Received: 30 April 2024 | Accepted: 22 August 2024

DOI: 10.1111/1365-2664.14785

Journal of Applied Ecology BRITISH ECOLOGICAL SOCIETY

RESEARCH ARTICLE

Climbing route development affects cliff vascular plants more than subsequent climbing: A guide to evidence-based conservation management to regulate climbing

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Funding information
National Geographic Society, Grant/Award Number: EC-50532R-18/NGS-82734R-20; FEDER-Andalucía 2014-2020 Program, Grant/Award Number: A-RNM-4-UGR20; Early Career Researcher (ECR) Support Programme of the Institute for Ecology, Evolution and Diversity at Goethe University Frankfurt; Talento César Nombela Grants of the Community of Madrid, Grant/Award Number: 2023-T1/ECO-29193

Handling Editor: Phil Martin

Abstract

1. Cliff ecosystems provide refuge to 35%–66% of the world's endemic plants. However, they face growing threats from sport climbing. Evidence suggests that unclimbed cliffs harbour approximately twice the plant richness compared with climbed cliffs, with increasing impact as climbing intensity increases. Unfortunately, it remains unknown whether the climbing impact on cliff vegetation originates from the development (opening) of climbing routes or from temporal changes resulting from subsequent climbing.
2. We recorded cliff vascular plants and lichens at the protected natural area of El Potrero Chico (Mexico) before and after the development of new climbing routes. Subsequently, we re-recorded the routes at sequential timepoints after 10, 20, and 30 ascents. Additionally, we examined whether the abundance of cliff vegetation influences the extent of climbing impact and whether the surroundings of the routes were also affected.
3. We found that the opening of climbing routes exerted the strongest negative effects on cliff plants, reducing species richness by 38%, while subsequent ascents generated a minimal impact. Worryingly, route opening affected not only species richness in the route itself but also the surroundings of the routes. After 30 ascents, cliff plant abundance decreased by 60.6% within the bolted routes, whereas it decreased by 42.3% in the surroundings. However, this impact depended on the original cliff vegetation abundance. 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 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

Felipe Morales-Armijo and Martí March-Salas equal contribution.

activities and preserve pristine cliffs. On yet unclimbed cliffs with narrow endemic, rare, or threatened species, we propose banning the establishment of new climbing areas. On climbed cliffs lacking protected species, dynamic management actions should be implemented, such as setting a maximum number of 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

1 | 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 (Chang & Xu, 2020; Larson et al., 2000). They harbour a high diversity of plants and other rock-dwelling organisms, comprising species that are highly specialized in cliff environments, many of them being endemic and endangered species, as well as ecologically more widespread species (Baur et al., 2017; Larson et al., 2000; March-Salas, Lorite, et al., 2023). 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 of vascular plants in cliff habitats, also catalysing a significant decline of rare plants and invertebrates (e.g. Lorite et al., 2017; March-Salas et al., 2018; March-Salas, Morales-Armijo, et al., 2023; Schmera et al., 2018; Tessler & Clark, 2016). 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 (Harrison et al., 2022; Holzschuh, 2016). 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. However, no studies have investigated which aspect of climbing activity exerts the greatest impact on cliff biodiversity.

Sport climbing is undergoing exponential and unplanned growth, with hundreds of new routes in previously unclimbed areas, leading to a significant decline in pristine cliffs and their biodiversity (Vogler & 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 in most countries, 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. If the people responsible for establishing and adding the bolts to the climbing routes (hereafter route developers) lack sufficient botanical and biological knowledge, this action may impact endemic, ecologically-relevant, and even endangered cliff-dwelling flora. Besides route opening, the increased climbing intensity may lead to more pronounced impacts on cliff plant communities (Clark & 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 (March-Salas, Morales-Armijo, et al., 2023; Schmera et al., 2018). 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 better protection of cliff biodiversity.

Concern regarding climbing impact is heightened particularly if the new climbing routes are planned to be installed in protected natural areas and/or in cliff areas with dense or unique vegetation. For instance, ~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 land 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 (i.e. the maximum number of climbers that the system can support; Stankey et al., 1985) of cliff ecosystems and their surroundings, and encourage limiting 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 opening of new climbing routes on cliffs with abundant vegetation and endemic and/or threatened cliff flora. Therefore, land managers need guidance on when and how to implement effective conservation actions, as well as the monitoring strategies required to surveil cliff biodiversity.

Here, we assess for the first time the origin of the impact of the climbing activity on cliff ecosystems by temporally comparing the effects originating from the development of the climbing route with those from subsequent climbing ascents. To this end, we asked local route developers to establish and bolt new climbing routes on pristine cliff ecosystems in the popular climbing site and protected natural area of El Potrero Chico (Nuevo Leon, Mexico). Thereafter, we recorded cliff plants and lichens both before and after new routes were established, and after 10, 20 and 30 ascents. The pristine cliffs varied in vegetation density (densely versus sparsely vegetated), allowing us to assess whether the abundance of cliff vegetation before route development influenced the climbing impact. 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.

2 | MATERIALS AND METHODS

2.1 | 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 2360 m a.s.l. This region is formed by Mesozoic sedimentary rocks, including shale and limestone cliffs that support rich and diverse cliff vegetation (INECC, 2017; Larson et al., 2000). 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 (García, 2004; March-Salas, Morales-Armijo, et al., 2023). 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 between winter 2022/23 and winter 2023/24. 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 favourable temperatures and low/scarce precipitation. 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).

