20 and 30 climbing ascents. These five times when plants and lichens were recorded are hereafter referred as 'measuring times'. We selected two cliffs situated 50 meters apart from each other. To assess whether the rock-climbing activity has variable impacts depending on the abundance of vegetation in the original and untouched cliffs, one studied cliff has originally dense and the other scarce vegetation (Fig. S1). Other criteria used for the selection of these cliffs included: feasibility of descending from the top of the cliff before the establishment of the new climbing route (rappelling), and easy access for the climbing community in order to foster their involvement in the study.

Following the recommendations from two local outfitters, we delineated four climbing routes on the pristine cliff with dense vegetation (25°57'18'' N 100°29'07'' W; called 'Sotol-Plutonia' climbing sector), and three on the pristine cliff with scarce vegetation (25°57'16'' N 100°29'00'' W; called 'Agave' climbing sector) (*see* Table S1). A total of 42 plots of 3 m^2 plots and 504 subplots of 0.25 m^2 were surveyed at each of the five measuring times (*see* 'Field monitoring method' below). Climbing routes were at least 3.5 meters apart from the next climbing route. To establish the climbing routes, the path of the upcoming climbing route was initially guided with tape. Cliff plants and lichens was then recorded by establishing three quadrats at different heights of the cliff face (*see* details in 'Field monitoring method'). This is considered as the 'pre-opening' measuring time. For replicability in subsequent surveys, the positions of the corners of the quadrats in each of the measured areas were marked on the cliff using tape. Thereafter, the two local climbing route outfitters installed the bolts, performing all the usual actions for establishing the seven climbing routes, following the delineation marked by the tape. The day after each route was established and bolted, we re-recorded the cliff plants and lichens at exactly the same points of the cliff-face as in the 'pre-opening' measuring time and was termed 'post-opening'. Finally, local climbers were contacted for climbing the studied routes. Once 10, 20, and 30 ascents were completed on each route, we subsequentially recorded the same points as in the 'pre-opening' and 'post-opening' measurements (Fig. S1).

Field monitoring method and data collection

To assess the strength and the origin of the climbing impact, we used a case-control design with a 3 m wide × 3 m high quadrat positioned at three zones of the climbing route (*see* March-Salas et al. 2023b). The quadrat consisted of: a central plot of 1 m width and 3 m height representing the central area of the climbing route (so called ‘within the climbing route’); two immediately adjacent surveyed plots of 0.5 m width and 3 m height, as this area could be potentially used by climbers during their ascent, and therefore would not be exempt from being disturbed; two plots 1 m far from the center of the climbing route of 0.5 m width and 3 m height on the left and right sides of the 3 m × 3 m quadrat that served as controls, representing areas not reached by climbers and outfitters (so called ‘near the climbing route’). This closely adjacent paired design was chosen to effectively assess the impact of rock climbing, minimizing variations in biotic or abiotic factors such as aspect, inclination, micro-topography, and insolation, as described in the methodological review by Boggess et al. (2021).

To characterize the spatial distribution of plants and lichens within each plot, both ‘within’ and ‘near’ plots were subdivided into 0.5 m × 0.5 m subplots (12 subplots in each ‘within’ plot and 12 subplots in each ‘near’ plot). Photographs were taken from each subplot as part of the data collection process. To consider the physical microtopography of the cliff, we calculated the proportion of cracks (crevices) in each 0.5 m × 0.5 m subplot using the ‘ImageJ’ program (Rueden et al. 2017). This measurement helps to reduce potential bias when modelling the climbing effect, since the establishment and development of plants are more plausible with a higher percentage of cracks (Holzschuh 2016). We identified all the plant species present in the plots (Velazco et al. 2011), and calculated the plant species richness in the ‘within’ and ‘near’ plots of each climbing route and quadrat, as well as the number of individuals per species (*i.e.*, abundance). In addition, the area (in cm^2) of each individual vascular plant (*i.e.*, plant cover), and the lichen and moss covers were calculated, also using the ‘ImageJ’ program. Since mosses covered only 0.74% of the monitored cliffs, this variable was not analyzed.

Data analysis

We conducted all statistical analysis with *R version 4.0.3* (R Development Core Team 2020). We assessed the origin of the climbing effect as well as the influence of the original cliff vegetation abundance on plant species richness, plant abundance, and vascular plant and lichen cover as response variables in four separate models. We used Linear Mixed-effects Models (LMMs) implemented in the ‘lme4’ package and the ‘lmer’ function (Bates et al. 2015). Measuring time (five levels: Pre-opening, Post-opening, and 10, 20 and 30 ascents), climbing route zone (two levels: within vs. near the climbing route), original cliff vegetation abundance (two levels: dense vs. scarce), and their two- and three-way interactions were modelled as fixed factors, and plot nested in cliff section and climbing route was included as random factor. In the models concerning vascular plants, the percentage of cracks was used as a covariate to control for the amount of micro-niches available for plant establishment and growth (Holzschuh 2016).

