

Context-dependent associations of climbing intensity and abiotic characteristics with cliff vegetation on limestone cliffs in Freyr, Belgium

Authors

Sarane Coen^{1,2,3} (<https://orcid.org/0009-0009-1317-1582>)

Georgia R. Harrison⁴ (<https://orcid.org/0000-0003-0544-4471>)

Amre van den Maagdenberg³

Christophe Metsu^{5,6} (<https://orcid.org/0000-0002-5153-9351>)

Laura M. Boggess⁷ (<https://orcid.org/0000-0003-4959-8464>)

Francisco Velasquez-Espin⁸ (<https://orcid.org/0009-0000-7606-2505>)

Martí March-Salas^{9,10} (<https://orcid.org/0000-0001-5347-4056>)

Kobe Burdack¹¹

Elias P. Goossens¹² (<https://orcid.org/0000-0002-4994-2029>)

Koenraad Van Meerbeek^{*5,6} (<https://orcid.org/0000-0002-9260-3815>)

Jonas J. Lembrechts^{*2,3} (<https://orcid.org/0000-0002-1933-0750>)

*Shared last

The author's institutional affiliations

¹Institute of Botany, University of Liège, Belgium

²Ecology & Biodiversity (E&B), Utrecht University, The Netherlands

³Research Group of Plants and Ecosystems (PLECO), Department of Biology, University of Antwerp, Belgium

⁴Department of Animal and Range Sciences, Montana State University, Bozeman, MT USA.

⁵Department of Earth and Environmental Sciences, KU Leuven, Leuven, Belgium

⁶KU Leuven Plant Institute, KU Leuven, Leuven, Belgium

⁷Ecology and Conservation Biology, Mars Hill University, North Carolina, USA

⁸Department of Biology and Biochemistry, University of Houston, 4302 University Drive, Houston, Texas 77004, USA

⁹Area of Biodiversity and Conservation, Department of Biology and Geology, Physics and Inorganic Chemistry, Universidad Rey Juan Carlos-ESCET, Móstoles, Madrid, Spain

¹⁰Instituto de Investigación en Cambio Global (IICG-URJC), Universidad Rey Juan Carlos, Móstoles, Madrid, Spain

¹¹Faculty of Engineering Technology, KU Leuven, Leuven, Belgium

¹²Department of Biology, Research group WILD, VUB, Brussels, Belgium.

Correspondence

Sarane Coen

Institute of Botany, University of Liège, Belgium

Ecology & Biodiversity (E&B), Utrecht University, The Netherlands

Research Group of Plants and Ecosystems (PLECO), Department of Biology, University of Antwerp, Belgium

Email: coen.sarane@gmail.com

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Author contributions

S.C., K.V.M., and J.J.L. conceived the research idea. S.C. handled data curation, project administration, visualisation, and wrote the original draft. Formal analyses were conducted by S.C., G.R.H., K.V.M., and J.J.L.; S.C., L.M.B., K.B., M.M.S., F.V.E., K.V.M., and J.J.L. developed the methodological protocols. Data were collected by S.C., K.B., E.P.G., A.M., C.M., K.V.M., and J.J.L. The project was supervised by J.J.L. and K.V.M. All authors contributed to validation, review, and editing of the manuscript.

ABSTRACT

Cliff ecosystems support diverse vascular plant communities due to high abiotic heterogeneity and their historical role as climatic refugia. However, cliffs are increasingly exposed to disturbances from recreational rock climbing. The ecological effects of climbing likely depend on abiotic cliff characteristics—such as slope, aspect, and microtopography—but these context-dependent relationships have not been consistently evaluated. We investigated how plant diversity, community composition, and community-level functional tendencies vary with climbing intensity and abiotic characteristics on limestone cliff faces in Freyr, Belgium. Vegetation was surveyed using a standardised protocol across 248 1-m² subplots along 13 vertical transects spanning unclimbed, low-intensity, and high-intensity climbing routes. We quantified species richness, vegetation cover, Shannon diversity, community composition, and community-weighted means of Grime's competitive, stress-tolerant, and ruderal strategies. We recorded 103 vascular plant species. Species richness etc. were more consistently associated with abiotic characteristics than with climbing intensity, whereas climbing intensity was mainly associated with community composition and functional strategies. Species richness and vegetation cover were highest at moderate microtopography and lower on steep slopes, and cover was lower on south-facing cliffs. The association between climbing intensity and richness depended on microtopography: richness peaked at low climbing intensity on cliffs with pronounced microtopography, consistent with the intermediate disturbance hypothesis. Competitive species were more abundant on unclimbed cliffs, whereas ruderal species were more abundant on climbed cliffs. Unclimbed cliffs were also associated with threatened (red-listed) indicator species, suggesting vulnerable vegetation may be at risk under increasing climbing pressure.

KEYWORDS

environmental filtering, Grime CSR, functional traits, Intermediate disturbance hypothesis, microclimate

INTRODUCTION

Rock cliffs host high vascular plant diversity, including rare and endemic species adapted to harsh, vertical environments ([Datar and Watve 2018](#); [Ellenberg 2009](#); [García et al. 2020](#); [Kuntz and Larson 2006](#); [Larson et al. 2005](#); [March-Salas et al. 2023](#); [Rusterholz et al. 2011](#); [Harrison et al. 2024](#); [Fitzsimons and Michael 2017](#)). The steep and fragmented nature of cliffs creates isolated habitats where pressure from competitive species is reduced ([Larson et al. 2005](#)). As a result, cliffs serve as one of the last holdouts for stress-tolerant taxa ([Ellenberg 2009](#)). However, spatial isolation also limits dispersal and connectivity. Under accelerating climate change and increasing anthropogenic pressure on biodiversity ([Hooper et al. 2012](#); [Calvin et al. 2023](#); [IPBES 2019](#); [De Pryck 2021](#)), this restricted migration may increase local extinction risk ([March-Salas et al. 2025](#)). Cliff ecosystems are therefore both rich in biodiversity and vulnerable to global change. Yet, they remain poorly studied and deserve greater ecological attention ([Capó et al. 2023](#); [Cartwright 2019](#); [March-Salas et al. 2023](#)).

Cliff biodiversity arises from limited historical disturbance, and fine-scale environmental heterogeneity. Variations in slope, aspect, and microtopography create gradients in solar radiation, moisture, and nutrient availability, resulting in a patchwork of microclimates that can buffer or amplify environmental extremes ([Larson et al. 2005](#); [Bartlett et al. 1990](#); [Bramer et al. 2018](#)). Cliff surfaces exhibit more complex radiation dynamics than horizontal or gently sloped surfaces ([Geiger et al. 2012](#); [Larson et al. 2005](#)). South-facing slopes in the Northern Hemisphere generally receive more solar radiation and are warmer and drier, while north-facing slopes are cooler and more humid ([Suggitt et al. 2011](#)). These microclimatic gradients are expected to strongly influence plant establishment, development and persistence; however, in situ measurements on vertical cliff faces remain limited, leaving key mechanisms misunderstood and calling for many more case studies. As a result, cliffs can function simultaneously as refugia for cold-adapted species, facilitating persistence during climatic change, and as stepping stones for warm-adapted taxa extending their ranges ([De Frenne et al. 2013](#); [Dobrowski 2011](#); [Speziale and Ezcurra 2015](#); [Keppel et al. 2015](#)).

Slope and microtopography strongly shape plant communities too ([Boggess et al. 2021](#); [Holzschuh 2016](#)). Steep cliffs are often well-drained and nutrient-poor, while cliffs with shallower slopes tend to trap more debris and moisture, creating sites suitable for plant establishment and growth ([Bartlett et al. 1990](#); [Clark and Hessel 2015](#); [Harrison et al. 2022](#); [Kuntz and Larson 2006](#); [Larson et al. 2005](#)). Microtopography—such as crevices, pockets, fractures, and surface irregularities—provides microsites for soil and water retention, creating places for propagule catchment and plant growth ([Nuzzo 1996](#); [Larson et al. 2005](#)). Increased microtopography often enhances species richness. Thus, the particular abiotic conditions of cliffs act as a strong mediator of the presence and structure of cliff vegetation ([Kuntz and Larson 2006](#); [Harrison et al. 2022](#)).

Due to their steepness and inaccessibility, cliffs have historically experienced lower levels of grazing, trampling, and development compared to surrounding landscapes. However, the rising popularity of outdoor recreation, such as rock climbing ([Aubel and Lefèvre 2022](#)), has resulted in increased disturbance regimes in these fragile ecosystems. For instance, the Flemish climbing federation (Klim-en Bergsportfederatie, KBF) recorded a 28% increase in its members between 2017 and 2024 (KBF, personal communication, 2024). Rock climbing can cause both mechanical and chemical disturbances, through vegetation and loose rock removal upon establishment, trampling and the use of climbing chalk ([Morales-Armijo et al. 2024](#)) ; Leduc, personal communication, 2024).

Research on the impact of rock climbing on vascular plants has revealed mixed results ([Boggess et al. 2021](#); [Holzschuh 2016](#)). Most studies have documented negative effects of climbing, including reduced species richness and abundance ([Camp and Knight 1998](#); [McMillan and Larson 2002](#); [Müller et al. 2004](#);

[Lorite et al. 2017; Schmera et al. 2018](#)), as well as shifts in community composition ([Morales-Armijo et al. 2024](#)). These compositional changes can involve a decline in specialist rock-dwelling species ([Müller et al. 2004; Lorite et al. 2017; Camp and Knight 1998](#)). In contrast, March-Salas et al. ([2018](#)) reported a shift primarily affecting generalist species, with reduced richness and cover of non-specialists in climbed areas. Nevertheless, several studies detected weak or no direct effect of climbing once variation in abiotic cliff characteristics was accounted for ([Clark and Hessler 2015; Boggess et al. 2017; Harrison et al. 2022; Nuzzo 1996; Kuntz and Larson 2006](#)).

Together, these findings indicate that the ecological effects of rock climbing on plants can be context dependent, varying with baseline vegetation composition, abiotic cliff characteristics, and climbing intensity ([Holzschuh 2016; Boggess et al. 2021](#)). In addition, climbers tend to preferentially select cliff faces that are naturally less vegetated, further complicating causal inference ([Boggess et al. 2017; Farris 1998; Kuntz and Larson 2006; Müller et al. 2004](#)). Consequently, expanding research to additional sites and new locations is essential to disentangle disturbance effects from abiotic filtering. Previous studies have been clustered in North America, with European research mostly limited to Switzerland and Spain ([Boggess et al. 2021](#)).

To enable more robust and long-term reproducibility and global comparability ([Boggess et al. 2021](#)), the international MIREN Rocks network, a global research community of rock climbing ecologists, developed a standardised sampling protocol (Appendix A.1). This protocol provides a consistent framework for quantifying vegetation, abiotic conditions, and microclimatic variation on vertical rock faces. Here, we present the first application of this protocol in Belgium, at the limestone cliffs of Freyr. Beyond extending the geographical coverage of existing research, this study applies a multi-faceted approach to estimate climbing intensity (Appendix A.2), and integrates in situ microclimatic measurements on vertical cliff faces.

Beyond species richness and cover, we focus on community composition and functional traits to capture subtle responses. Functional strategies are interpreted through Grime's ([1977](#)) CSR framework, which classifies species as competitive (C), stress-tolerant (S), or ruderal (R), with most species combining strategies to cope with local stress (e.g., limited resources) and disturbance (e.g., biomass removal). Harsh cliff conditions favour stress-tolerant strategies, yet disturbance may shift communities toward ruderal species, potentially altering functional composition ([Rusterholz et al. 2011](#)).

Specifically, we examine how species richness, vegetation cover, functional traits (CSR strategies), and community composition vary along gradients of climbing intensity, slope, aspect, and microtopography

in Freyr, to assess whether associations between climbing intensity and vegetation vary with abiotic conditions.

METHODS

Study site

The study was conducted at the Freyr climbing site in the Meuse Valley, Belgium (50.223697, 4.895386) (fig. 1A). This Natura 2000 protected area is characterised by limestone cliffs and species-rich calcareous grasslands of high conservation value ([Newton et al. 2012](#)). Freyr has been Belgium's largest climbing crag in terms of both area and number of routes since the 1930s and supports year-round climbing. ([Bott 2022](#)). The Club Alpin Belge (CAB) manages site access and maintenance.