2.2 | Field monitoring design

To understand whether cliff communities are more affected either by the opening of the new routes or by subsequent climbing, we recorded the vegetation of pristine cliffs before (pre-opening) and immediately after (post-opening) the opening of the climbing routes

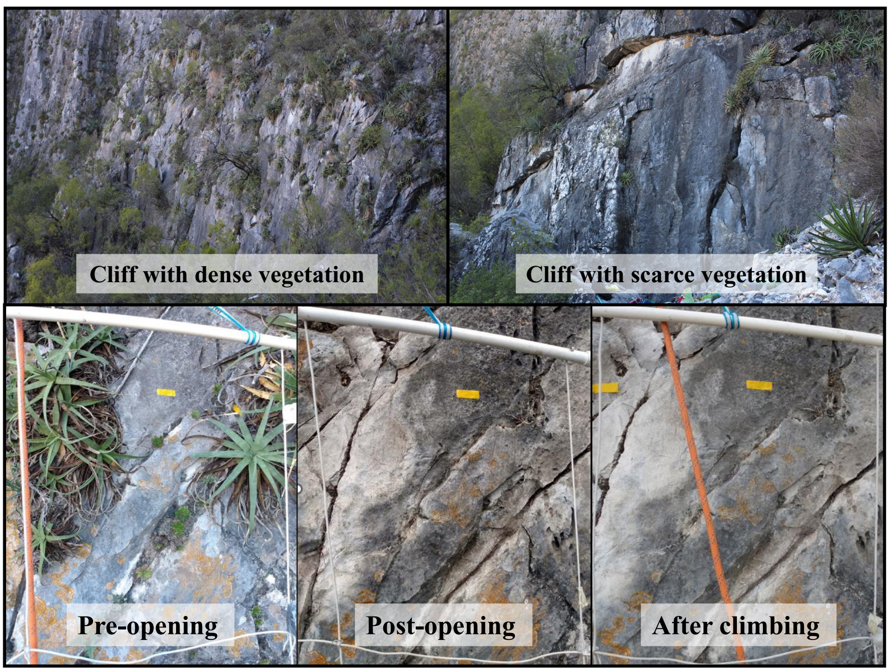

FIGURE 1 Example images of the studied cliffs. Cliffs with dense (top left) and scarce (top right) vegetation abundance were selected for the establishment of new climbing routes. Vegetation and lichens were recorded before (pre-opening) and after (post-opening) the establishment of the climbing routes. Subsequently, climbers ascended the routes 30 times, and cliffs were recorded after every 10 climbers' ascents.

in September–October 2022 (please, note that no permits were required for the fieldwork activities). Thereafter, we recorded the cliff plant diversity and abundance and lichen cover after 10, 20 and 30 climbing ascents until January 2023. These five times when plants and lichens were recorded are hereafter referred to as 'measuring times'. We selected two cliffs situated 50 m apart from each other. Both had an average slope of 83°, were higher than 11 m, and were facing North. To assess whether the rock-climbing activity has variable impacts depending on the abundance of vegetation in the original unclimbed cliffs, one studied cliff has originally dense and the other scarce vegetation (Figure 1). Other criteria used for the selection of these cliffs included: the feasibility of descending from the top of the cliff before the opening of the new climbing route (rappelling), and easy access for the climbing community to foster their involvement in the study.

Following the recommendations from two local route developers, 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 m 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 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 developers 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 (Figure 1).

2.3 | 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, Morales-Armijo, et al., 2023). 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'; as 'cases'); 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 centre of the climbing route of 0.5 m width and 3 m height on the left and right sides of the 3 × 3 m quadrat that served as 'controls', representing areas not reached by climbers and route developers (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, microtopography, 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 × 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 × 0.5 m subplot using the 'ImageJ' programme (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' programme. Since mosses covered only 0.74% of the monitored cliffs, this variable was not analysed.

2.4 | 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. Plot nested in cliff section and the climbing route was included as a 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).

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, plant species richness, and total cover of vascular plants and lichens.

		Plant abundance[a]		Plant species richness		Plant cover		Lichen cover[b]	
Parameter	df	Chi^2	*p*-value	Chi^2	*p*-value	Chi^2	*p*-value	Chi^2	*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

Note: 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 ($0.1 > p \geq 0.05$). Transformations: *a*: log(*x*); *b*: $x^{1.5}$.

3 | RESULTS

Plant abundance, species richness, and both plant and lichen cover exhibited significant changes across the measuring times (Table 1). These changes depended on the climbing route zone for plant abundance and lichen cover (significant two-way interaction; Table 1; Figure 2), 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; Figure 3).

Plant abundance was significantly lower post-opening compared with 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 (Figure 2A). In contrast, no significant differences in plant abundance existed between the measurements post-opening and after 10, 20, or 30 climbers' ascents (Figure 2A). Lichen cover was not significantly different before than after the opening of the climbing route, nor after 10 ascents (Figure 2B). Nevertheless, lichen cover was significantly lower after 20 ascents compared with the pre-opening measurements (post hoc test: $t = -4.445$; $p < 0.001$), and significantly lower after 30 ascents compared with the pre- (post hoc test: $t = -5.592$; $p < 0.001$) and post-opening (post hoc test: $t = -4.334$; $p = 0.001$) measurements (Figure 2B).