After conducting all LMMs, we tested the assumptions of normality and homogeneity of variance of the residuals using the Shapiro-Wilk test and the Bartlett test, respectively. If the residuals were not normally distributed, we transformed the response variable (*see* transformations in Table 1). Whenever there was a significant effect in measuring time or significant interactions, we applied post-hoc contrasts by Tukey tests using the 'lsmeans' package (Lenth 2016) .

RESULTS

Plant abundance, species richness, and both plant and lichen cover exhibited significant changes across the measuring times (Table 1). Changes across measuring times depended on the climbing route zone for plant abundance and lichen cover (significant two-way interaction; Table 1; Fig. 1), and on the original cliff vegetation abundance, specifically for plant species richness and cover (significant two-way interaction between measuring time and original cliff vegetation abundance; Table 1; Fig. 2).

Plant abundance was significantly lower post-opening compared to before the opening of the new climbing routes, both within (post-hoc test: $t = -5.889$; $p < 0.001$) and near (post-hoc test: $t = -3.268$; $p = 0.043$) the transect bolted for climbing (Fig. 1A). In contrast, no significant differences in plant abundance existed between the measurements post-opening and after 10, 20 or 30 climbers' ascents (Fig. 1A). Lichen cover was not significantly different before than after the opening of the climbing route, nor after 10 climbers' ascents (Fig. 1B). Nevertheless, lichen cover was significantly lower after 20 climbers' ascents compared to the pre-opening measurements (post-hoc test: $t = -4.445$; $p < 0.001$), and significantly lower after 30 climbers' ascents compared to the pre- (post-hoc test: $t = -5.592$; $p < 0.001$) and post-opening (post-hoc test: $t = -4.334$; $p = 0.001$) measurements (Fig. 1B).

Plant species richness (Fig. 2A) and total plant cover (Fig. 2B) were significantly lower in the post-opening compared to the pre-opening measurements in initially densely vegetated areas (post-hoc tests, for species richness: $t = -6.317$; $p < 0.001$; for plant cover: $t = -5.972$; $p < 0.001$). In contrast, there were no significant differences between the pre- and post-opening measurements in pristine cliffs with scarce vegetation (Fig. 2). Climber ascents did not significantly affect species richness or total plant cover, regardless of the amount of vegetation on the pristine cliffs (Fig. 2).

DISCUSSION

As hypothesized, opening of the climbing route is the most detrimental phase of rock climbing for cliff vegetation and lichens. To date, this impact was primarily attributed to an increase in climber frequency (e.g., Vogler and Resich, 2011; Clark and Hessl, 2015; Lorite et al, 2017; Harrison et al., 2022). However, we found that it is precisely during the opening when the greatest impact on cliff vegetation occurs, while repeated ascents by climbers generate a relatively lower impact. Yet, the extend of this impact depends on the original vegetation abundance of the pristine cliffs, and the decrease in lichens appears to be influenced by both activities: the opening of the new route as well as by the repeated friction produced by climbers during repeated ascents. Considering the almost non-existent regulation of climbing route opening in most countries (Hanemann, 2000; March-Salas et al., 2023a), and the significant negative effect of rock climbing on these habitats, we advocate and suggest clear conservation management strategies to be implemented in order to control the establishment of new climbing routes in cliff ecosystems.

The origin and extent of climbing impact

The opening of new routes represents the phase with the strongest negative effect on cliff biodiversity, affecting not only the bolted area that will be directly used by climbers but also an extended area located 1 to 2 m away from the route, normally unused by climbers. However, after 30 climbers' ascents, vascular plants in the areas away from the climbing routes remained intact, indicating that the impact of the climbers themselves mainly occur within the 1 m wide of the bolted climbing route. Within the climbing route, actions carried out during route opening reduced cliff vegetation abundance by 60.6% (Fig. 1A, right panel), whereas it decreased by 42.3% in the area near the climbing route (Fig. 1A, left panel). After 30 climbers' ascents, 30.2% of the remaining cliff vegetation after route opening was lost within the route, although this decrease was not supported statistically (Fig. 1A, right panel). This decrease is equivalent to the loss of around two plant individuals per climbing ascent, mostly occurring during the first 10 climbers' ascents. This is in line with the results of Schweizer et al. (2021), which revealed that climber impacts occur mostly during the climbers' first ascents. Climbing outfitters typically remove loose rocks that might pose a safety risk for climbers. During route cleaning, they also remove plants and soil from cliff crevices that could obstruct climbers' progress. Moreover, if mosses or lichens on the cliff could potentially cause climbers to slip, outfitters often use metal brushes to remove them. These actions explain the strong impact of the establishment of new climbing routes.