Data acquisition

Vegetation data were collected following the *MIREN Rocks* survey protocol (Appendix A.1). Fieldwork was conducted in June and July 2024, during peak flowering. Vegetation surveys followed a hierarchical structure (site > zone > transect > plot > subplot). The site corresponded to the Freyr climbing area (fig. 1A), within which seven cliff zones (i.e. standalone cliffs) were surveyed. Thirteen vertical transects were established across these zones (fig. 1A), encompassing a total of 18 climbing routes. A single transect could include sections of multiple routes, as routes in Freyr can deviate from the vertical axis or consist of multiple routes above each other. Survey transect length varied between 18 and 76 m, depending on cliff height. Along each transect, between three and nine plots were placed, with longer transects having more plots, resulting in a total of 62 plots. Each plot covered 4 m² and consisted of four 1 m² subplots (fig. 1B-C), yielding 248 subplots in total. Subplots were the primary observational units for vegetation data collection and analysis, with plots, transects, and zones treated as nested random effects.

At the plot level, we measured abiotic cliff characteristics, including height above the base of the cliff and aspect, which was determined using a compass. At the subplot level, slope was measured with an inclinometer, and microtopography was quantified using a surface heterogeneity index ranging from one (smooth rock surface) to ten (high surface heterogeneity characterised by abundant fissures, cracks, crevices, and/or pockets) (Appendix A.1 fig.7; [Boggess et al. 2021](#); [Boggess et al. 2017](#)). All vascular plant species present in each subplot were identified, and both total vegetation cover and species-specific cover were visually estimated as percentages of subplot area. Overall, 71.8% of taxa were identified to species level, 16.5% to genus level only, and 11.6% remained unidentified. Taxa identified only to genus were treated as distinct operational taxonomic units in all diversity and community analyses.

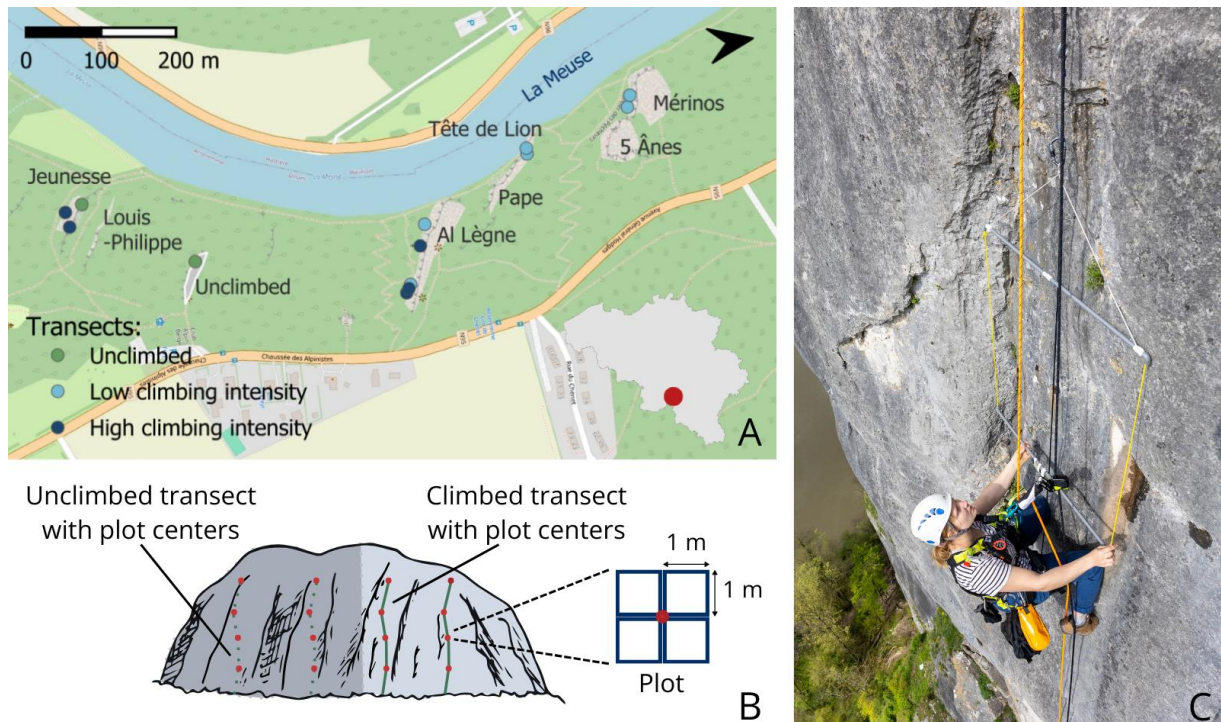


Figure 1: A) Map (OpenStreetMap) of the Freyr study area, showing the different cliff zones (grey). Each dot represents a transect; colours indicate the dominant climbing intensity level of the transect. Inset: location of Freyr in Belgium B) Sampling design for cliff faces with climbed and unclimbed zones. The vegetation was surveyed along vertical transects, with each plot composed of four 1 m² subplots. C) Picture of the vegetation survey on the cliff of Al Lègne, performed while rappelling down, using a 1 m² frame attached to a rope as subplot.

Climbing intensity

The MIREN Rocks protocol recommends monitoring vegetation in paired climbed and unclimbed transects. This was, however, impractical for our study because unclimbed zones were scarce or unsafe to access. Instead, we initially assessed climbing intensity of the climbed transects with the Climbing Use Index (CUI) based on guidebook star ratings and walking approach time (Clark and Hessler 2015), and PCA-based metrics derived from online ascent logs and guidebook information. However, all of these approaches proved unsuitable for Freyr. The CUI produced only a narrow range of values and relied on subjective route ratings that reflect appreciation rather than actual use in our study area. PCA-based scores did not match local climbers' experience (see Appendix A.2. for details). Given these limitations, climbing intensity was estimated using a survey of eight experienced local climbers, who ranked the sampled routes according to perceived use.

Agreement among individual rankings was tested using Kendall's coefficient of concordance (W), which indicated moderate alignment ($W=0.473$, $p<0.001$). To avoid overconfidence with the ranking, climbing intensity was classified at the plot level into three categories based on average ranks: unclimbed ($n=28$ subplots), low ($n=116$), and high ($n=104$); plot-level classification allowed climbing intensity to vary within transects composed of different climbing routes. The proportion of climbers whose ranking

placed each route in the same category was calculated to evaluate how well the classification reflected climbers' perceptions. Most routes showed high agreement (11 of 18 routes >85%), while only two routes showed <50% consensus, indicating that surveys of experienced local climbers provided a reliable estimate of climbing intensity at Freyr.

Data analysis

Alpha diversity metrics

Diversity metrics were quantified at subplot level as follows: species richness was calculated as the number of vascular plant species, total vegetation cover was estimated as proportion of each subplot covered by vascular plants, and Shannon diversity index, calculated using the vegan package ([Oksanen et al. 2024](#)), integrating species richness and relative abundances to account for evenness, from species-specific cover values to account for both richness and evenness. Subplots without vegetation were excluded from this calculation, resulting in $n = 150$ subplots. Simpson index was calculated as well and displayed in Appendix A.5.

Species richness, Shannon diversity and total vegetation cover were analysed using generalised linear mixed models (GLMMs; glmmTMB package ([Brooks et al. 2017](#))). Species richness was modelled with a negative binomial GLMM to account for overdispersion, total vegetation cover with a beta regression GLMM and Shannon diversity with a GLMM using a Tweedie distribution with zero-inflation to accommodate positive continuous values with many zeros.

Fixed effects included climbing intensity (factor with three levels: unclimbed, low, high), aspect (factor with two levels: north- vs. south-facing), slope (continuous, standardised to mean = 0 and SD = 1), and microtopography (discrete, standardised). Based on visual inspection, a quadratic effect of microtopography was included for species richness and total vegetation cover. Interactions between climbing and microtopography were included for all response variables to account for the potential differences in how microtopography modifies the effect of climbing on vegetation structure and diversity.

To account for the nested sampling design (subplot < plot < transect < zone), all models were initially fitted with plots nested within transects nested within zones as random effects structure. If convergence or singularity issues arose, the random-effects structure was simplified. In that case, the random term with the smallest variance was removed and the model refitted, until the fit was no longer singular (Bates et al., 2015; Lüdecke et al., 2021). In all models, transect explained no variance (variance < 10^{-7}) and was removed. The final species richness and total vegetation cover models

therefore included zone and plot as random intercepts, whereas the Shannon diversity model included plot only, as the zone variance also resulted in a singular fit.

Functional diversity (CSR strategies)

Plant strategies were quantified using Grime's CSR framework (C = competitive, S = stress-tolerant, R = ruderal) based on the KS index, which assigns each species proportional C, S, and R values (summing to one) derived from functional traits related to growth, persistence, and disturbance tolerance ([Ivanova and Zolotova 2023](#)). When species-level values were unavailable, genus-level means derived from the KS dataset were used, but only when within-genus variation in CSR values (standard deviation) was below 1. For each subplot, relative abundance in the community-weighted mean of each strategy was calculated by multiplying each species' CSR values by its proportional cover, summing these values across species, and dividing by the total cover of all species with available CSR data. These CWM values reflect the dominant functional strategies within each plant community. Subplots with less than 70% representation of species with known CSR values were excluded, resulting in 137 subplots, nested within 52 plots, 13 transects, and 7 zones.

Separate Tweedie GLMMs were fitted for each strategy (C, S, R) to test associations with climbing intensity, slope, aspect, and microtopography. Quadratic terms were excluded as they were not expected, and interaction terms were not included to avoid overfitting. Here also, random-effects structures were adapted to each strategy to ensure model convergence and avoid singularity. The final stress-tolerant model included plots nested in transects, and the ruderal model included plots nested in zones. For the competitive model, all random-effect variances were estimated at zero, so it was fitted without random effects.

Differences in relative representation between strategies were evaluated using a linear model with CWM as the response variable and strategy (C, S, R) as a fixed effect with the lme4 package ([Bates et al. 2015](#)). Pairwise comparisons between the strategies were performed using the emmeans package ([Lenth and Piaskowski 2017](#)) and Tukey-adjusted p-values.

Model diagnostics for both alpha diversity and CSR models, including residual distribution, overdispersion, and multicollinearity, were assessed using DHARMA ([Hartig 2024](#)) and performance ([Lüdecke et al. 2021](#)), which was also used to calculate marginal and conditional R^2 for all models. Figures and model predictions were generated using ggplot2 ([Wickham 2009](#)) andggeffects ([Lüdecke 2018](#)).

Community composition

We tested whether species composition differed among climbing intensities and abiotic cliff characteristics using multivariate analyses. Analyses were restricted to subplots containing at least three species because extremely low species counts prevented reliable multivariate analysis due to near-zero stress in the NMDS, retaining 91 subplots in 41 plots and 11 transects. Community dissimilarities were calculated using Bray–Curtis distances. Patterns in community composition were visualised with non-metric multidimensional scaling (NMDS; $k=3$) using the ‘metaMDS’ function from the vegan package ([Oksanen et al. 2024](#)). Effects of climbing intensity (categorical; unclimbed, low, high), aspect (categorical; North–South), slope (continuous), and microtopography (continuous) were tested using permutational multivariate analysis of variance (PERMANOVA; (M. J. Anderson, 2001)) implemented with function ‘adonis2’ (999 permutations, marginal tests). This approach evaluates whether multivariate community centroids differ among factor levels or along environmental gradients. Because of the hierarchical survey design with subplots nested within plots, transects and zones, each predictor was tested at the level at which it varied, to avoid pseudoreplication (M. Anderson & Braak, 2003; Hurlbert, 1984). For plot- and transect-level predictors, species cover was averaged per plot or transect. Permutations were restricted within a higher grouping level, which was also entered as the first term in the model; the tested predictor was entered last, and only this term was interpreted. Microtopography was thus tested on subplot data grouped by plot. Climbing intensity and slope were tested on plot means grouped by zone, each with the other plot-level predictors as covariates; zones rather than transects were used because climbing intensity and slope varied little within transects. Aspect was tested on transect means with unrestricted permutations; as all north-facing transects were located in a single zone, aspect could not be separated from zone identity.

