Abiotic constraints and recreational rock climbing shape cliff vegetation in Freyr, Belgium

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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

Aim: 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 climbing intensity and abiotic characteristics jointly influence plant diversity, community composition, and community-level functional tendencies in a local case study on limestone cliff faces.

Location: Freyr limestone cliffs, Belgium

Methods: Vegetation was surveyed in the Freyr climbing site in Belgium using a standardised protocol across 248 1-m² subplots distributed 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 (CWMs) of Grime's CSR strategies (competitive, stress-tolerant, and ruderal) to characterise community-level functional tendencies. We examined the effects of climbing intensity, and of abiotic factors such as slope, aspect, and microtopography using generalised linear mixed models, multivariate ordination and an indicator species analysis.

Results: A total of 103 vascular plant species were recorded. Abiotic factors influenced vegetation patterns more than climbing intensity. Species richness and vegetation cover were highest at moderate levels of microtopography, lower at steep slopes, and cover was reduced on south-facing cliffs. The effect of climbing intensity depended on microtopography: species richness peaked at low climbing intensity on cliffs with pronounced microtopography, consistent with the intermediate disturbance hypothesis. Functional and species composition shifted with climbing: competitive and stress-tolerant 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.

Conclusions: At Freyr, cliff vegetation was mainly structured by abiotic conditions, with climbing acting as a context-dependent disturbance that influenced community composition and functional tendencies rather than overall cover or richness. Cliffs with high microtopography under moderate climbing disturbance supported the highest diversity, while unclimbed cliffs harboured more stress-tolerant and red-listed species, indicating a potential loss of vulnerable vegetation under increasing climbing pressure. These site-specific findings underscore the need for multi-site studies and detailed

analyses of abiotic factors to better understand and manage the ecological impacts of recreational climbing.

KEYWORDS

Cliff ecology, rock climbing, disturbance, 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 Hessl 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) ; Léduc, 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 Hessl 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 clarify how disturbance interacts with abiotic filtering to shape cliff-face vegetation.

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 eight 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.