We also found a gradual decrease in lichen cover, indicating that saxicolous cliff-dwelling lichens are affected by both the route opening and subsequent climbers' ascents (Fig. 1B, right panel). Significant differences in lichen cover were observed after 20 ascents compared to the pre-opening monitoring, and after 30 ascents compared to the post-opening monitoring, resulting in an overall reduction of 34.6%. These findings also align with the results of Schweizer et al. (2021), who reported a strong reduction in lichen cover within the first 50 ascents, with no significant decreases afterwards. However, lichen cover was constant in the nearby area of the climbing route (Fig. 1B, left panel), indicating that climbers can greatly impact lichens, as previously observed (e.g., Adams and Zaniewski, 2012; Clark and Hessel, 2015; Tessler and Clark, 2016). This gradual impact may be attributed to the abovementioned activities during outfitting and the repetitive friction during the first climbers' ascents. Fine-scale studies identifying rare and unique cliff lichen species (e.g., Boggess et al, 2017) emphasize the importance of considering lichens and cliff erosion in conservation planning.

It is worth noting that the extent of the impact from the opening depended on the abundance of vegetation in the pristine cliffs. The opening of the new routes significantly impacted plant species richness and total plant cover in those pristine cliffs with dense vegetation, while weaker effects were observed in cliffs with originally scarce vegetation (Fig. 2). Species richness decreased by 40.9% and 29.2% in cliffs with original dense and scarce vegetation, respectively, whereas total plant cover was reduced by 48.9% in cliffs with originally dense vegetation, and 50.6% in those with originally scarce vegetation. However, climbers' ascents showed minimal effects on species richness and plant cover, with reductions of 11-14.9% in all cases (Fig. 2). Both Farris (1998) and Kuntz and Larson (2006) suggested that outfitters select cliffs with scarce vegetation, avoiding heavily vegetated cliffs that could hinder the establishment of new climbing routes. However, cliffs with scarce vegetation may harbor plants of high conservation value, such as rare, endemic, or even endangered species. Thus, regardless the abundance of vegetation on the pristine cliffs, an exhaustive species inventory should be conducted before establishing new routes, as indicated in our management protocol (Fig. 3). This is especially demanding in the case of very narrow specialists that occur in small areas of one cliff (*i.e.*, *Borderea chouardii,* a very ancient Dioscoraceae living on a unique cliff in Pyrenees; *see* García et al. 2012) or some specialists of overhanging cliff habitats such as some relatives of the *Sarcocapnos* genus (Lorite et al. 2017).

Outfitters also tend to select dry areas for route establishment, as wet rocks may be uncomfortable and hazardous for climbing (Boggess et al. 2021). Dry cliff areas usually have lower vegetative abundance but otherwise may be more strongly covered by lichens (Boggess et al. 2021). This trade-off between vegetation or lichen cover is also suggested by the measurements we obtained near the climbing route (*see* Fig. 1A-B). In addition, outfitters likely prioritize the removal of lichens that are less firmly attached to the rock, such as leafy foliose and fruticose species, while crustose lichens are likely removed due to continuous friction from climbers' ascents, as our results suggest (Fig. 1B). Although it may be thought that lichens or other organisms may be less relevant for conservation compared to plants and vertebrates (Rubio-Salcedo et al. 2013), Reding (2019) found that endolithic and rare lichens are understudied but may have a significant presence on cliffs. Moreover, the erosion generated by repeated climbers' ascents may negatively affect other valuable cliff organisms such as soil and rock-dwelling fungi, algae, cyanobacteria, mosses or different seed dispersers and pollinators (Cooper, 1997; Gerrath et al., 2000; Horath and Bachofen, 2009; Coleine et al., 2021; Krah and March-Salas, 2021), also causing indirect negative effects on cliff plant communities.

Furthermore, our study provides a new interpretation of results from previous studies on this topic. Our findings on the effect of route opening within and in the areas close to the climbing routes suggest that the climbing effects previously found in other studies with closely-paired designs showed conservative results (e.g., Clark and Hessl, 2015; Tessler and Clark, 2016; Boggess et al., 2017; Reding, 2019; March-Salas et al. 2018, 2023b). The climbing impact found in these studies should then be primarily attributed to the repeated climbers' ascents rather than to the opening of the climbing route, which is clearly the bottleneck of the detrimental process.