Homogeneity of multivariate dispersion was assessed for the categorical predictors (climbing intensity and aspect) using the ‘betadisper’ function followed by a permutation test (‘permutest’, 9999 permutations) to test for differences in within-group dispersion, at the same level and with the same permutation restrictions as the corresponding PERMANOVA. NMDS ordinations were visualised using ggplot2.

Indicator species were identified using multilevel pattern analysis (function ‘multipat’, 999 permutations) from the indicpecies package ([De Cáceres and Legendre 2009](#)). This uses permutations to test the strength of association between each species and level of climbing intensity, without including the additional environmental covariates. In contrast to the multivariate analyses, the indicator species analysis was conducted on the full species matrix.

Microclimate

Microclimatic variation was assessed using fifteen TOMST thermologgers ([Wild et al. 2019](#)). They measured the air temperature 8 cm in front of the cliff face, and were equipped with the factory-provided single shield. They were placed at different heights on north- and south-facing cliffs for approximately one year. Two sets of three sensors were installed along a vertical gradient on one north-facing and one south-facing cliff; the remaining sensors were distributed across additional cliffs. In total, six sensors were located on north-facing cliffs and nine on south-facing cliffs. Daily mean, minimum, and maximum temperatures were calculated and analysed with linear mixed-effects models to test for seasonal differences between aspects. See Appendix A.3 for full methodological details. The microclimate data were insufficient to be included as an explanatory variable in analyses.

All analyses were conducted in R version 4.3.1 (R core team, 2023).

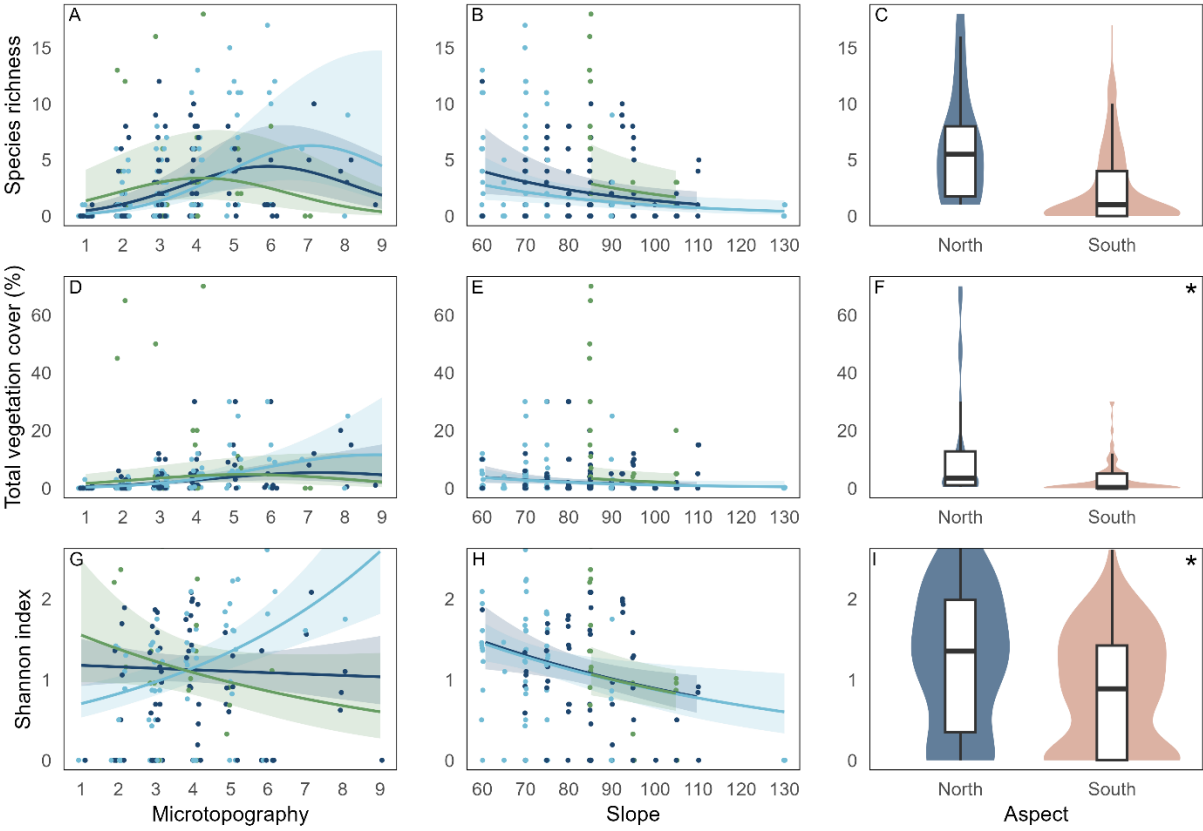
RESULTS

Alpha diversity

Across all plots, we recorded 103 vascular plant species. Species richness and Shannon diversity showed significant interactions between microtopography and climbing intensity, whereas for total vegetation cover the interaction terms were not significant (tab. 1). Species richness had a negative quadratic relationship with microtopography, and response varied by climbing intensity. Richness increased more steeply with microtopography under low than under high climbing intensity, so that richness was higher under low intensity at higher microtopographic complexity, whereas under unclimbed conditions richness increased less with microtopography than under high intensity (fig. 2A). Because only a small number of plots combined high microtopographic complexity with low climbing intensity, we repeated the analyses excluding these plots; the observed interaction patterns remained qualitatively similar (Appendix A.4). Vegetation cover showed a similar relationship, where cover was higher with greater microtopography, but the interaction terms with climbing intensity were smaller in magnitude than those observed for species richness (fig 2D). Shannon diversity increased with microtopography under low climbing intensity, but not under high climbing intensity or on unclimbed cliffs (fig. 2G).

Besides microtopography, there were differences in vegetation across other abiotic variables regardless of climbing intensity. Slope was negatively associated with all vegetation metrics: steeper cliffs consistently supported lower species richness, reduced vegetation cover, and lower Shannon diversity (fig 2B,E,H). Vegetation cover (fig 2F) and diversity (fig. 2G) differed between aspects, species

richness (fig. 2C) did not. South-facing cliffs exhibited lower cover and reduced Shannon diversity compared to north-facing cliffs. Patterns for the Simpson index closely matched those observed for the Shannon index (Appendix A.5.).



Climbing intensity: ■ Unclimbed ■ Low ■ High

Figure 2: Relationships between climbing intensity, abiotic cliff characteristics and alpha diversity metrics. Species richness (A–C), total vegetation cover (D–F), and Shannon diversity index (G–I) are shown in relation to microtopography (A, D, G) and slope (B, E, H). The number of subplots for species richness and vegetation cover is $n=248$, for the Shannon index $n=150$. Points represent observed values in subplots and are coloured by climbing intensity. Lines show fitted relationships from generalized linear mixed models (GLMMs), with shaded areas indicating 95% confidence intervals. Panels C, F, and I display violin plots with embedded boxplots summarizing the distribution (median and interquartile range) of each response variable by cliff aspect, with significant differences among aspect indicated by $*(p<0.05)$.

Table 1: Fixed-effect estimates from separate generalised linear mixed models (GLMMs). Cells show the estimate, its p -value (in parentheses). Significant predictor effects are in bold. Marginal and conditional R^2 values from the GLMMs indicate the proportion of variance explained by fixed effects and by both fixed and random effects, respectively. Continuous predictors were standardised (mean = 0, SD = 1) prior to analysis; estimates are per standard deviation.

Predictor	Species richness	Total vegetation cover	Shannon index
Intercept	1.440 ($p=0.01$)	-2.717 ($p<0.001$)	0.439 ($p=0.002$)

Microtopography (linear)	0.864 (p<0.001)	0.841 (p<0.001)	-0.027 (p=0.66)
Microtopography (quadratic)	-0.268 (p<0.001)	-0.172 (p=0.004)	-
Slope	-0.372 (p=0.01)	-0.422 (p=0.04)	-0.175 (p=0.01)
Aspect (North/South)	-0.647 (p=0.27)	-1.182 (p=0.01)	-0.321 (p=0.02)
Low climbing intensity	-0.360 (p=0.18)	-0.027 (p=0.92)	-0.126 (p=0.30)
Unclimbed intensity	0.343 (p=0.38)	0.632 (p=0.14)	0.054 (p=0.73)
Microtopography : low climbing	0.363 (p=0.02)	0.299 (p=0.09)	0.305 (p<0.001)
Microtopography : unclimbed	-0.564 (p=0.04)	-0.415 (p=0.11)	-0.175 (p=0.20)
R ² Marginal	0.536	0.371	0.337
R ² Conditional	0.801	0.592	0.575

CSR strategies

The relative abundance (community-weighted means) of plant functional strategies (CSR) was strongly uneven. Stress-tolerant plants dominated cliff vegetation, while competitive species were less abundant and ruderal species were least abundant (Appendix A.7). Post hoc Tukey tests confirmed that the relative abundance of all three strategy types differed significantly from each other (Tukey-adjusted $p < 0.001$) although strategy explained only a small part of the variation in CWM ($R^2 = 0.16$), as CWMs varied considerably among subplots.

Responses of community-weighted means to climbing intensity and abiotic conditions differed among strategies (tab. 2, fig. 3). Competitive plants were more abundant in unclimbed subplots than in plots with high climbing intensity and were more present on south-facing than on north-facing cliffs. Their relative abundance was lower on steeper slopes. Microtopography had a positive but non-significant correlation with the relative abundance of competitive species (fig 3A-C). In contrast to competitive species, stress-tolerant plants were more abundant on steeper slopes, while microtopography and aspect had no detectable correlations (fig. 3D-F). The relative abundance of ruderals was lower in unclimbed than in highly climbed plots, but did not differ between low and high climbing intensity. Ruderal plants were also less abundant at higher microtopographic heterogeneity and on south-facing cliffs (fig.G-I).

Table 2: Predictors of Community-weighted means (CWM) of CSR plant strategies. Fixed-effect estimates from separate generalised linear mixed models (GLMMs) with Tweedie distribution for each strategy-specific CWM. Cells show the estimate, its p-value (in parentheses). Significant values are bolted. Marginal and conditional R^2 values from the GLMMs indicate the proportion of variance explained by fixed effects and by both fixed and random effects, respectively.

Predictor	Competitive (C)	Stress-tolerant (S)	Ruderal (R)
Intercept	2.749 (p < 0.001)	3.607 (p < 0.001)	4.300 (p < 0.001)
Microtopography	0.107 (p = 0.14)	0.018 (p = 0.60)	-0.178 (p = 0.005)

Slope	-0.271 (p=0.001)	0.080 (p = 0.04)	0.141 (p = 0.07)
Aspect (north/south)	0.797 (p =0.002)	0.053 (p = 0.72)	-1.148 (p<0.001)
Low climbing intensity	-0.276 (p=0.07)	0.105 (p = 0.25)	0.200 (p = 0.24)
Unclimbed intensity	0.627 (p=0.003)	0.125 (p = 0.37)	-1.257 (p<0.001)
R²_{Marginal}	0.006	0.061	0.325
R²_{Conditional}	0.018	0.213	0.380