Plant species richness (Figure 3A) and total plant cover (Figure 3B) were significantly lower in the post-opening compared with 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 cliffs with initially scarce vegetation (Figure 3A,B). Climbing ascents did not significantly affect species richness or total plant cover, regardless of the amount of initial vegetation on the cliffs (Figure 3).

4 | DISCUSSION

As hypothesized, opening the climbing route is the most detrimental phase of rock climbing for cliff vascular plants, but not for cliff lichens. To date, this impact was primarily attributed to an increase in climber frequency (e.g. Clark & Hessl, 2015; Lorite et al., 2017; Vogler & Reisch, 2011). However, we found that it is precisely during the opening when the greatest impact on cliff vegetation occurs, while the first 30 climbing ascents generate a relatively lower impact. Yet, the extent 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 initial ascents. Considering the almost non-existent regulation of climbing route opening in most countries (Hanemann, 2000; March-Salas, Lorite, et al., 2023), and the significant negative effect of rock climbing on these habitats, we advocate and suggest clear conservation management strategies to be implemented to control the establishment of new climbing areas in cliff ecosystems.

4.1 | 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 1–2 m away from the route, normally unused by climbers. However, after 30 climbing ascents, vascular plants in the areas away from the routes remained intact, indicating that the impact of the climbers themselves mainly occurs within the 1 m wide of the bolted route. Within the climbing route, actions carried out during route opening reduced cliff vegetation abundance by 60.6% (Figure 2A, right panel), whereas it decreased by 42.3% in the area near the climbing route (Figure 2A, left panel). After 30 ascents,

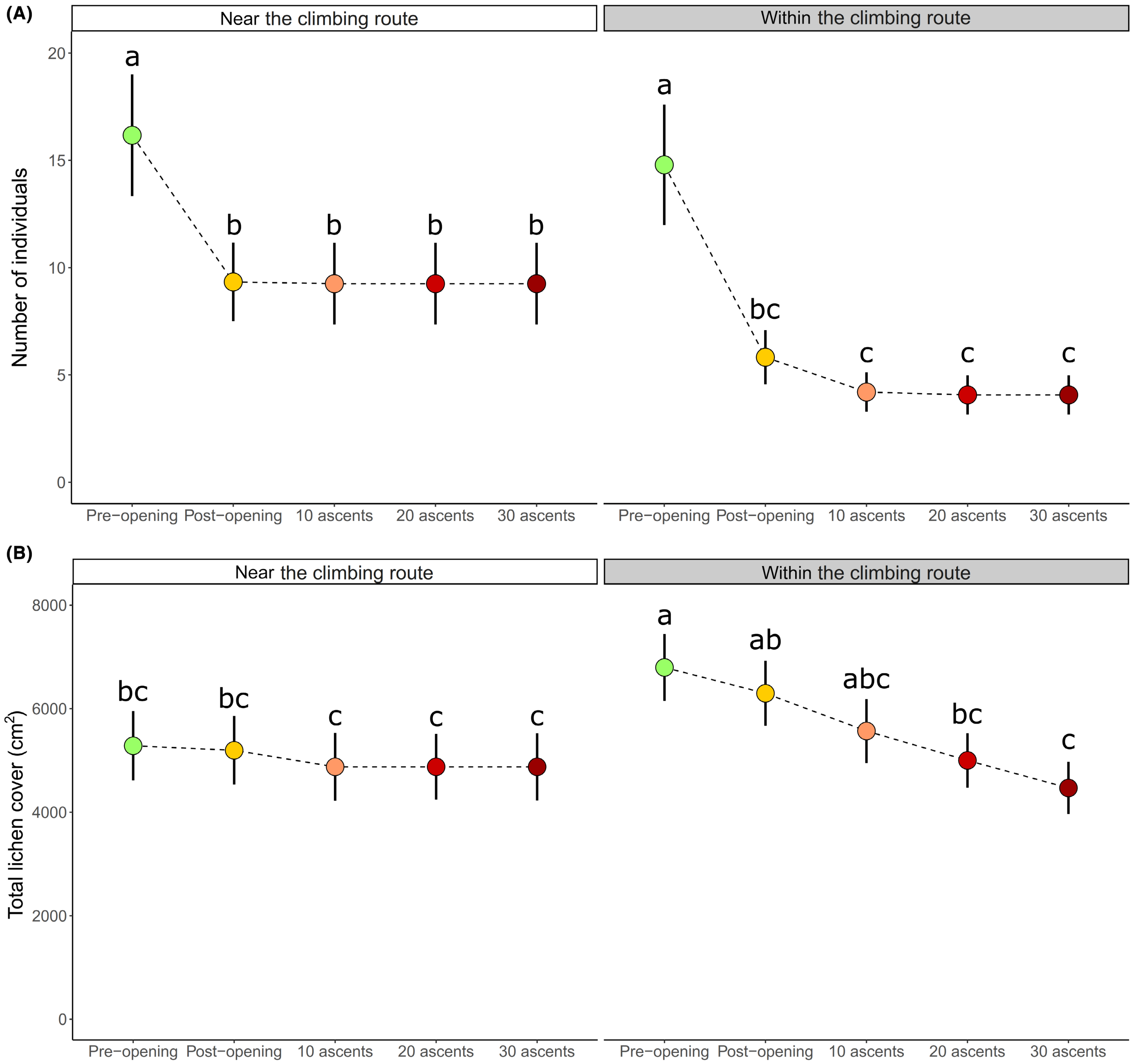

FIGURE 2 Differences in plant abundance and total lichen coverage between pristine cliffs and different phases of climbing activity. Mean ± standard error (SE) in the number of individuals (A) and the total lichen coverage in the studied cliffs (in cm^2; B) measured before (pre-opening) and after (post-opening) the opening of the new climbing route are displayed 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 among the measuring times are indicated with different letters, and colours represent the increased climbing pressure over time.