Conservation management in cliff ecosystems

Despite its growing popularity, rock climbing is a recreational activity with scarce management guidelines (March-Salas et al., 2023a). Regulations and accepted practices regarding the establishment of new climbing routes are almost non-existent, or ambiguous and differing among countries and regions. However, recently the U.S. National Park Service (NPS) and U.S. Forest Service (USFS) identified environmental hazards associated with the establishment and bolting of new routes for sport climbing. In January 2024, they proposed to ban fixed anchors in wilderness areas, unless granted special permission (National Park

Service, 2024). In Ireland, guidelines have been developed to strive for a balance between the development of new climbing areas, the consideration of the nature environment, and climbing ethics (Mountaineering Ireland, 2023). Except in cases of cliffs with rare or endangered species, these guidelines consist solely of non-mandatory recommendations, such as removing only as much soil as necessary from cliff crevices, considering pruning rather than tree removal, or removing plants only after ensuring they are not rare or protected (Mountaineering Ireland, 2023). Therefore, there are still no protocols that can help authorities and practitioners to follow standardized management and monitoring strategies in pristine cliffs.

We propose a conservation management protocol that includes data collection and monitoring that would allow gathering information on cliff ecosystems for adequate decision-making, plus management actions to be implemented (Fig. 3). Monitoring strategies would offer an opportunity for managers to promote environmental stewardship of cliffs and define specific regulations to be implemented. We categorized these regulations into: *strict* (i) regulation due to the presence of singular species (*i.e.*, rare, endemic, endangered or millennial-old species); *intermediate* (ii) and *moderate* (iii) regulations for pristine cliffs with respectively dense or scarce non-protected vegetation abundance; and *basic* (iv) regulation for already-climbed cliffs with no singular species in the cliff edges or in areas between the climbing routes (Fig. 3). If *intermediate* (ii) and *moderate* (iii) conservation management is applied, traditional (*i.e.*, climbing that do not follow previously-established routes and fixed anchors in the cliff) or low-intensity climbing may be allowed in pristine cliffs. Then, the maximum number of new climbing routes should be evaluated, considering the ecosystem carrying capacity, and establishing *Limits of Acceptable Change* (Stankey et al., 1985; March-Salas et al., 2023a). This would require long-term monitoring of biodiversity changes, listing species, assessing site conditions over time, and comparing those data to the initial state of the pristine cliff (Schatz et al., 2014). Particularly, this should include direct measurements of population size, tracking singular species, and assessing the erosion of cliff faces (e.g., lichen cover, changes in cliff physical features, signs of rock erosion, or marks of excessive use of climbing chalk) and their surroundings such as cliff bases, cliff edges and the pathways to the climbing area (Boggess et al., 2021; Fragnière et al. 2024). Furthermore, in these management scenarios, quantifying the climbing frequency is a critical factor to determine the climbers' impact (Boggess et al. 2021). Guiding agencies and local climbing organizations may be able to provide information regarding route use.

Since there are no benchmarks for each management scenario, we should conduct adaptive strategies before having ranges of thresholds that describe desired conditions, climbing pressure and cliff status (Webb et al., 2020). Therefore, when these benchmarks are surpassed, it should trigger the implementation of previously-defined management actions, raising the conservation management level, and probably requiring additional data collection (Webb et al., 2020; Harrison et al. *unpublished*). All this will require revisiting the climbed cliffs and conducting continuous monitoring and assessments, so agencies should require and increase investment in management support.

Conclusions

Our study shows that the climbing-related action with the strongest impact on cliff plant communities is the establishment of new climbing routes. Certain cliffs are likely among the last pristine ecosystems in many countries. These pristine cliffs, especially those harboring unique species – whether endemic, rare, or threatened –, must be protected, which may require banning the establishment of new climbing areas. In cases of pristine or climbed cliffs with no unique or singular species, dynamic management actions (*i.e.*, those that can vary over time, such as less restriction in non-reproductive seasons of birds or plants) and continuous monitoring should be implemented, including setting maximum numbers of climbing routes to be established in each cliff and defining *Limits of Acceptable Change* as climbing intensity increases. We also advocate for a framework that mandates an environmental assessment prior to the opening of new climbing areas, in addition to providing outfitters with best practice guides and training in cliff nature conservation. The protection of cliff ecosystems from human disturbances is certainly crucial to halt biodiversity loss, but this requires an increased conservation effort and detailed guidelines for effective management of cliff ecosystems.

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Author's contributions

FMA and MMS designed the study, and MMS, FMA and JL designed the field-monitoring methodology. FMA conducted the field surveys and gathered the data with the help of AS, while EEC helped to identify the cliff plant species. MMS analyzed the data and wrote the original draft of the manuscript, with review and editing by all authors.

Acknowledgements

We thank the local climbing route outfitters, Karla Moya and Marco San Miguel, and the climbing community of El Potrero Chico for their assistance in developing this study. We also thank Eduardo Araisa for welcoming us to Finca El Caminante, for his willingness to support science, and for promoting the best practices for sport climbing. The PhD of Felipe Morales-Armijo was funded by CONACYT (National Council of Science and Technology, México). *National Geographic Society* and *FEDER-Andalucía 2014-2020 Program* supported the projects that gave rise to the design and conceptual part of this work (Grant numbers: EC-50532R-18 – WorldClimb, and NGS-82734R-20 – ReCOVIDiv, and A-RNM-4-UGR20 – *EcoClimb*). The field research was supported by the project "Phylogenetic and Experimental Approaches to Understand Cliff Plant Strategies in Coping with Drought", which was awarded to Martí March-Salas through the Early Career Researcher (ECR) Support Programme of the Institute for Ecology, Evolution and Diversity at Goethe University Frankfurt.