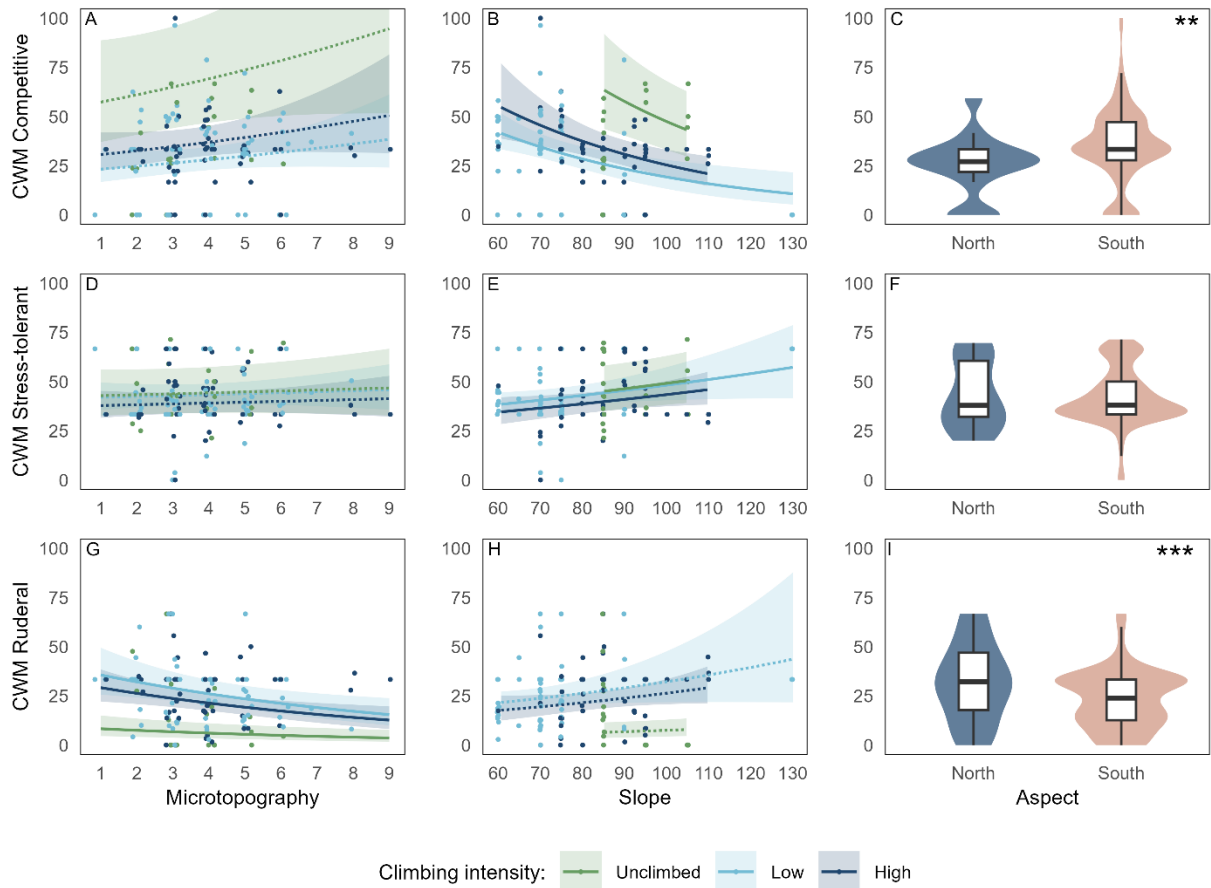


Figure 3: Relationships between climbing intensity, abiotic cliff characteristics and community-weighted mean (CWM) of Grime plant strategies with n=137 subplots. Competitive (A–C), Stress-tolerant (D–F), and ruderal (G–I) strategies are shown in relation to microtopography (A, D, G) and slope (B, E, H). Points represent observed values and are coloured by climbing intensity. Lines show fitted relationships from generalized linear mixed models (GLMMs), with shaded areas indicating 95% confidence intervals. Panels C, F, and I display violin plots with embedded boxplots summarizing the distribution (median and interquartile range) of each response variable by cliff aspect, with significant differences among aspect indicated by **($p<0.01$) and *($p<0.001$).**

Community composition

PERMANOVA indicated that mean species composition differed with climbing intensity and microtopography, but not with slope. Weak but significant differences with microtopography were found among subplots within the same plot, and differences between climbing intensities among plots

within the same zone. Aspect explained a considerable share of variation among transects but was not significant; because all north-facing transects were located in a single zone, this result should be interpreted with caution. Most variation among subplots was between plots (63%), and 28% of the variation among plots was between zones. PERMDISP indicated that variability in species composition did not differ among climbing intensities. Variability was lower among north-facing than among south-facing transects, but this comparison was likewise based on only two north-facing transects (Table 3; NMDS ordination in Fig. 4).

Table 3: PERMANOVA and PERMDISP results for the effects of climbing intensity and abiotic cliff characteristics on species composition. Analyses included the 91 subplots with at least three species, located in 41 plots, 11 transects and 7 zones. Each predictor was tested at the hierarchical level at which it varied, with permutations restricted within the grouping level (Bray–Curtis dissimilarities, 9999 permutations). PERMDISP was tested at the same level and with the same permutation restrictions as the PERMANOVA

		PERMANOVA		PERMDISP
<i>Permutations restricted within</i>	<i>Predictor</i>	<i>R²</i>	<i>p-value</i>	<i>p-value</i>
<i>Plots</i> (n = 91 subplots; plot R ² = 0.634; residual R ² = 0.353)				
	Microtopography	0.012	0.02	-
<i>Zone</i> (n = 41 plot means; zone R ² = 0.279; residual R ² = 0.595)				
	Climbing intensity	0.078	<0.001	0.09
	Slope	0.018	0.79	-
<i>Unrestricted</i> (n = 11 transect means; residual R ² = 0.859)				
	Aspect	0.141	0.11	0.02

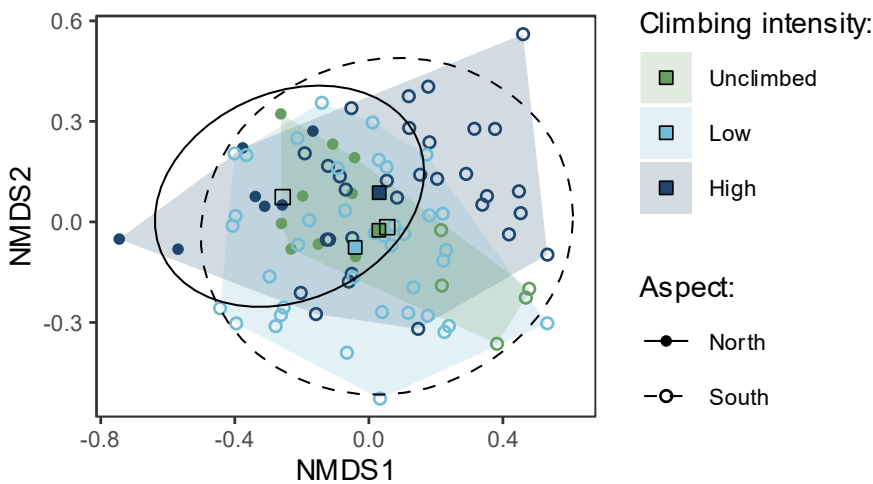


Figure 4: NMDS ordination (3D, stress = 0.18) of species composition across 91 subplots with at least three species, located in 41 plots and 11 transects, shown for the first two axes. Points are coloured by climbing intensity and filled by aspect. Coloured convex hulls illustrate the range of subplots for each climbing intensity, and ellipses show 95% confidence

intervals for north- and south-facing aspects. Squares indicate group centroids, coloured for climbing intensity and empty for aspect. The ordination combines all zones; statistical tests are reported in Table 3

A total of 19 indicator species of climbing-intensity categories were identified (detailed results table in Appendix A.6). Only one species was indicative of low climbing intensity and two species were associated with high climbing intensity, whereas, in comparison, sixteen species were associated with unclimbed plots, three of which are threatened and listed on the local red list (*Scabiosa columbaria* L., *Hieracium murorum* Jord., *Festuca pallens* Host.). In total, six red-listed species were observed across all plots, including *Lactuca perennis* L., *Melampyrum arvense* L., and *Thymus praecox* Opiz.

Microclimate

Temperatures differed strongly between aspects. South-facing cliffs were generally warmer than north-facing cliffs, but the magnitude of this difference varied seasonally. For daily mean temperatures, differences by aspect were most pronounced and highly significant in summer, moderately significant in spring and fall, and small and non-significant in winter. Daily maximum temperatures differed significantly in all seasons, and daily minimum temperatures were significantly higher on south-facing cliffs in summer (Appendix A.3).

DISCUSSION

We surveyed vascular plant communities on Freyr's limestone cliffs in Belgium to examine how cliff vegetation varies with climbing intensity across a range of abiotic cliff characteristics. Climbing intensity alone did not show strong main effects on alpha diversity, but was associated with shifts in functional structure and species composition and the effects depended on microtopographic heterogeneity. Together, these results suggested that the differences associated with climbing intensity were subtle, expressed primarily through community composition rather than reductions in vegetation cover, and strongly related to abiotic cliff characteristics.

Climbing intensity and vegetation diversity, functional structure and composition

Climbing intensity was not consistently associated with lower richness, cover or diversity; differences were mainly in composition and functional structure. Differences in diversity among climbing classes coincided with differences in the relative dominance of plant functional strategies and species composition.

Species composition on unclimbed cliffs likely reflected a combination of historical disturbance regimes and strong microhabitat filtering. Unclimbed cliffs had a higher relative abundance of competitive (C-strategy) species than cliffs with high climbing intensity. Within this low-disturbance

context, competitive species may dominate locally, which could limit richness through competitive exclusion, particularly where microtopographic complexity is high. Competitive indicator species associated with unclimbed areas included *Sesleria caerulea* (L.) Ard. and *Silene nutans* L. These areas also hosted stress-tolerant taxa such as *Umbilicus rupestris* (Salisb.) Dandy, *Carex humilis* Leyss., *Erysimum cheiri* (L.) Crantz, *Sedum album* L., and threatened (red-listed) species, including *Scabiosa columbaria* L., *Hieracium murorum* L., and *Festuca pallens* L., none of which were indicator species of climbed areas. This finding indicates a potential loss of vulnerable vegetation due to climbing. Although not identical, these results reflect a pattern partly in line with Müller et al. (2004), who found that specialised rock species—often stress-tolerant—occurred less frequently on climbed cliffs than on unclimbed cliffs in Switzerland.

Low-intensity climbing areas hosted a mixture of species with competitive, stress-tolerant, or ruderal strategies. At high microtopographic complexity, richness peaked here, possibly because moderate disturbance limits local competitive dominance. Nevertheless, the relative abundance of competitive species did not differ significantly between low and high intensity. Additionally, stress-tolerant species remained present, but several that were associated with unclimbed cliffs in the indicator species analysis no longer showed this association. This indicates that, even where richness is highest, low-intensity routes had fewer unique (indicator) species.

High intensively climbed cliffs supported disturbance-driven communities: ruderal indicator species, such as *Taraxacum* sp., were associated with high climbing intensity, consistent with biomass removal by climbing favouring ruderal and opportunistic species. Such effects of disturbance have been found before, potentially at the expense of more specialised taxa (Radujković et al. 2025). In contrast, March-Salas et al. (2018) found that fewer generalist species occurred on climbed cliffs, while specialised and moderately specialized rock species were not significantly affected by climbing intensity.

Only one and two indicator species were associated with low- and high-intensity climbing, respectively, compared to 16 species associated with unclimbed cliffs. This pattern suggests that climbing disturbance may reduce the complexity and uniqueness of cliff communities, as reported for other types of disturbance (Radujković et al. 2025). However, the three climbing intensity levels were unevenly represented (unclimbed = 28; low = 116; high = 104), and unclimbed subplots were concentrated in a few transects only. Species restricted to these transects can therefore more easily reach high indicator values, so the larger number of unclimbed indicator species should be interpreted with caution. Together with the absence of differences in species richness and cover among climbing levels, these results suggest that climbing intensity is more strongly associated with species composition than with alpha diversity.

Abiotic constraints

Abiotic cliff characteristics were more consistently associated with vegetation structure and diversity than climbing intensity. Slope acted as a strong environmental filter. Steeper cliffs had lower vascular plant richness, cover, and Shannon diversity, likely due to gravitational instability, reduced water retention, and limited soil and nutrient accumulation. Slope was, however, not associated with species composition. These effects were consistent across climbing intensities, suggesting that slope constrains vegetation more strongly than climbing disturbance. This finding is similar to existing studies ([Bartlett et al. 1990](#); [Clark and Hessler 2015](#); [Larson et al. 2005](#)). The relative abundance of competitive species declined on steeper slopes, consistent with the expectation that competitive plants are disadvantaged in resource-poor, stressful environments. Stress-tolerant species showed only a weak tendency to increase with slope ([Grime 1977](#)).

Species richness did not differ between aspects, suggesting that both north- and south-facing cliffs offer sufficient habitat heterogeneity for species persistence. This result is consistent with findings by March-Salas et al. ([2018](#)) and Graham and Knight ([2004](#)), whereas Boggess ([2017](#)) reported the highest vascular plant diversity on west-facing slopes. In contrast, vegetation cover was higher on north-facing cliffs, likely reflecting cooler microclimatic conditions, which may reduce evaporative stress and promote plant growth. These findings align with Müller et al. (2004), who reported higher plant cover on shaded cliffs. Compositional variability was lower among north- than among south-facing transects, which could reflect stronger competition under the higher vegetation cover on north-facing cliffs. South-facing cliffs were warmer, which may limit growth and could contribute to lower cover and Shannon diversity. On North faces, species with a ruderal plant strategy were more abundant, on South faces, competitive strategies were more prevalent, though it is not clear what is driving this pattern. These aspect effects should be interpreted with caution: all north-facing subplots were located in two transects within a single zone, so aspect cannot be fully separated from site-specific conditions. Additional processes and environmental drivers likely contribute to this trend but are not captured in our models of relative CSR strategy abundance, as indicated by their low R^2 values, especially for the competitive model. Potential interactions with climbing intensity, due to route selection, may also influence these patterns, although limited data across aspects and climbing levels prevent further testing.