30.2% of the remaining cliff vegetation after route opening was lost within the route, although this decrease was not supported statistically (Figure 2A, right panel). This decrease is equivalent to the loss of around two plant individuals per climbing ascent, mostly occurring during the first 10 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. Route developers 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, route developers often use metal brushes to remove them. These actions explain the strong impact of the opening 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 ascents (Figure 2B, right panel). Significant differences in lichen cover were observed after 20 ascents compared with the pre-opening monitoring, and after 30 ascents compared with the post-opening monitoring, resulting in an overall reduction of 34.6%. These findings also align with the results of Schweizer

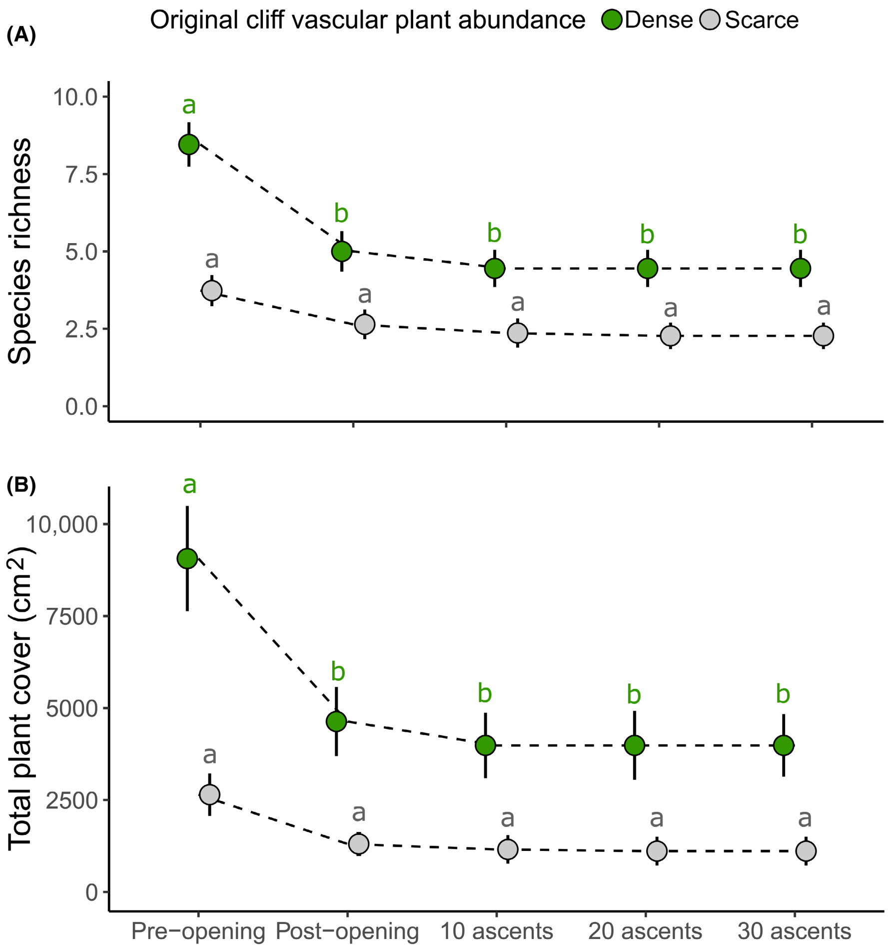

FIGURE 3 Plant species richness (A) and total vascular plant cover (B) between the pre-opening of the climbing route and different phases of the climbing activity in cliffs that originally hold dense (green) or scarce (grey) vegetation abundance. Mean ± standard error (SE) are shown, and significance of post hoc contrasts among measuring times within dense and scarce vegetation abundance are indicated.

et al. (2021), who reported a strong reduction in lichen cover within the first 50 ascents, with no significant decreases afterward. However, lichen cover was constant in the nearby area of the route (Figure 2B, left panel), indicating that climbers can greatly impact lichens, as previously observed (e.g. Adams & Zaniewski, 2012; Clark & Hessl, 2015; Tessler & Clark, 2016). This gradual impact may be attributed to the above-mentioned activities during outfitting and the repetitive friction during the first 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 cliffs with originally dense vegetation, while weaker effects were observed in cliffs with originally scarce vegetation (Figure 3). Species richness decreased by 40.9% and 29.2% in cliffs with originally 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 (Figure 3). Both Farris (1995) and Kuntz and Larson (2006) suggested that route developers select cliffs with scarce vegetation, avoiding heavily vegetated cliffs that could hinder the establishment of new climbing routes. However, cliffs with scarce vegetation may harbour plants of high conservation value, such as rare, endemic, or even endangered species. Thus, regardless of 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 (Figure 4). 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 *Sarcocapnos pulcherrima* (Lorite et al., 2017).