Data availability

Data will be made available in a public repository upon acceptance for publication.

Tables

Table 1: Results of the Linear Mixed-effects Models (LMMs) investigating the origin of the climbing effect, and the influence of the vegetation abundance of pristine cliffs on plant abundance, species richness, and total coverage of vascular plants and lichens. LMMs included climbing route zone (near vs. within the climbing route), measuring time (pre- and post-opening the route, and 10, 20 and 30 climbers' ascents), cliff vegetation abundance, and their two- and three-way interactions, as well as the percentage of cracks. Transformations applied to the response variable are indicated below the table. Significance is indicated as * $0.05 > P \geq 0.01$; ** $0.01 > P \geq 0.001$; *** $P < 0.001$, and • reflects marginal effects ($0.1 > P \geq 0.05$).

		Plant abundance [a]			**Species richness**			**Plant coverage**			**Lichen coverage** [b]		
Parameter	**df**	**Chi²**	***P-value***		**Chi²**	***P-value***		**Chi²**	***P-value***		**Chi²**	***P-value***	
Percentage of cracks	1	2.254	0.133		0.672	0.412		2.319	0.128		-	-	-
Climbing route zone (Zone)	1	38.631	<0.001	***	18.898	<0.001	***	55.735	<0.001	***	8.078	0.004	**
Measuring time (Measuring)	4	101.888	<0.001	***	83.267	<0.001	***	66.171	<0.001	***	28.847	<0.001	***
Cliff vegetation (Veg)	1	3.492	0.062	•	9.376	0.002	**	7.979	0.005	**	0.314	0.575	
Zone × Measuring	4	10.337	0.035	*	4.899	0.298		0.085	0.999		14.028	0.007	**
Zone × Veg	1	8.267	0.004	**	2.969	0.085	•	17.134	<0.001	***	7.047	0.008	**
Measuring × Veg	4	2.169	0.705		12.729	0.013	*	14.987	0.004	**	0.201	0.995	
Zone × Measuring × Veg	4	0.196	0.995		0.095	0.999		0.002	0.999		0.252	0.993	