Microtopography, in our study area, was the main source of heterogeneity and availability of microhabitats. Species richness and vegetation cover showed a hump-shaped response to microtopography, with the highest values at intermediate levels of structural complexity. On smooth cliff surfaces, plant establishment is constrained by the limited availability of suitable microhabitats, whereas higher microtopographic complexity initially increases the number of microhabitats with

accumulation of soil, nutrients, moisture, and propagules ([Larson et al. 2005](#); [Kuntz and Larson 2006a](#); [Kuntz and Larson 2006b](#)). Similar positive effects of microtopographic complexity on cliff vegetation have been reported in numerous studies ([Clark and Hessler 2015](#); [Farris 1998](#); [March-Salas et al. 2018](#); [Harrison et al. 2022](#); [Müller et al. 2004](#); [Nuzzo 1996](#)). As such, at lower microtopographic complexity, the pattern is consistent with the habitat heterogeneity hypothesis, which predicts that environmental complexity promotes species coexistence through niche differentiation, as species with differing requirements can exploit varying conditions ([Graham and Duda 2011](#); [Stein et al. 2014](#)).

At high levels of microtopographic complexity, however, species richness declined again. Although the number of plots representing the highest levels of microtopographic complexity was limited in this study, one plausible explanation is increased competitive exclusion under locally less stressful conditions, although we found no significant relationship between microtopography and the relative abundance of competitive species. In addition, inspection of plot photographs revealed that several high-complexity plots with low richness were characterised by pronounced blocky overhangs or strong dominance by a single species, suggesting that extremely complex surfaces may become unsuitable for plant establishment when structural overhangs reduce substrate stability or light availability, consistent with the strong negative effects of slope on vegetation observed in this study.

In contrast to species richness, Shannon diversity increased with microtopography only under low climbing intensity, and not under high intensity or on unclimbed cliffs; likely because this metric is influenced by species evenness ([Shannon 1948](#)). Although greater microtopographic complexity can increase the number of available microhabitats and species, dominance by a few competitive taxa may persist or even increase, limiting changes in evenness.

Climbing as context dependent disturbance mediated by habitat heterogeneity

At high microtopographic complexity species richness peaked at a low climbing intensity level, but only under conditions of high microtopography, whereas both unclimbed and high-intensity climbed areas exhibited lower diversity. This interaction suggests that the association between climbing intensity and richness varies with microtopography. These patterns are consistent with the Intermediate Disturbance Hypothesis ([Connell 1978](#); [Fox 1981](#)), but only under structurally heterogeneous conditions, suggesting that habitat complexity moderates whether disturbance is associated with higher richness. Together, our results suggest that relationships between climbing and vegetation are not uniform but depend on abiotic conditions that already structure these ecosystems.

Future directions

Although climbing and abiotic variables were significantly associated with diversity and species composition, they explained only a modest share of compositional variation. Climbing intensity explained 8% of the variation in composition among plots within zones, slope 2% among plots within zones and microtopography 1% among subplots within plots, whereas aspect explained 14% of the variation among transects but was not significant. In contrast, plot identity explained 63% of the variation among subplots, and zone identity 28% of the variation among plots. Composition was thus strongly spatially structured, but largely by factors other than those we measured.

Further research could consider detailed drivers, including substrate and soil analyses, as well as UAV-derived digital elevation models combined with thermal imaging for microclimates to improve understanding of microhabitat conditions ([Metsu et al. 2026](#)). Drone-based vegetation surveys could also improve data collection in hazardous or difficult-to-access cliff areas ([Nyberg et al. 2024](#)). This study focused on vascular plants, but cliff ecosystems also host mosses and lichens and include the cliff edge and base, which may respond differently to climbing disturbance (Larson et al. 2005; Boggess et al. 2021). Including these additional taxa and zones would provide a more comprehensive understanding of climbing impacts at the ecosystem scale.

Multi-site studies across different climates, rock types, and management regimes, and long-term monitoring will help to understand and assess the generality of the observed patterns ([Boggess et al. 2021](#)). Using standardised methodology and global networks such as MIREN Rocks could facilitate this comparability among studies. This further research is essential to better understand and protect these unique cliff ecosystems and to develop science-based strategies that balance outdoor recreation with biodiversity conservation.

CONCLUSION

Our findings showed that the relationships between climbing intensity and vegetation in Freyr were complex and context-dependent. Climbing intensity was associated with differences in species and community composition under certain habitat conditions, not with lower overall cover or richness. Low-intensity climbing was associated with higher species richness under highly heterogeneous microtopography. Climbed cliffs had a higher relative abundance of ruderal species and fewer indicator species, including red-listed species, than unclimbed cliffs.

Vegetation also varied with abiotic cliff characteristics, shaping microhabitat availability. This indicates that more detailed analyses of environmental factors, such as microtopography and microclimate, are

needed to fully understand the underlying ecological processes. This abiotic importance and site-specific results were consistent with previous research.

These results have important implications for the conservation and management of cliff habitats and climbing areas. They highlight the conservation value of unclimbed cliffs, which support typical stress-tolerant and red-list species and should therefore be prioritised for protection to safeguard these vulnerable populations. Previous studies made similar recommendations for the protection of climbing-free zones ([Harrison et al. 2022](#); [Müller et al. 2004](#); [Lorite et al. 2017](#); [Camp and Knight 1998](#); [McMillan and Larson 2002](#)).

Overall, these findings suggest that recreational rock climbing may be compatible with biodiversity conservation when appropriately managed, while emphasising the importance of maintaining some cliffs free from climbing to protect sensitive vegetation.

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MIREN ROCKS

The MIREN rock survey



Pictures: Simon Dierickx

1 Overview of the MIREN rock survey protocol and contributions

The overall goal of the Mountain Invasion Research Network (MIREN) rock survey protocol is to study rock cliff vegetation around the world. We aim to (1) investigate the impact of rock climbing on these communities, (2) investigate the impact of rock climbing on the spread of alien plant species, (3) study the importance of rocks in species ranges edges, (4) compare the species composition of rock cliff vegetation with their surroundings and (5) assess the importance of the rock microclimates as microrefugia and on the distribution of rock vegetation. Data generated using the standardized protocol described in this document can be used to evaluate and quantify the processes and mechanisms shaping rock cliff communities at regional to global scales. We encourage the implementation of the protocol across the globe. We envisage revisiting the plots every five years to facilitate the investigation of long-term changes in rock vegetation. We primarily target bolted climbing routes (sport climbing, with fixed anchors), but we are open to trad(itional) climbing routes (without fixed anchors) as well. The protocol described below is developed for sport climbing. If you want to sample trad climbing routes, the protocol will be slightly different (see section 5.1). We explicitly exclude Bouldering and Via Ferrata (Or Klettersteig) routes.

If you plan to join MIREN Rocks, please let us know at miren.rocks@gmail.com!

2 Safety and permits

General safety statement:

As rock climbing inherently carries a significant level of risk, we want to stress the importance of following all rock climbing safety measures. Participation in the MIREN rock survey is therefore limited to individuals with **sufficient rock-climbing experience**. MIREN is not responsible for possible accidents during the MIREN rock survey.

Team composition:

Fieldwork must not be conducted alone. We strongly recommend a minimum of two people for sampling plots. At least one team member should be familiar with the local flora. Identifying species while hanging on the rocks can be quite time-consuming if you're not confident in your plant knowledge.

The second person is essential for both safety and efficiency. Responsibilities include:

- Conducting partner safety checks
- Belaying (if required by the chosen system)
- Monitoring safety while the climber is identifying plants or installing sensors
- Managing equipment
- Providing rapid assistance in case of an incident

Access and rope systems:

Always follow established safety standards. Ensure there is no risk of accidentally unlocking or misusing safety equipment during operations.

The most practical and controlled approach is to access rock cliffs from above, where possible.

We recommend using rope access techniques designed specifically for work at height. This includes:

- Using an additional safety rope, so fieldworkers are secured by two ropes all times
- Using semi-static ropes (never climb dynamically and fall on them)

- Using harnesses designed for height-work, which provide better comfort and stability during prolonged vertical tasks

However, all participants must use only rope access techniques in which they are properly trained, experienced, and fully competent.

Helmets must be worn at all times during fieldwork. **Rope protectors** should be used at all friction points.

Weather:

Safety in fieldwork does not rely solely on rope techniques. Rock-based fieldwork is physically demanding and often exposed to extreme environmental conditions.

- Bring ample drinking water.
- Monitor weather forecasts carefully.
- Select cooler, stable weather conditions whenever possible or prefer working during cooler parts of the day. Avoid working in extreme heat and unstable weather.
- Wear appropriate sun protection

These precautions help maintain fieldworker comfort, productivity, and reduce the risk of heat-related or weather-related incidents.

Collaboration with local climbing community and authorities:

We think it is also very important to reach out to the local climbing community and communicate openly about the goals of our research project. We encourage interested researchers to team up with local climbers since they often have invaluable information on the rock site, safety measures and the legal framework.

Lastly, be sure to contact local authorities or the organizations managing the rock climbing site to obtain the necessary permits for your fieldwork! If you install temperature sensors, make sure to communicate this to the local climbing community. You can find an example of affiche about the sensor as an appendix of the protocol.

3 Protocol methodology

Within each **Site**, sampling occurs along **transects**. Whenever feasible, we strongly encourage sampling **paired transects** (one climbed and one unclimbed). However, we acknowledge that unclimbed transects are often difficult or impossible to find. In such cases, working with unpaired transects (e.g., only climbed transects, or fewer unclimbed than climbed transects) is acceptable.

Along each transect, plant species composition will be recorded in several **Plots** of 2 by 2 m², composed out of 4 subplots of 1 m². Sites are potentially subdivided into different **Sectors** (e.g. a north facing and a south facing sector within one site). Further description of Sites, sectors, Transects and Plots can be found below. We have set the minimum amount of plots to be able to join MIREN rocks at 30 (=120 & m² subplots).

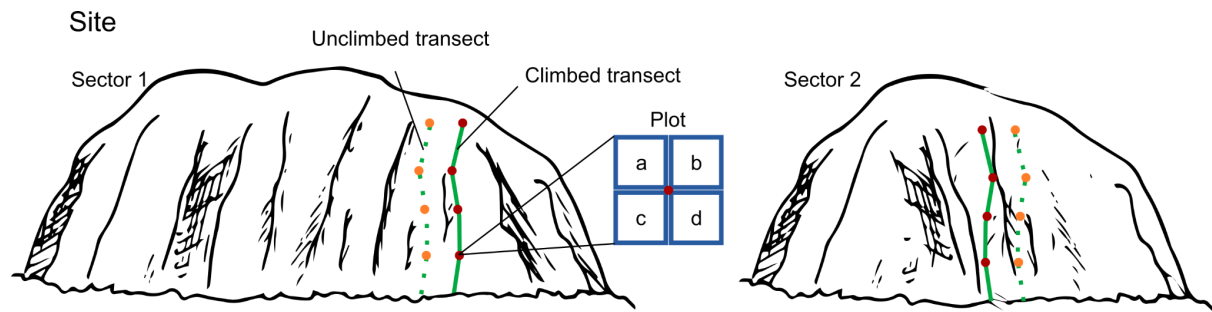


Figure 1: A rock climbing site with 2 paired transects (in total 2 climbed and 2 unclimbed transects). The vegetation is recorded in a plot of 2 m x 2 m, consisting of 4 subplots of 1 m² (a, b, c, d)

3.1 Site

In this survey, a Site is defined as a rock cliff which is used and equipped for rock climbing. The protocol is specifically designed for climbing sites with routes having fixed anchors (but see section 5), which are used to locate the plots and mark them for resurveys. It could be that a Site consists of different climbing Sectors, which are often physically isolated from each other. These sectors often get distinct names. If this is the case, the hierarchical protocol gets an additional fifth layer: Sites>Sectors>Transects>Plots>Subplots.