Route developers also tend to select dry areas for route opening, 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 densely 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 Figure 2A,B). In addition, route developers 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 (Figure 2B). Although it may be thought that lichens or other organisms may be less relevant for conservation

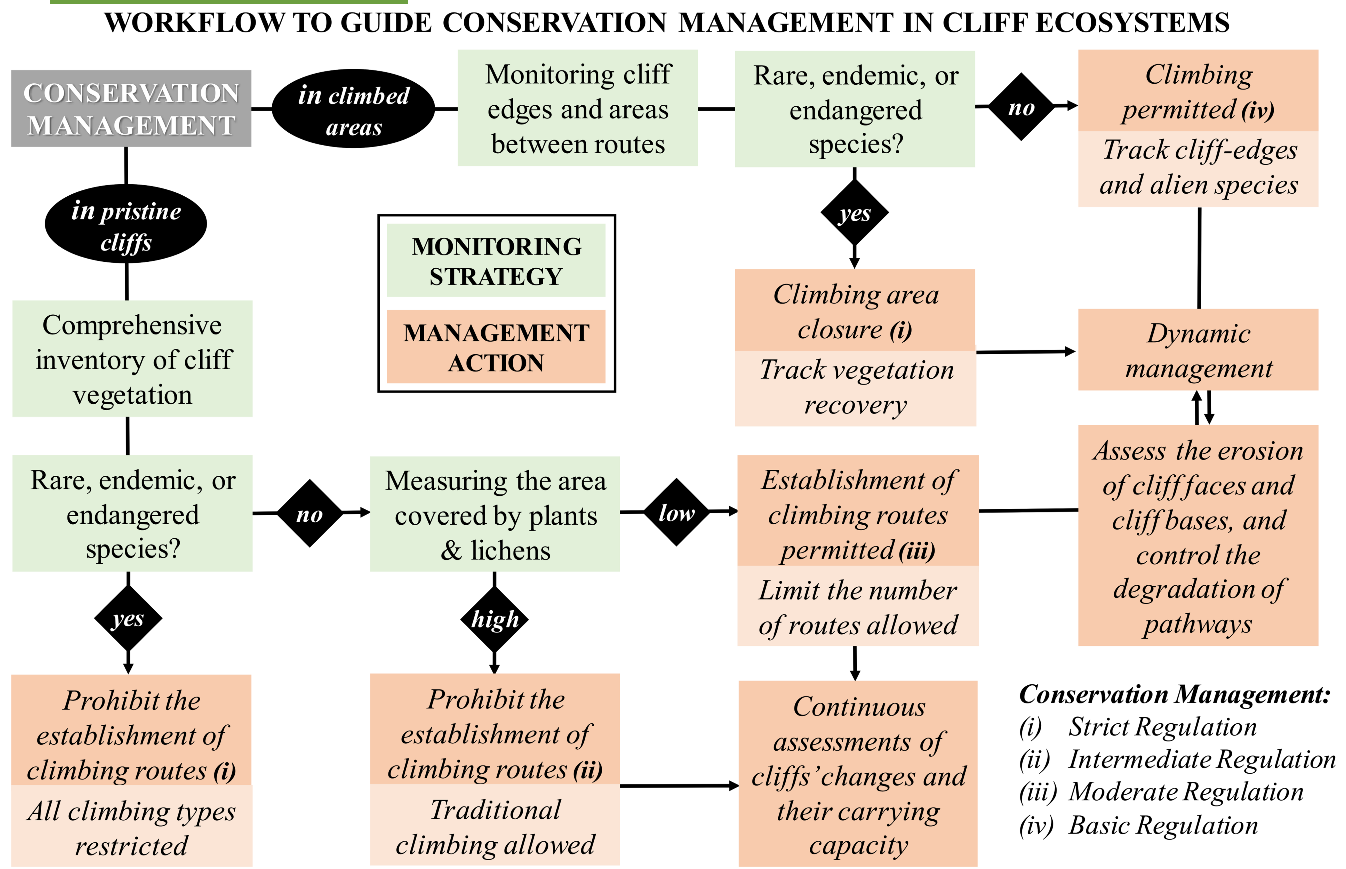

FIGURE 4 Workflow diagram as guidance for implementing conservation management actions in both pristine and climbed cliffs. The green boxes represent the associated field monitoring strategy to gather adequate information for decision-making, while the orange boxes represent the management actions to 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.

compared with 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 ascents may negatively affect other cliff organisms such as soil and rock-dwelling fungi, algae, cyanobacteria, invertebrates, mosses or different seed dispersers and pollinators (Baur et al., 2017; Coleine et al., 2021; Cooper, 1997; Gerrath et al., 2000; Horath & Bachofen, 2009; Krah & March-Salas, 2022; Schmera et al., 2018), 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. Boggess et al., 2017; Clark & Hessl, 2015; March-Salas et al., 2018; March-Salas, Morales-Armijo, et al., 2023; Reding, 2019; Tessler & Clark, 2016). They used as controls nearby areas that considering our results, may be more or less equally affected by the route development compared with the climbing route area. Therefore, the climbing impact found afterward in these studies should then be primarily attributed to the repeated ascents rather than to the opening of the climbing route, which is clearly the bottleneck of the detrimental process. Yet, considering that only seven new routes were investigated and that popular climbing routes support many more than 30 ascents per year, future studies should include a larger number of study areas and a longer temporal scale with more climbing ascents in order to increase precision in the assessment of long-term climbing impacts. Future studies can also consider the assessment of the effect of sports climbing on cliff edges and talus areas. Furthermore, since our results showed that the areas near the climbing routes are affected by route opening, future studies should include transects on cliff faces that are untouched by climbing as additional controls.