transformations: a: log(x); b: x^1.5

Figures

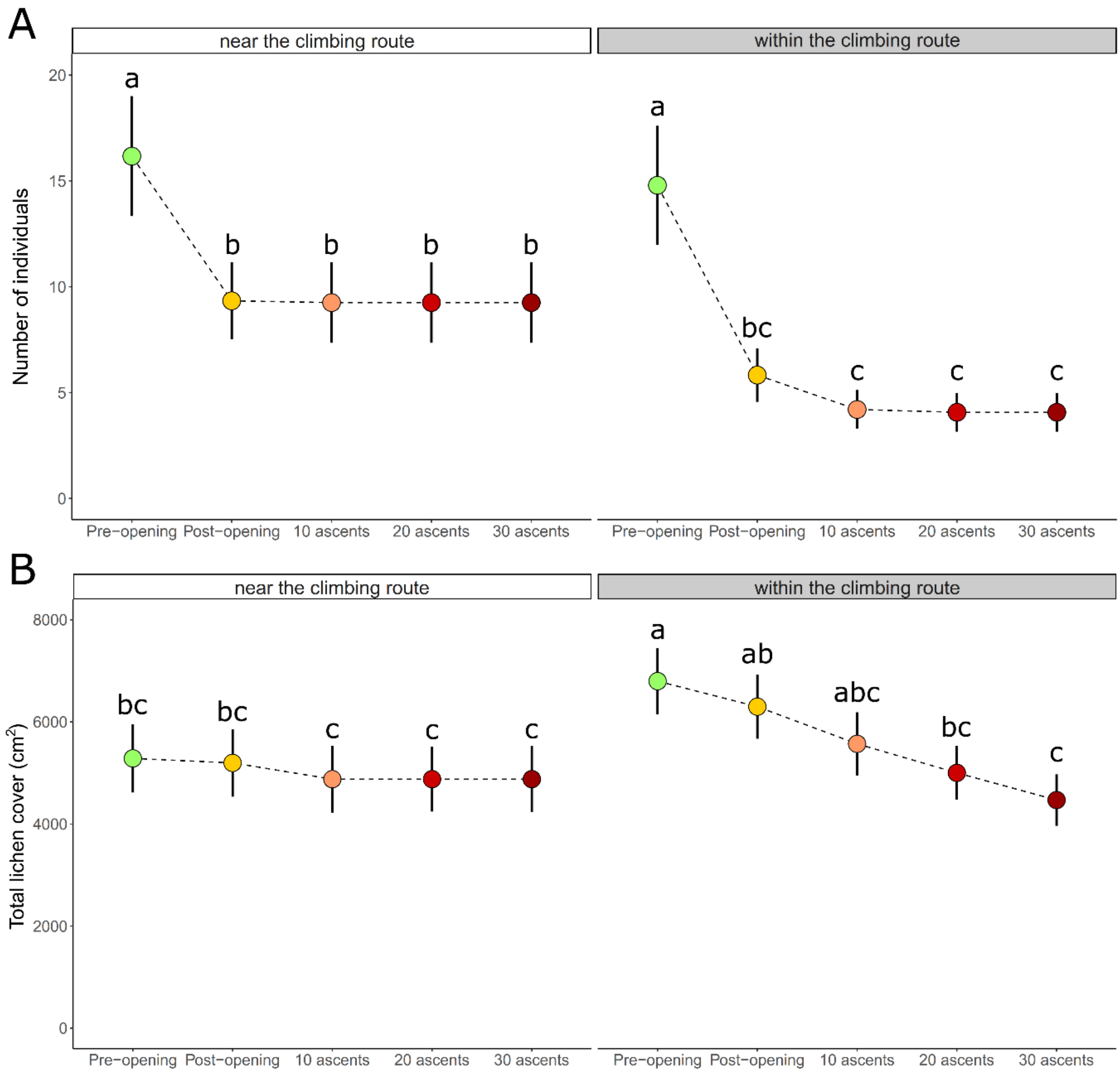

Figure 1: Differences in plant abundance and total lichen coverage between pristine cliffs and different phases of the climbing activity. Mean ± standard error (SE) in the number of individuals (A) and the total lichen coverage in the studied cliffs (in cm^2; B) measured before (pre-opening) and after (post-opening) the establishment of the new climbing route are as well as after 10, 20 and 30 climbers' ascents are shown for the area near (panel on the left) and within (panel on the right) the climbing routes. Significant differences in post-hoc contrasts are indicated with different letters.