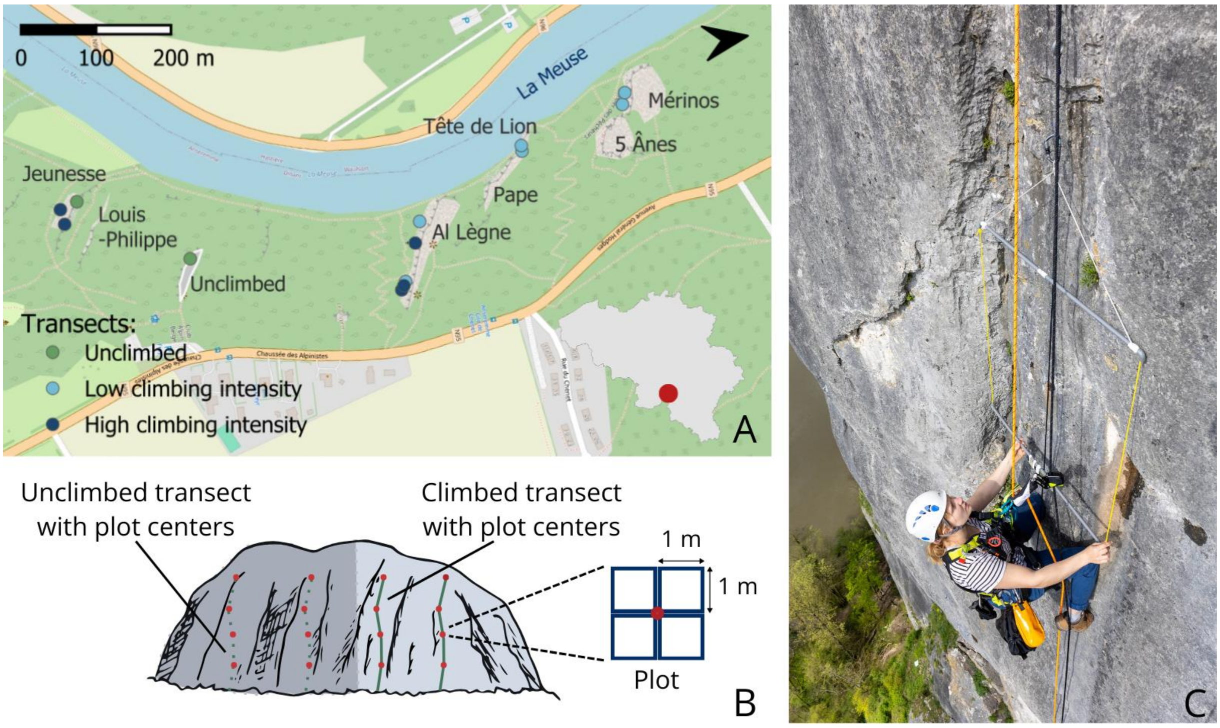

Figure 1: A) Map (OpenStreetMap) of the Freyr study area, showing the different cliff zones (grey). Each dot represents a transect; colours indicate the dominant climbing intensity level of the transect. Inset: location of Freyr in Belgium B) Sampling ***design for cliff faces with climbed and unclimbed 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 Hessl 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 included a hierarchical random-effects structure. If convergence or singularity issues arose, the random-effects structure was simplified. Specifically, species richness models included plots nested in transects nested within zones; total vegetation cover models included plots nested within transects; and Shannon diversity included plots only.

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 136 subplots, nested within 51 plots, 13 transects, and 8 zones.

Separate Tweedie GLMMs were fitted for each strategy (C, S, R) to test for effects of climbing intensity, slope, aspect, and microtopography. Quadratic terms were excluded as they were not expected, and interaction terms were not included to avoid overfitting. Random-effects structures were adapted to each strategy to ensure model convergence: stress-tolerant CWMs included plots nested in transects and zones, competitive CWMs excluded zones, and ruderal CWMs included plots only.

Differences in occurrence between strategies were evaluated using a linear model with CWM as the response variable and strategy (C, S, R) as a fixed effect, and (subplot < plot < transect < zone) as random effects 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) and ggeffects (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. 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) implemented with function 'adonis2' (999 permutations, marginal tests). This approach evaluates whether multivariate community centroids differ among factor levels or along environmental gradients while accounting for other predictors. Homogeneity of multivariate dispersion was assessed for categorical predictors (climbing intensity and aspect) using 'betadisper' function followed by permutation-based ANOVA to test for differences in within-group dispersion. NMDS ordinations were visualised using ggplot2.

Indicator species were identified using multilevel pattern analysis (function 'multipat', 999 permutations) from the indicspecies 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, total vegetation cover, and Shannon diversity showed significant interactions between microtopography and climbing intensity (tab. 1). Species richness had a negative quadratic relationship with microtopography, and response varied by climbing intensity. Species richness was higher under low than under high climbing intensity across the microtopographic gradient, whereas unclimbed plots supported lower richness than highly climbed plots (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 was higher only under low climbing intensity compared to high climbing intensity (fig. 2G).

Besides microtopography, there were differences in vegetation across other abiotic variables regardless of climbing intensity. Slope had a negative effect on all vegetation metrics: steeper cliffs consistently supported lower species richness, reduced vegetation cover, and lower Shannon diversity (fig 2B,E,H). Aspect influenced vegetation cover (fig 2F) and diversity (fig. 2G) but not species richness (fig. 2C), with south-facing cliffs exhibiting 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.).