4.2 | Conservation management in cliff ecosystems

Despite its growing popularity, rock climbing is a recreational activity with few management guidelines (March-Salas, Lorite, et al., 2023). Regulations and accepted practices regarding the opening of new climbing routes are almost non-existent, or ambiguous and differing among countries and regions. Our results clearly indicate that this is an important issue to consider by conservation managers. However, it is also true that recently, the

U.S. National Park Service (NPS) and U.S. Forest Service (USFS) identified environmental hazards associated with the opening 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 natural 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 follow standardized management and monitoring strategies in cliff ecosystems.

We propose a conservation management protocol that includes data collection and monitoring that would allow gathering information on cliff ecosystems over time for adequate decision-making, plus management actions (Figure 4). 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 (Figure 4). For *basic* management, the unintentional introduction of seeds of ruderal or even invasive species, which can change the species composition and overcome cliff-specialist plants (Rusterholz et al., 2011), should receive particular attention. If *intermediate* (ii) and *moderate* (iii) conservation management is applied, traditional (i.e. climbing that does not use fixed gear and anchors in the cliff, and that does not always follow a clear previously-established route) 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* (a framework that quantitatively defines acceptable ecological conditions on a system used for recreation activities, and the appropriate management actions to prevent further changes; March-Salas, Lorite, et al., 2023; Stankey et al., 1985). In light of the results of our study, this would ideally 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), as well as their surroundings such as cliff bases, cliff edges and the pathways to the climbing area, since they can hold important diversity (Boggess et al., 2021; Fragnière et al., 2024). Moreover, in these management scenarios, further issues should be contemplated: quantifying the climbing frequency is a critical factor to determine the climbers' impact (Boggess et al., 2021); moreover, the climbing time-period (seasonal or year-round climbing) should be considered not only for birds, but also for vascular plants, since the impact can be strongest if seeds that accumulate in cliff fissures are cleaned-up, when plants are emerging, or if climbers can disturb the pollination activity. 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, acceptable climbing pressures, and data on the 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 (Harrison et al., 2024; Webb et al., 2020). All this will require revisiting the climbed cliffs and conducting continuous monitoring and assessments, so agencies should require and increase investment in management support.

5 | CONCLUSIONS

Our study shows that the climbing-related action with the strongest impact on cliff plant communities is the opening of new climbing routes. Yet, more routes investigated over a longer temporal scale with more climbing ascents should be considered to draw more reliable conclusions about the impact that climbers themselves can generate over time. Certain cliffs are likely among the last pristine ecosystems in many countries. These pristine cliffs, especially those harbouring 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 route developers with best practice guides and training in cliff nature conservation. Protecting cliff ecosystems from human disturbance is crucial to slow down biodiversity loss, but this requires increased conservation efforts based on detailed guidelines for effective management.

AUTHOR CONTRIBUTIONS

Felipe Morales-Armijo and Martí March-Salas designed the study, and Martí March-Salas, Felipe Morales-Armijo and Juan Lorite designed the field-monitoring methodology. Felipe Morales-Armijo conducted the field surveys and gathered the data with the help of

Andrea Sobrevilla-Covarrubias and inputs from Martí March-Salas, while Eduardo Estrada-Castillón helped to identify the cliff plant species. Martí March-Salas analysed the data and wrote the original draft of the manuscript, with interpretation of the data, review, and editing by Adrián Escudero, J. F. Scheepens, and Juan Lorite. All authors approved the final version of the manuscript.

ACKNOWLEDGEMENTS

We thank the local climbing route outfitters, Karla Moya, 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 sports climbing. The PhD of Felipe Morales-Armijo was funded by CONACYT (National Council of Science and Technology, México). National Geographic Society, FEDER-Andalucía 2014–2020 Programme and Talento César Nombela Grants of the Community of Madrid 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, A-RNM-4-UGR20—*EcoClimb*, and 2023-T1/ECO-29193—CONCLIFFS). 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.

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

Data available via the Dryad Digital Repository https://doi.org/10.5061/dryad.g1jwstr0z (March-Salas et al., 2024).

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REFERENCES

Adams, M. D., & Zaniewski, K. (2012). Effects of recreational rock climbing and environmental variation on a sandstone cliff-face lichen community. *Botany*, *90*, 253–259.

Bates, D., Mächler, M., Bolker, B. M., & Walker, S. C. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, *67*, 1–48.

Baur, B., Baur, A., & Schmera, D. (2017). Impact assessment of intense sport climbing on limestone cliffs: Response of rock-dwelling land snails. *Ecological Indicators*, *72*, 260–267.

Boggess, L. M., Harrison, G. R., & Bishop, G. (2021). Impacts of rock climbing on cliff vegetation: A methods review and best practices. *Applied Vegetation Science*, *24*, e12583.