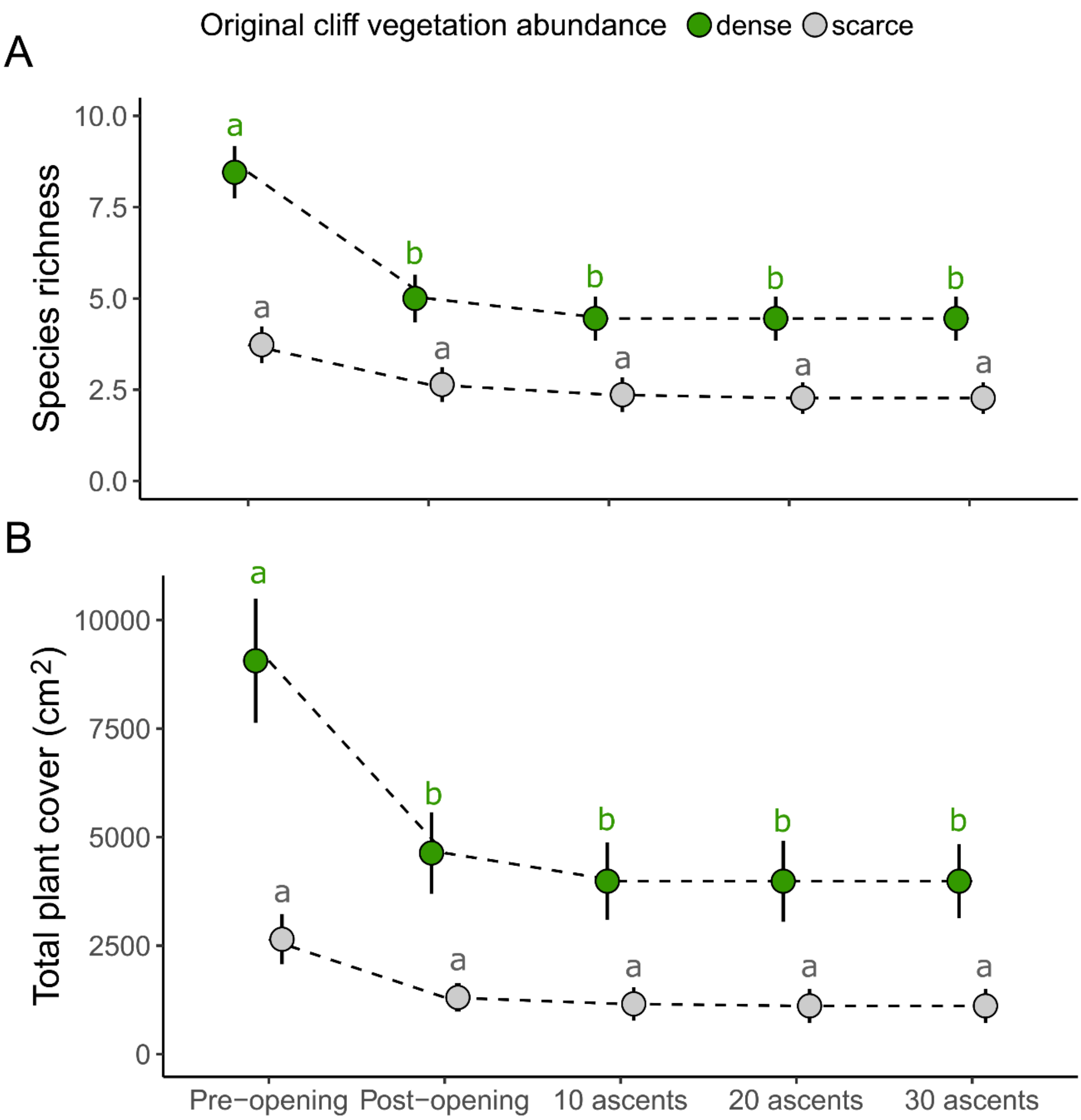

Figure 2: Plant species richness (A) and total vascular plant cover (B) between the pre-opening of the climbing route and different phases of the climbing activity in cliffs that originally hold dense (green) or scarce (grey) vegetation abundance. Mean ± standard error (SE) are shown, and post-hoc contrasts between measuring times within dense and scarce vegetation abundance are indicated.

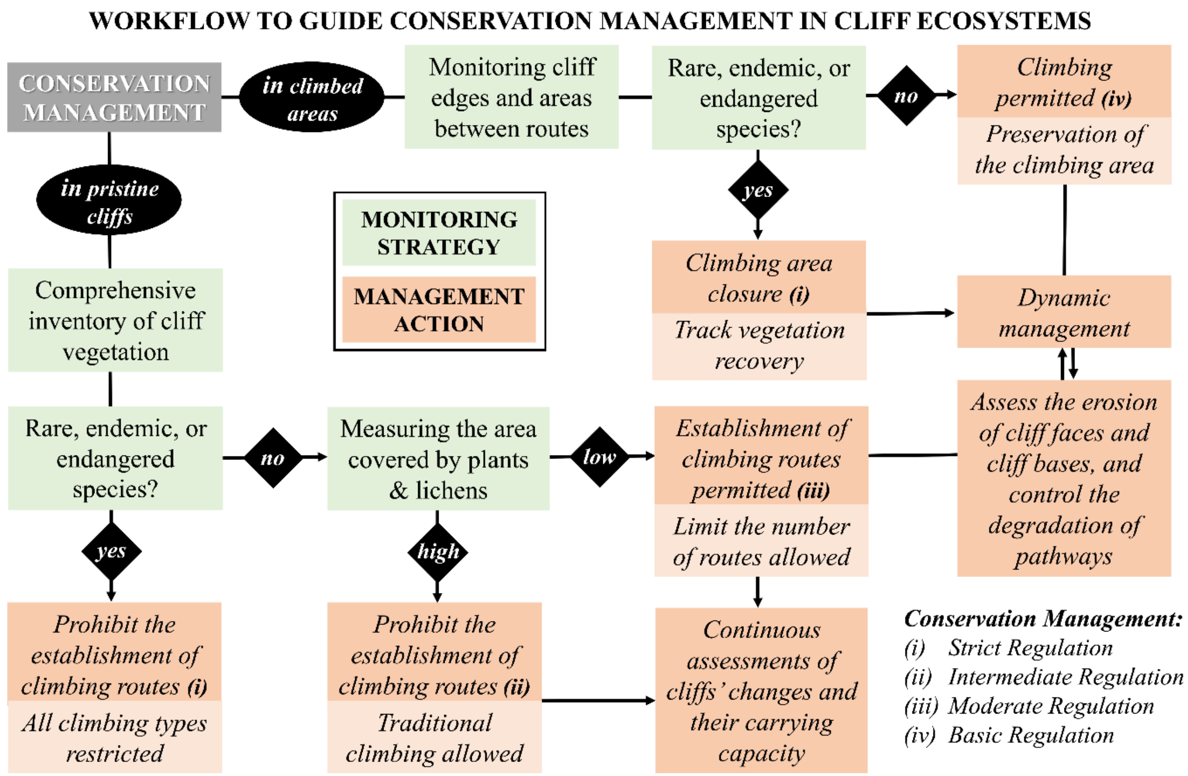

Figure 3: Workflow diagram as guidance for implementing conservation management actions in both pristine and climbed cliffs. The green boxes represent the associated field monitoring strategy to gather adequate information for decision-making, while the orange boxes represent the management actions to be implemented in each scenario. The light orange boxes show a complementary action to be implemented. The type of regulation to be implemented for each action is also highlighted and categorized into strict (i), intermediate (ii), moderate (iii) and basic (iv) regulation.