The delineation of a Site will depend on many local factors and we do not seek to constrain these. Ideally, a new Site should not be in, or part of, an existing 'MIREN rocks' site (see <https://www.mountaininvasions.org/miren-rocks> for an up-to-date map). Please contact us (miren.rocks@gmail.com) before starting the survey to check whether your region is suitable for inclusion in the MIREN rocks database.

3.2 Transects

Paired transects

As much as possible, we will sample pairs of transects, consisting of a climbed and an unclimbed transect. A climbed transect is a climbing route, which is equipped with fixed anchors for climbing (e.g. bolts, pitons). These climbing routes should have a minimum length of 15 m. We did not set a maximum length. Unclimbed transects have no evidence of climbing (no chalk or permanent equipment), are not mentioned in local guidebooks and occur at least 2 m from established climbing routes (Harrison et al, 2022, see Figure 2 - Option 1). Given our 2 m by 2 m plots, centered around the bolted anchor, the plots of the climbed and unclimbed transect will touch at the sides. Please consider a wider spacing between climbed and unclimbed transects if you notice that the impact of climbing goes beyond 1 meter at either side of the bolted anchor. It is important that paired climbed and unclimbed transects have similar environmental conditions (e.g. slope, aspect, microenvironment) and only differ in terms of climbing use.

Unpaired transects

In climbing sites where a dense network of routes does not allow the placement of unclimbed transects directly next to the climbed transects as described above, the unclimbed transects could also be placed in a separate, unclimbed part of the rock site (Figure 2 - Option 2). Since bolting is missing here (or climbing is not allowed), we advise reaching the transect via the top of the rock (rappelling down). Also in option 2, paired climbed and unclimbed transects should have similar

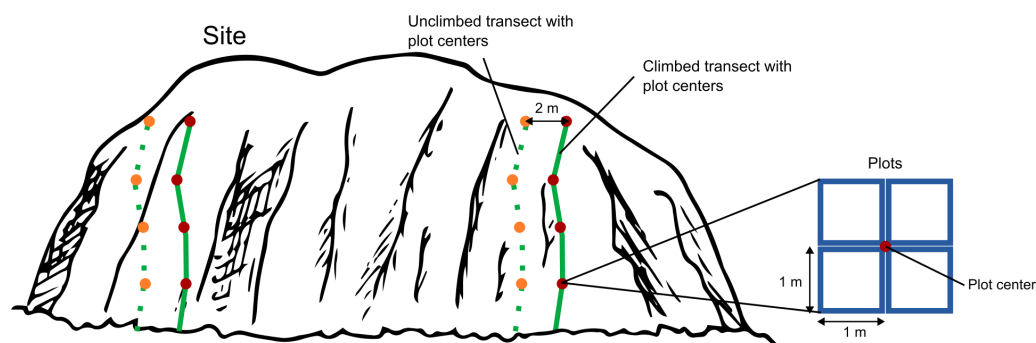
environmental conditions, if possible. Consider contrasting highly popular with rarely used transects to get contrasting climbing intensity.

For both in paired and unpaired transects, we are interested in climbing intensity. Empirical count data on climbing frequency are often difficult to obtain. In a previous case study, we explored several approaches, including online ascent logs (e.g., 8a.nu or TheCrag), the Climbing Use Index (Clark & Hessel, 2015), and information from local guidebooks, as well as **surveys of local climbers**.

We ask you to conduct a similar survey at your study site. This involves listing all routes where inventories were conducted and sending this list to at least 10 climbers who are very familiar with the area and its routes. Ask them to rank the routes from least frequently climbed to most frequently climbed, based on their own experience, perception, and observations. An example of such a survey is provided in the appendix 6.7 of this protocol.

There is no minimum amount of transects to survey to be included in the database, since transect length will differ considerably among regions. However, we estimate that at least 30 plots (15 climbed and 15 unclimbed if using paired transects) would be needed to have sufficient regional explanatory power. Note that 30 plots are 120 1 m² subplots. More might be necessary if the diversity and heterogeneity in microenvironments and plant communities are high, or if rock faces are very smooth and vegetation presence is low in general. In that case, consider monitoring across a range of climbing grades, as vegetation is usually more present on easier climbs. Of course, we want to stimulate you to sample as many plots as possible.

Option 1



Option 2

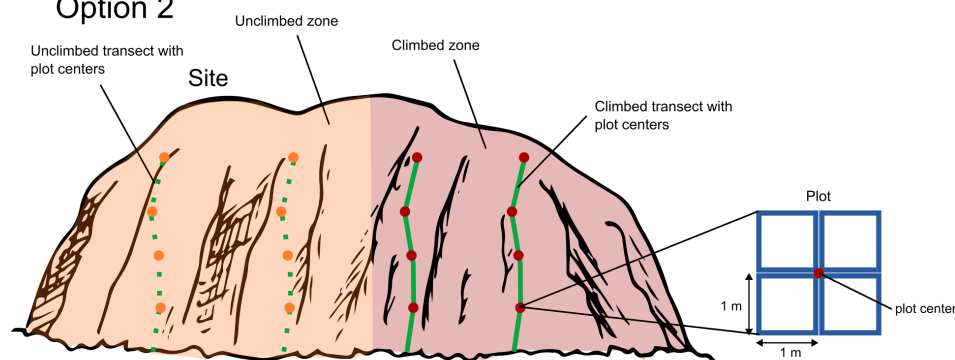


Figure 2: two options to position paired climbed and unclimbed transects within a rock site

3.3 Plots

Along each transect, we will sample the vegetation and environmental conditions in squared plots of 2 m by 2 m, consisting of 4 subplots of 1 m². For the climbed transect, the squared plots will be centered around the fixed anchors (e.g. fixed bolts and pitons). These fixed anchors serve as permanent markings and will allow resurveys in the future. The minimum separation between the plot centers of two consecutive plots should be 3 m. You should aim to have at least 3 plots per transect.

For option 1 (Figure 2), unclimbed transects will be chosen at either side of a climbed transect. The plot centers of the unclimbed transect will be positioned at the same height as the plot centers of the climbed transect and at a minimum distance of 2 m from the plot centers of the climbed transect. At this minimum distance of 2 m, the subplots of the climbed and unclimbed transect touch each other at the sides. Paired plots must have similar conditions (heterogeneity, slope, aspect). For option 2 (Figure 2), try to position the unclimbed plots at the same height as the climbed plots of the corresponding transect. Also here, pay special attention to having similar environmental conditions in paired plots.

We will work with a fixed grid of 1 m by 1 m (e.g. consisting of plastic tubes, see Appendix 6.1) to position the subplots around a plot center. We advise using chalk to draw each of the subplots consecutively on the rock, after which you can start collecting data in each of the subplots (see section 4). Please remove the chalk after the survey.

4 Data collection

The following descriptions are based on the criteria to include a dataset in the global MIREN Rocks database. All data sheets must include the date of the survey and the names and emails of recorders to facilitate data checking. If you have any questions regarding data collection, contact miren.rocks@gmail.com.

All data should be submitted to miren.rocks@gmail.com using [this template](#). For the northern hemisphere, the deadline to submit the data is October 30th 2026. For the surveys in the southern hemisphere, data should be submitted before April 30th 2026. Please contact us if you want to join, but the initiated deadlines are too soon.

Appendix 6.9 shows an A5 summary sheet of the data that must be collected in the field. Print it out and take it with you during fieldwork. You can also use it as a template for your notes.

4.1 Site

- Country/location
- Site name: Official name of climbing site
- Type of cliff: Natural cliff, quarry, ...
- Grade system of routes: Yosemite Decimal System, French Grading Scale, UIAA, Australian scale, UK system - numerical, UK system - adjective
- Is the site managed/cleaned for climbing purposes by local climbing organizations?: Yes/No
 - How is it cleaned?

- How often is it cleaned? Multiple times per year/ once per year / once every few years
- When was the last cleaning (if known?)
- If the Site has different sectors, also record the sector names
- Estimate of climbing intensity of site:
 - Numbers of climbers per year (in classes: 1: 0-100, 2: 100-500, 3: 500-1000, 4: 1000-2000, 5: >2000. Sources: climbing books, local climbing association or websites like thecrag.com or mountainproject.com)
 - Year of opening of the site
 - Climbing season length (months)
- Microclimate temperature (optional, see section 4.4)
- For communication purposes, we welcome pictures of the surveyed sites and of you when climbing and conducting the research protocol

4.2 Transect

- Geolocation: Coordinates should be recorded at the base of each transect and reported as latitude and longitude in decimal degrees using the WGS 84 datum; please check that the mapped locations are correct using GIS or Google Earth before submitting data.
- Elevation at the base of the transect: in meters above sea level; obtained using a digital elevation model or Google Earth; at the same locations as geolocation is recorded.
- Overall aspect/orientation (°) using a compass
- Overall slope (°) - overhanging transect (>90°), slab transects (<90°) using an inclinometer
- Type of rock substrate: we will follow the classification system of thecrag.com (see Appendix 6.2)
- Total length of the transect (m)
- Date of survey: dd/mm/yyyy
- For climbed transects:
 - Local name of the route
 - Year the route opened
 - Multipitch: Yes/No
 - Grade of route
 - Popularity of the individual climb (0-5; relative within the site) inferred by the number of stars or popularity (source: climbing books, local climbing association or websites like thecrag.com or mountainproject.com)
 - Time to approach the transect (in minutes)
- For unclimbed transects
 - Position compared to the paired climbed transect: Left/Right
 - Distance to paired climbed transect (in m)

4.3 Plot

The following is to be recorded in each 2 m x 2 m plot:

- Plot code: Unique identifier for each plot, recorded in the form **Country.Site.Transect.PlotSubplot** (e.g. BE.FRE.C6.2a).
 - Country is the official two-letter country code (e.g. Belgium = BE).

- Site should be three letters (e.g. FRE = Freyr). This code will be given to you by MIREN. If there are different sectors in one site, please number them (eg. FRE1, FRE2, ...)
- Transect consists of a letter (C1-C... for climbed routes, U1-U... for unclimbed routes) and a number. Transects are numbered from 1 onwards. Pairs of transects get the same transect number (e.g. C6 and U6 = 6th climbed and unclimbed transect).
- Plots are numbered from 1 onwards, with 1 being the lowest plot. Paired plots should get the same number.
- Subplots are labelled a (top left), b (top right), c (bottom left), d (bottom right) (see Figure 1)
- Name and cover of each species: see section 3.3.1 for species nomenclature information and see section 3.3.2 for the ordinal projective foliage cover estimates to be used.
- Height of the plot center above the base of the route (m)
- Anchor number (measured from bottom)
- Aspect (°) - measured using a compass
- Slope (°) - measured at plot centre using (in)clinometer
- At the subplot level: surface heterogeneity in classes (see Appendix 6.3)
- At the subplot level: total vegetation cover (by vascular plants, in %)
- Take a picture of every subplot

4.3.1 Species information

Vascular plants

All angiosperms, gymnosperms, and ferns, both native and non-native, that create foliar cover in a subplot are to be recorded.

- If a species can only be identified to the family or genus level, assign a region-specific name. This name should combine the taxonomic level, country code, site code, and a unique identifier (e.g., *Acacia* BE.FRE1 or *Asteraceae* BE.FRE2).
- If a species cannot be identified even to the family level, use a name consisting of its life form (e.g., graminoid, herb, fern, vine, shrub, or tree), the region code, and a unique identifier (e.g., *shrub* BE.FRE3).

Bryophytes

Bryophytes (mosses, liverworts, and hornworts) present in each subplot will also be recorded. Since field identification of these groups is challenging, we will employ the following dual approach:

1. **Morphotype classification**
 - Bryophytes will be classified into morphotypes instead of species, following the guidelines in Appendix 6.4.
2. **Bryophyte harvesting**
 - In each subplot, carefully remove a small, representative fragment of each moss cushion using a knife or similar tool, minimizing damage to the remaining

cushion. Place the collected samples in a pre-labeled paper bag (with the subplot code).