Boggess, L. M., Walker, G. L., & Madritch, M. D. (2017). Cliff flora of the big south fork national river and recreation area. *Natural Areas Journal*, *37*(2), 200–211.

Chang, Y., & Xu, A. (2020). An evaluation of the impact of natural ecotourism on environmental pollution. *Environmental Science and Pollution Research*, *28*(26), 33764–33770.

Clark, P., & Hessl, A. (2015). The effects of rock climbing on cliff-face vegetation. *Applied Vegetation Science*, *18*, 705–715.

Coleine, C., Stajich, E., de Los Ríos, A., & Selbmann, L. (2021). Beyond the extremes: Rocks as ultimate refuge for fungi in drylands. *Mycologia*, *113*, 108–133.

Cooper, A. (1997). Plant species coexistence in cliff habitats. *Journal of Biogeography*, *24*, 483–494.

deCastro-Arrazola, I., March-Salas, M., & Lorite, J. (2021). Assessment of the potential risk of rock-climbing for cliff plant species and natural protected areas of Spain. *Frontiers in Ecology and Evolution*, *9*, 611362.

Estrada-Castillón, E., Villarreal-Quintanilla, J. A., Jurado-Ybarra, E., Cantú-Ayala, C., García-Aranda, M. A., Sánchez-Salas, J., Jiménez-Pérez, J., & Pando-Moreno, M. (2012). Clasificación, estructura y diversidad del matorral submontano adyacente a la planicie costera del Golfo Norte en el Noreste de México. *Botanical Sciences*, *90*(1), 37–52.

Farris, M. (1995). *The effects of rock climbing on the cliff flora of three Minnesota state parks*. Final report to the Minnesota department of natural resources. Conservation Biology Research Grants Program.

Fragnière, Y., Champoud, L., Küffer, N., Braillard, L., Jutzi, M., Wohlgemuth, T., & Kozlowski, G. (2024). Cliff-edge forests: Xerothermic hotspots of local biodiversity and models for future climate change. *Global Change Biology*, *30*(2), e17196.

García, E. (2004). *Modificaciones al sistema de clasificación climática de Köppen*. Universidad Nacional Autónoma de México.

García, M. B., Espadaler, X., & Olesen, J. M. (2012). Extreme reproduction and survival of a true cliffhanger: The endangered plant *Borderea chouardii* (Dioscoreaceae). *PLoS One*, *7*(9), e44657.

Gerrath, J. F., Gerrath, J. A., Matthes, U., & Larson, D. W. (2000). Endolithic algae and cyanobacteria from cliffs of the Niagara escarpment, Ontario, Canada. *Canadian Journal of Botany*, *78*, 807–815.

Hanemann, B. (2000). *Cooperation in the European Mountains 3: The sustainable management of climbing areas in Europe*. IUCN. xviii + 158pp.

Harrison, G. R., Boggess, L. M., Budke, J. M., & Madritch, M. D. (2022). Rock-climbing shifts cliff-face vegetation community composition based on site characteristics. *Applied Vegetation Science*, *25*(2), e12667.

Harrison, G. R., Boggess, L. M., McCord, S. E., & March-Salas, M. (2024). A call to action for inventory and monitoring of cliff ecosystems to support conservation. *Basic and Applied Ecology*, *80*, 31–39.

Hepenstrick, D., Bergamini, A., & Holderegger, R. (2020). The distribution of climbing chalk on climbed boulders and its impact on rockdwelling fern and moss species. *Ecology and Evolution*, *10*(20), 11362–11371.

Holzschuh, A. (2016). Does rock climbing threaten cliff biodiversity?—A critical review. *Biological Conservation*, *204*, 153–162.

Horath, T., & Bachofen, R. (2009). Molecular characterization of an endolithic microbial community in dolomite rock in the Central Alps (Switzerland). *Microbial Ecology*, *58*, 290–306.

INECC. (2017). *Chapter II. Environmental characterization of Mexico and its correlation with the classification and nomenclature of plant communities*. http://www2.inecc.gob.mx/publicaciones2/libros/421/cap2.html.

Krah, F. S., & March-Salas, M. (2022). eDNA metabarcoding reveals high soil fungal diversity and variation in community composition among Spanish cliffs. *Ecology and Evolution*, *12*(12), e9594.