Supplementary material

Table S1: Information about the newly established climbing routes, including the name we chose for the climbing sector and climbing route, the amount of vegetation of each climbing sector, the climbing difficulty (measured with the Yosemite Decimal System – YDS grades), and the route height (in m). All climbing routes were oriented to the north.

Sector	Amount of vegetation	Route name	Difficult	Height
Agave	Scarce	Golden Tacos	5.9	12
		Olor a Huevo	5.10b	15
		Nada es lo que parece	5.10a	11
Plutonia-Sotol	Dense	Mitlan	5.11b	29
		Entre agaves y sotoles	5.10c	20
		En memoria	5.10b	21
		Es musgo	5.9	17

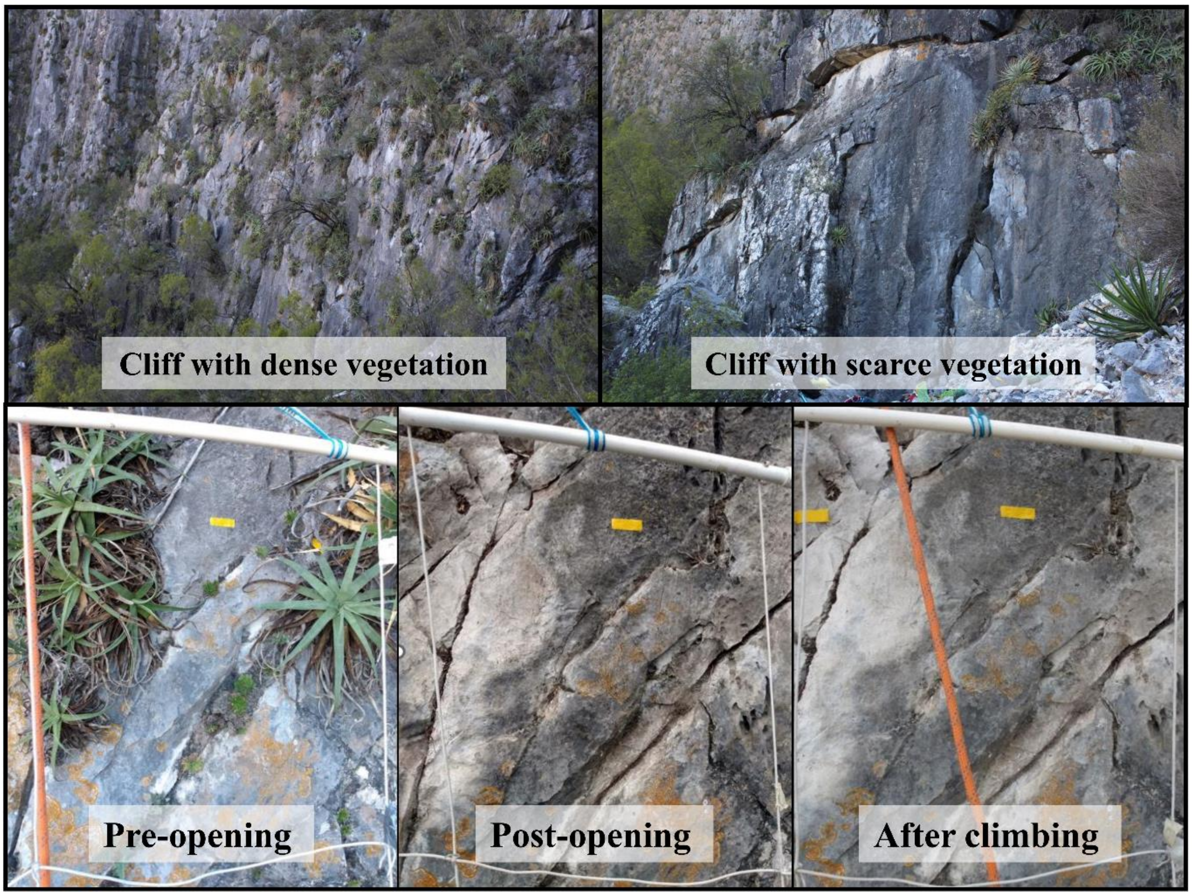

Figure S1: Exemplary images of the studied cliffs. Cliffs with dense (top left) and scarce (top right) vegetation abundance were selected for the establishment of new climbing routes. Vegetation and lichens were recorded before (pre-opening) and after (post-opening) the establishment of the climbing routes. Subsequently, climbers ascended the routes 30 times, and cliffs were recorded after every ten climbers' ascents.