- Dry the samples at room temperature for three days, then send them for identification to:

Alain Vanderpoorten

BAT. B22 Biologie de l'évolution et de la

conservation-aCREA-Ulg

Quartier Vallée 1

chemin de la Vallée 4

4000 Liège 1

Belgium

- Please notify us by email once the moss samples have been shipped.

Lichens

Lichens will also be classified into **morphotypes** instead of species, following the guidelines in Appendix 6.4. **Harvesting lichens for the MIREN Rocks protocol is not needed.**

If in-house expertise is available for identifying bryophytes and/or lichens to the species level, such data is encouraged in addition to morphotype classifications. These observations should be recorded in the same form and using the same methods as those for vascular plants.

4.3.2 Species cover estimates

Estimate total plant cover (in %) of each plant species. Plant cover is defined as the proportion of the rock that is shaded by vegetation foliage when projecting it perpendicularly on the rock surface. This value needs to include cover from all locations of each species within the plot boundaries. Note that the sum of all species-specific cover estimates can exceed 100 % due to overlap in coverage. In order to help the estimation of the plant cover, you can find physical representations of 1, 2 and 5% as a reference in Appendix 6.5. We urge you to take these examples with you in the field.

Estimates are at the 1% resolution, yet for small plants, covers of 0.1 (~3 x 3 cm) and 0.5% (~7 x 7 cm) could be used. It is important to calibrate cover assessment among a survey team, and an accuracy assessment should be conducted (see Appendix 6.6). Surveying should only begin once accuracy standards have been met.

4.4 Microclimate measurements

The measurements of the microclimate temperature are optional. The goal is to measure microclimate temperature at the rock site level (or sector level) and compare it to the microclimate temperature of an open (non-shaded), flat habitat near the rock site. More specifically, we ask you to install (1) one temperature logger at the rock face of every site or at every sector within a rock site. Make sure to cover the different rock cliffs facing different directions, since we expect the microclimate to differ strongly between different directions, and (2) one temperature logger in an open (non-shaded), flat habitat near every rock site which serves as a control. The data should be delivered in the SoilTemp data format: <https://www.soiltempproject.com/how-to-submit-data/>.

Here, we describe the specifics of the temperature measurements:

- Temporal specifications of the measurements:

- We ask you to measure temperature during the growing season for at least 3 months
- Measure at a minimal temporal resolution of 1 measurement every 30 minutes.
- Installation location:
 - The logger in the rocks should also be installed above the trees and away from shrubs to avoid their shade. Being exposed to the sun, it is absolutely necessary to shield the sensors from the sun!
 - The logger in the open habitat should be installed just above the soil surface (e.g. between 5 and 15 cm above the surface) at a non-shaded location, far from trees or other shade-casting objects. Being exposed to the sun, it is absolutely necessary to shield the sensors from the sun! If there is a lot of wildlife in the region, it could be necessary to protect the logger with a wire cage (e.g. a [shopping basket](#)).
- Recommended loggers:
 - We recommend using the [TOMST Thermologger](#) on the rock face, because it is very accurate and it comes with a handy screw to attach it to the rock (Figure 3). Best use the included screw and a plug (not included) to attach it to the rock. Please make sure to order the triple radiation shield from TOMST to shield this logger from the sun (per default it comes with a single shield). This logger can also be used to measure the temperature in the open, flat habitat. [Maclean et al. \(2021\)](#) have shown that a single radiation shield is not enough.
 Note: installing the microclimate sensors on the rock face can be challenging. Some cliffs have cracks that you can utilize, while others don't. Some participants have used drills, but that can add extra complexity to the process.
 - For the open flat habitat, you can also use the Thermologger, or you can use the (more expensive) [TOMST TMS-4](#), which is specifically designed to be installed in the soil. Please make sure to order the triple radiation shield from TOMST to shield this logger from the sun (per default it comes with a single shield). If these TOMST sensors are not available in your country, we recommend using Lascar or Hobo loggers (or another brand with similar accuracy), installed with a Gill-style radiation shield (which can be self-made, see Figure 4).



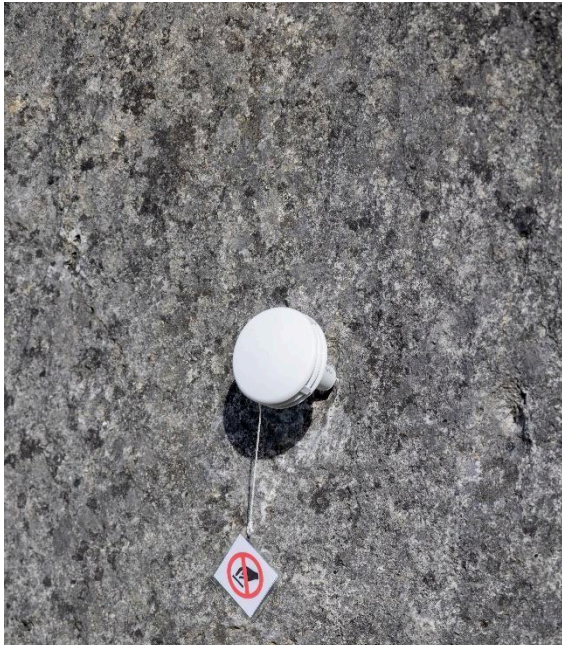


Figure 3: TOMST Thermologger can be used to measure the temperature at the rockface, as it comes with a handy screw and triple radiation shield. Pictures from <https://tomst.com/>, Jonas Lembrechts and Kobe Burdack



Figure 4: Lascar logger with a self-made double radiation shield, made from two white funnels. The inner funnel has holes to stimulate air flow. Pictures from Pieter De Frenne

4.5 Surrounding vegetation

To answer research questions 3, 4 and 5, we would need information on plant species occurring in open habitats in the region surrounding the surveyed rock sites. Therefore, we ask you to provide a list of plant species that occur in open natural habitats in the region surrounding the surveyed rock sites. This list can be expert-based or extracted from databases, like GBIF. If you have the time or just happen to have data, community data (i.e. plot-level data) are welcome as well (but not mandatory).

5 Deviations from standard protocol

5.1 Traditional climbing

The protocol above is developed for sport climbing routes with fixed anchors. If you want to join with a traditional climbing site, there are a few things to consider:

- If you aim to compare climbed and unclimbed transects (but see 5.2), make sure the climbed transect is being climbed (e.g. existing route in a climbing book, signs of chalk). The same for unclimbed transects: make sure it is not climbed.
- Since it will be hard to have permanent markings to facilitate resurveys, we don't consider these sites for future resurveys
- Data on anchor numbers are not needed
- Be extra careful!!

6. Appendices

6.1 Fixed frame

We advise using a frame consisting of two plastic tubes of 1 m, connected with 1 m ropes (Figure 5). Best to hang the frame to a second rope with a prusik knot for easy vertical movement along the wall. A spirit level attached to one of the tubes allows to level the frame horizontally. Adding coloured tape could aid the estimation of the species cover (Figure 6).



Figure 5: Fixed frame connected with a prusik knot to a second rope

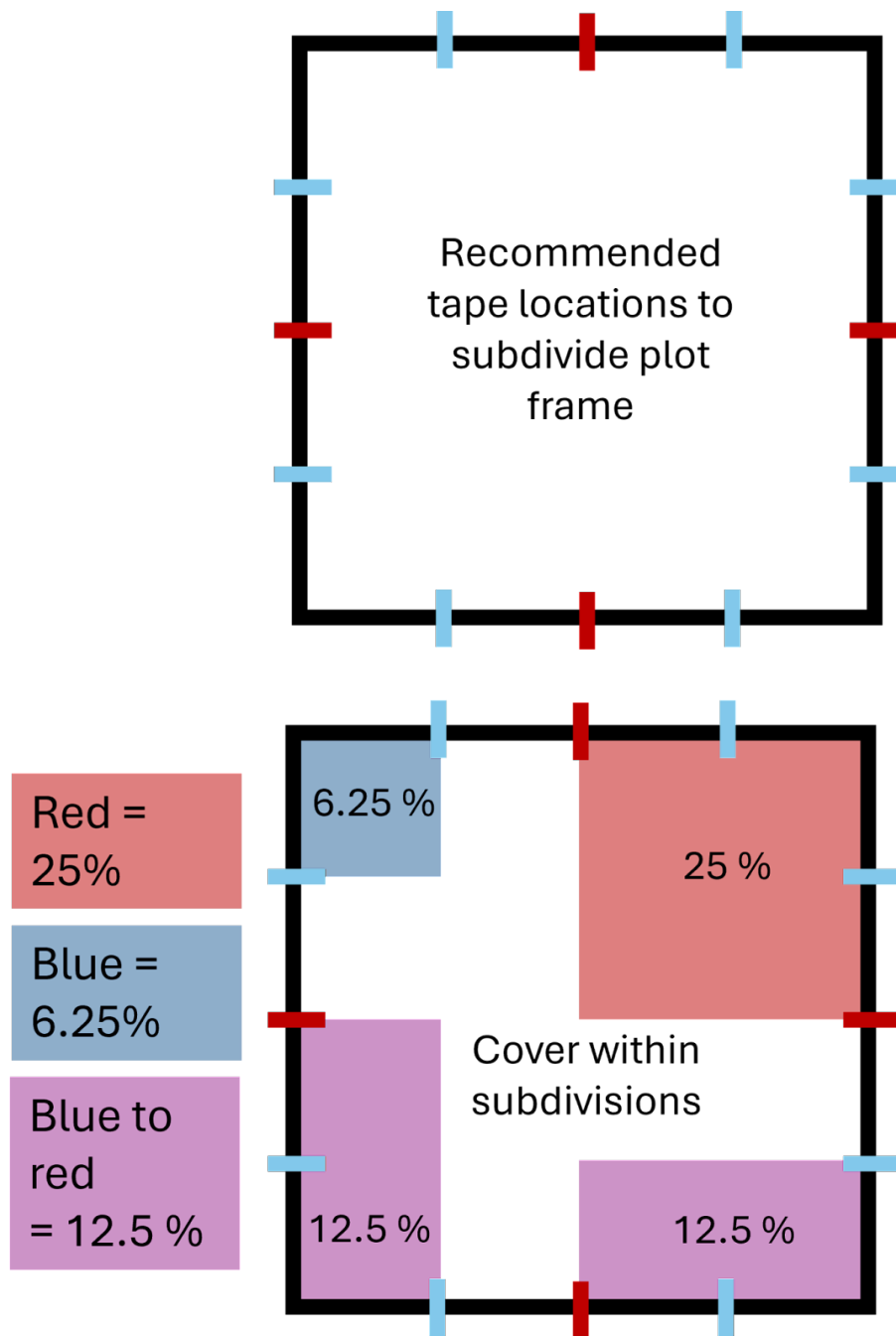


Figure 6: Recommendations for plot subdivisions to assess cover using colored guides (tape). Figure from Georgia Harrison & Laura Boggess

6.2 Geological substrates

We will follow the classification system of thecrag.com, which can be downloaded [here](#). For more information, you can visit thecrag.com

6.3 Surface heterogeneity classification (Protocol from Georgia Harrison & Laura Boggess)

Surface heterogeneity describes the abundance and size of surface features on cliff faces such as ledges, pockets, and cracks. These features can capture soil, water, and propagules so quantifying their abundance is key to understanding cliff-face vegetation. In addition, overhanging features can impact the vegetative community below, and their presence should be considered.

Assign a surface heterogeneity value between 0-10 for each plot. 0 is smooth rock, 10 is highly fissured. Score only the rock, so if vegetation is present, try to picture the plot without any vegetation or soil, and score only the rock. See photos (Figure 7) below for proposed examples.

Only quantify features **within the plot**. Exclude features that are not inside the plot boundary. Note if a plot is below an overhang. Overhangs should be at least 0.5 m deep.