Kuntz, K. L., & Larson, D. W. (2006). Influences of microhabitat constraints and rock-climbing disturbance on cliff-face vegetation communities. *Conservation Biology*, *20*, 821–832.
Larson, D. W., Matthes, U., & Kelly, P. E. (2000). *Cliff ecology: Pattern and process in cliff ecosystems*. Cambridge University Press.
Lenth, R. V. (2016). Least-squares means: The {R} package {lsmeans}. *Journal of Statistical Software*, *69*, 1–33.
Lorite, J., Serrano, F., Lorenzo, A., Cañadas, E. M., Ballesteros, M., & Peñas, J. (2017). Rock climbing alters plant species composition, cover, and richness in Mediterranean limestone cliffs. *PLoS One*, *12*, e0182414.
Madden, F. (2022). *EPC climbing: A climber's guide to El Potrero Chico*. 3rd edition. 400 pp.
March-Salas, M., Lorite, J., Bossdorf, O., & Scheepens, J. F. (2023). Cliffs as priority ecosystems. *Conservation Biology*, *37*(5), e14166.
March-Salas, M., Morales-Armijo, F., Hernandez-Aguero, J. A., Estrada-Castillon, E., Sobrevilla-Covarrubias, A., Arevalo, J. R., Scheepens, J. F., & Lorite, J. (2023). Rock climbing affects cliff-plant communities by reducing species diversity and altering species coexistence patterns. *Biodiversity and Conservation*, *32*, 1617–1638.
March-Salas, M., Morales-Armijo, F., Sobrevilla-Covarrubias, A., Estrada-Castillon, E., Escudero, A., Scheepens, J. F., & Lorite, J. (2024). Data from: Climbing route development affects cliff vascular plants more than subsequent climbing: A guide to evidence-based conservation management to regulate climbing. *Dryad Digital Repository*. https://doi.org/10.5061/dryad.g1jwstr0z
March-Salas, M., Moreno-Moya, M., Palomar, G., Tejero-Ibarra, P., Haeuser, E., & Pertierra, L. R. (2018). An innovative vegetation survey design in Mediterranean cliffs shows evidence of higher tolerance of specialized rock plants to rock climbing activity. *Applied Vegetation Science*, *21*, 289–297.
Mountaineering Ireland. (2023). *Climbing Development Guidelines aim to inform climbers wishing to develop climbing areas*. https://www.mountaineering.ie/content/ClimbingDevelopmentGuidelines/30.
National Park Service. (2024). *Evaluation and authorization procedures for fixed anchors and fixed equipment in National Park Service Wilderness*. https://parkplanning.nps.gov/document.cfm?documentID=132387.
R Development Core Team. (2020). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. http://www.r-project.org/index.html.
Reding, J. (2019). *Rock climbing or lichen climbing? How rock climbing impacts bryophyte and lichen communities within the Red River Gorge*. M.S. thesis. The Ohio State University.
Rubio-Salcedo, M., Martínez, I., Carreño, F., & Escudero, A. (2013). Poor effectiveness of the Natura 2000 network protecting Mediterranean lichen species. *Journal for Nature Conservation*, *21*(1), 1–9.
Rueden, C. T., Schindelin, J., Hiner, M. C., DeZonia, B. E., Walter, A. E., Arena, E. T., & Eliceiri, K. W. (2017). ImageJ2: ImageJ for the next generation of scientific image data. *BMC Bioinformatics*, *8*(1), 1–26.
Rusterholz, H. P., Verhoustraeten, C., & Baur, B. (2011). Effects of long-term trampling on the above-ground forest vegetation and soil seed bank at the base of limestone cliffs. *Environmental Management*, *48*, 1024–1032.
Schatz, B., Gauthier, P., Debussche, M., & Thompson, J. D. (2014). A decision tool for listing species for protection on different geographic scales and administrative levels. *Journal for Nature Conservation*, *22*, 75–83.
Schmera, D., Rusterholz, H., Baur, A., & Baur, B. (2018). Intensity-dependent impact of sport climbing on vascular plants and land snails on limestone cliffs. *Biological Conservation*, *224*, 63–70.
Schweizer, A.-M., Höschler, L., & Steinbauer, M. J. (2021). Quantifying the physical damage of climbing activity on sandstone lichen: No low impact climbing possible. *Sustainability*, *12*(24), 13590.
Stankey, G. H., Cole, D. N., Lucas, R. C., Peterson, M. E., & Frissell, S. S. (1985). *The limits of acceptable change (LAC) system for wilderness planning (General Technical Report INT-176)*. USDA, Forest Service, Intermountain Forest and Range Experiment Station.
Tessler, M., & Clark, T. A. (2016). The impact of bouldering on rock-associated vegetation. *Biological Conservation*, *204*, 426–433.
The Crag. (2022). https://www.thecrag.com/
Velazco, M. C., Analís, G. F., Alvarado, M. A., Ramírez, F., & Forouhhbakhch, P. (2011). Flora endémica de Nuevo León, México, y estados colindantes. *Journal of the Botanical Research Institute of Texas*, *5*, 275–298.
Vogler, F., & Reisch, C. (2011). Genetic variation on the rocks–the impact of climbing on the population ecology of a typical cliff plant. *Journal of Applied Ecology*, *48*(4), 899–905.
Webb, N. P., Kachergis, E., Miller, S. W., McCord, S. E., Bestelmeyer, B. T., Brown, J. R., Chappell, A., Edwards, B. L., Herrick, J. E., Karl, J. W., Leys, J. F., Metz, L. J., Smarik, S., Tatarko, J., Van Zee, J. W., & Zwicke, G. (2020). Indicators and benchmarks for wind erosion monitoring, assessment and management. *Ecological Indicators*, *110*, 105881.

SUPPORTING INFORMATION

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

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 using a quality approach: moderately difficult, difficult, fairly difficult, very difficult), and the route height (in m). The routes were developed in September–October 2022, and all climbing routes were oriented to the North.

How to cite this article: Morales-Armijo, F., Sobrevilla-Covarrubias, A., Estrada-Castillón, E., Escudero, A., Scheepens, J. F., Lorite, J., & March-Salas, M. (2024). Climbing route development affects cliff vascular plants more than subsequent climbing: A guide to evidence-based conservation management to regulate climbing. *Journal of Applied Ecology*, *00*, 1–11. https://doi.org/10.1111/1365-2664.14785