Table 1. Example Table of plot-level abiotic information to be collected:

Subplot ID	Surface heterogeneity (0-10)
BE.FRE.C6.2a	2
BE.FRE.C6.2b	4

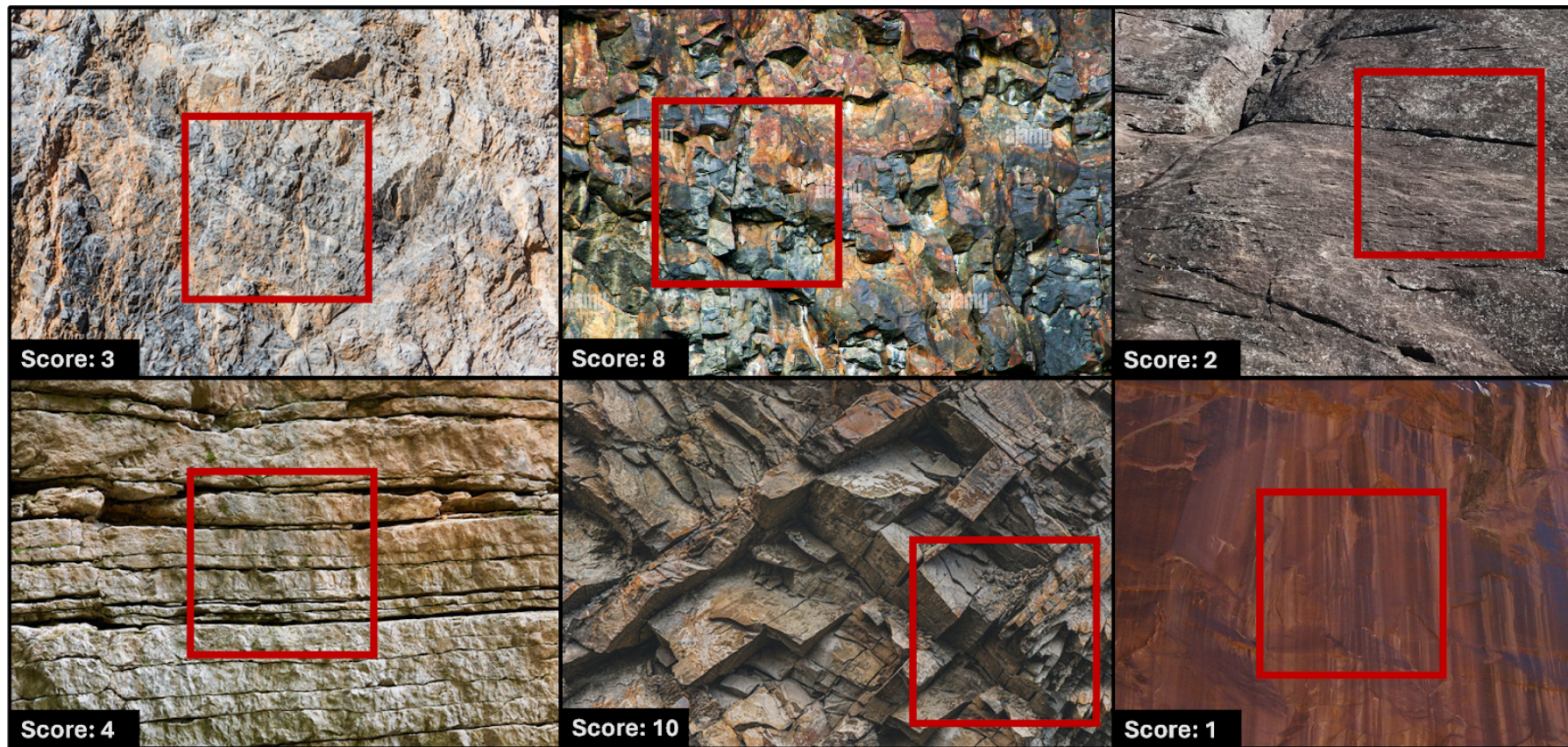


Figure 7: Example cliff face photos to score surface heterogeneity. Red box is plot frame, only score surface heterogeneity within plot frames. Not included in photos is the distinction between overhanging or non-overhanging features.

**Note: these photos are just found from the internet, but it may be useful to create a guide with example photos and their scores with photos from a specific site.*

6.4 Bryophyte and lichens classification (Protocol from Georgia Harrison & Laura Boggess)

Lichens and bryophytes (mosses, liverworts, and hornworts) are the most abundant and diverse taxa on cliffs. While identification can be challenging, collecting at least some data for these groups is essential to understanding ecological processes on cliffs. When species identification is not possible, recording cover for lichen and bryophyte morphotypes can still provide valuable information. Here, we use this morphotype identification in addition to species-level identification.

6.4.1 Lichens

Lichens are symbiotic organisms composed of fungi and algae or cyanobacteria. They are phenotypically plastic and the same species can look different under different environmental conditions, making them difficult to identify in the field. To meet this challenge, we recommend assigning a unique morphotype to each unidentified species of lichen.

Lichens are generally categorized into three main growth forms (Figure 8):

1. Crustose: These lichens form a crust adhering tightly to the substrate. They cannot be removed without damaging the substrate. Crusts are the most common morphotype in cliff plots.
 - a. *optional*: Powder lichens are a subtype of crusts whose bodies (thalli) are covered in powdery lichenized propagules and tend to occupy ecologically different niches from non-powder crustose lichens. To distinguish between powder or non-powder lichens, rub a finger on top of the thallus and if dust or powder comes off, this organism can be classified as a powder lichen.
2. Foliose: These are leaf-like lichens that are attached at some points, allowing some parts to lift away from the substrate. They generally have a flat, leafy appearance and a distinct upper and lower surface.
3. Fruticose: These lichens are bushy or hair-like and grow away from the substrate in all directions. They are often cylindrical or branched and do not have a distinct upper and lower surface.

When collecting lichen data, describe the morphotype by determining growth form, then noting the color and texture (Table 2). Overall, classifying into lichen morphotypes is still likely underestimating overall diversity. As a result, if you're not sure if two lichens are the same or different species, split the species and give it a different descriptor for morphotype so that you could recognize it in future plots. It is better to have more, distinct groups which are recognizable in future plots than fewer, coarse groups.

Table 2. Example Cover table for functional groups. For Taxon Group, L = Lichen, B = Bryophyte

Subplot ID	Taxon Group	Growth form	Color	Texture/additional notes (optional)	Cover (%)
BE.FRE.C6.2a	L	Crustose	White	bubbles	10
BE.FRE.C6.2b	B	Acrocarp moss	Light green	feathery	15



Figure 8: Three main lichen morphotypes. Powder lichens (not pictured) are a sub-type of the crustose group.

6.4.2 Bryophytes

Bryophytes are non-vascular plants, including mosses, liverworts, and hornworts. They are typically found in moist, shaded environments. First, determine the major group (Figures 9 and 10).

1. Mosses: usually have clearly differentiated stems and leaves. They grow in dense green clumps or mats.
2. Liverworts: can be leafy like mosses, but often have a flatter, more ribbon-like appearance with less obvious differentiation between stems and leaves. They can also be thalloid, which are flat and spread out like a thin crust.
3. Hornworts: These have a thalloid body similar to some liverworts but differ mainly in their reproductive structures which are elongated and horn-like.

Mosses can be further delineated into two main groups: "acrocarp" and "pleurocarp" based on growth patterns and reproductive structures (Figure 9). Acrocarp vs Pleurocarp:

1. Growth Pattern: Acrocarpous mosses grow upright and tend to form dense clumps, while pleurocarpous mosses spread out, forming mats.
2. Reproductive Placement: Acrocarpous mosses have reproductive structures at the top of vertical stems; pleurocarpous mosses bear theirs along the sides of branches.
3. Environmental Preference: Acrocarpous mosses are more adaptive to varying moisture conditions and can survive drying, whereas pleurocarpous mosses thrive in consistently wet habitats.

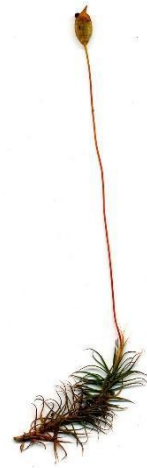


Figure 9: Major groups of mosses: Top row: acrocarpous moss with reproductive structures on the tip of the stalk. Bottom row: pleurocarpous moss with the reproductive structure emerging from a side branch



Figure 10: Left: Hornwort with typical horn-like reproductive structures. Right: Liverwort, here with umbrella shaped reproductive structures

6.5 Physical representations of 1, 2 and 4% cover as a reference (print on A4 format!)

1%

This square should be

10 cm x 10 cm

2%

This square should be

14.14 cm x 14.14 cm

4%

This square should be 25 cm x 16 cm

6.6 Setting accuracy standards (Protocol from Georgia Harrison & Laura Boggess)

To ensure data collection with high accuracy, conduct a calibration test and accuracy assessment for surface heterogeneity and cover (either virtually or in-person) at each site. The team leader should explain the protocol and provide a few examples (i.e. show a picture of a plot with a surface heterogeneity score of 0, 5, and 10) and justification for the score. Then, to ensure that the sampling group will be consistent, each member of the group should conduct their own assessment for standard plots. Repeat until the group is consistently scoring within accuracy standard.

We recommend using a 10% accuracy standard, and aiming for at least three plots in a row that meet the accuracy standard. Virtually, this accuracy assessment could also be conducted with a form or survey, but it is best if surveyors receive instant feedback (i.e. I scored this plot a 5, but the team agrees it is a 3).

Table 3. Example accuracy training table for surface heterogeneity. Set a standard for accuracy (i.e. within 1 surface heterogeneity unit, or within 10% cover).

Plot	Surface heterogeneity (personal)				
	Team member 1	Team member 2	Team member 3	Team member 4	Meeting accuracy standards?
A	8	2	5	6	No
B	6	4	7	5	No
C	9	8	8	9	Yes

6.7 Estimating climbing intensity with a survey

To estimate climbing intensity, prepare an Excel file (or similar spreadsheet format) and send it to around 10 local climbers who are very familiar with the site and its routes.

List all climbing routes where you conducted vegetation inventories. Ask the participants to rank the routes according to climbing intensity, from least frequently climbed to most frequently climbed, based on their own experience, observations, and perception. They do not need to have personally climbed all routes to provide a ranking.

Each respondent should provide their ranking in a separate column next to the column listing the routes.

Please submit the completed spreadsheet together with your data submission.

Below, you will find a screenshot of a similar survey used in a previous case study.

L19		fx													
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	Route_name	Order (1 Lowest, 18 Highest)	<div>Rank these routes from least climbed (1) to most climbed (18) according to your own perception of current climbing intensity. Write the numbers 1 to 18 to the corresponding routes in column Order.</div>												
2	Armba Bolivia														
3	Super Vol-au-vent L1														
4	La Cerise Depart Propaganda														
5	La Cerise L3														
6	La Gamma														
7	La Grune														
8	La Lili														
9	La Tjetten														
10	L' Ascendente														
11	L'Avenue Chlorophyl														
12	Le Dernier Combat														
13	Le Rab Directe														
14	Les Anciens Belges														
15	Mongolito														
16	Negresses Vertes														
17	The Wall														
18	Troucage														
19	Cool Cat														
20															



6.8 Example communication thermologgers

SENSOR ON THE WALL



Chers grimpeurs,
Des capteurs ont été placés sur ce rocher à des fins de recherche scientifique sur la végétation rocheuse. Ils sont placés de manière à ne pas gêner l'escalade. Ne les touchez pas et laissez les capteurs sur place. Nous vous remercions de votre coopération.

Beste klimmers,
Op deze rots zijn sensoren geplaatst voor wetenschappelijk onderzoek over rotsvegetatie. Ze zijn zo gepositioneerd dat ze het klimmen niet verstoren. Gelieve de sensoren niet aan te raken en te laten hangen. Dank voor jullie medewerking.

Dear climbers,
Sensors have been placed on this rock for scientific research on rock vegetation. They are positioned so as not to disturb climbing. Please do not touch the sensors and leave them in place. Thank you for your cooperation.

Contact: miren.rocks@gmail.com



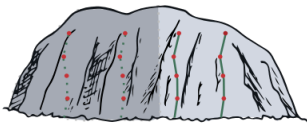
6.9 Summary sheet field data collection



Date of the survey

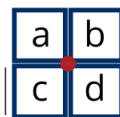
MIREN Rocks survey summary

Transect



- Length
- Coordinates
- Elevation
- Overall slope and aspect
- Climbed?
 - Y – Route (+ info)
 - N – Position & distance to route

Plot



- Anchor number
- Height
- Aspect
- Slope

Subplot



- Microtopography



Vegetation:

Vascular plants	Mosses	Lichens
% total cover	% total cover	% total cover
Species <ul style="list-style-type: none"> • identification • % cover 	Morphotype Harvest fragment from each cushion + %cover	Morphotype <ul style="list-style-type: none"> • Crustose • Foliose • Fruticose + %cover