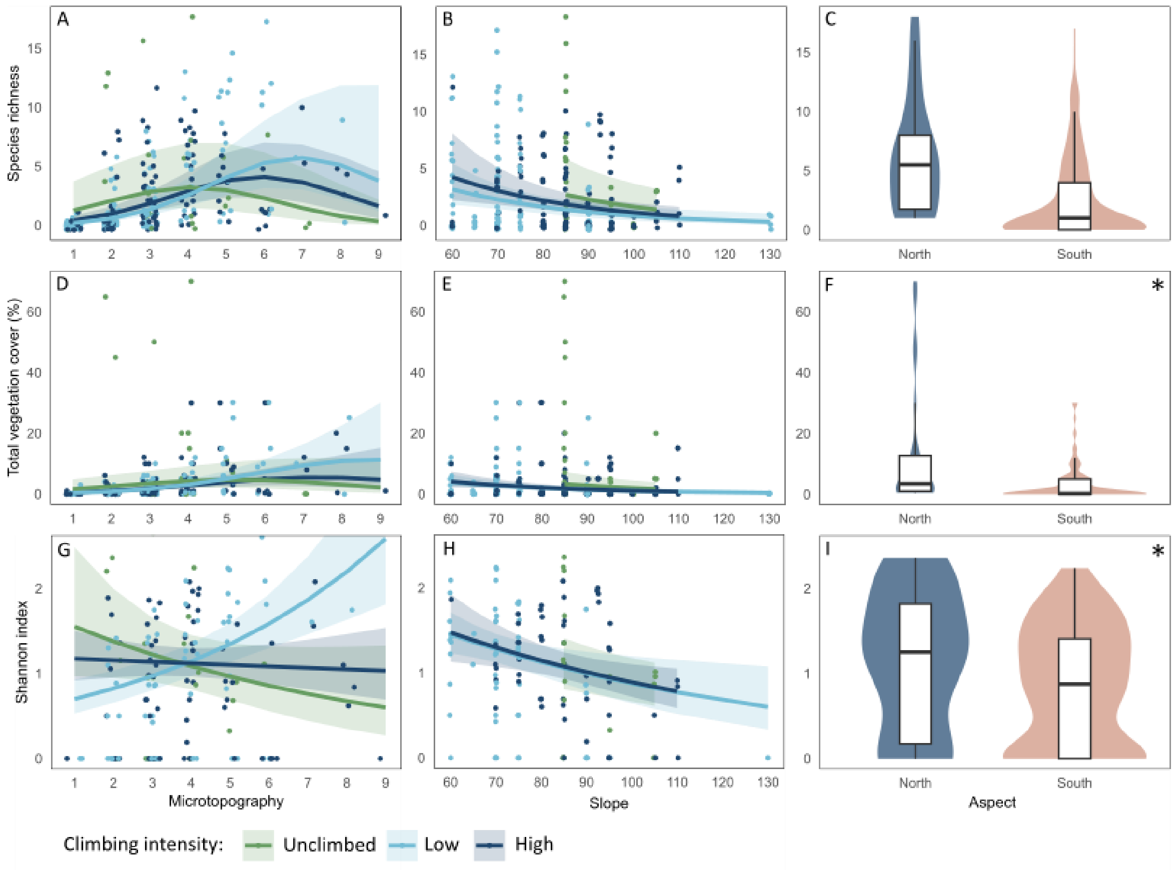

Figure 2: : Effects of climbing intensity and abiotic cliff characteristics on alpha diversity metrics. Species richness (A–C), total vegetation cover (D–F), and Shannon diversity index (G–I) are shown in relation to microtopography (A, D, G) and

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 R² values from the GLMMs indicate the proportion of variance explained by fixed effects and by both fixed and random effects, respectively. Continuous predictors were not standardised prior to analysis; estimates are presented on the original measurement scale.

Predictor	Species richness	Total vegetation cover	Shannon index
Intercept	**1.440 (p=0.007)**	**-2.718 (p<0.001)**	**0.439 (p=0.002)**
Microtopography (linear)	**0.880 (p<0.001)**	**0.853 (p<0.001)**	-0.027 (p=0.66)
Microtopography (quadratic)	**-0.276 (p<0.001)**	**-0.172 (p=0.003)**	-
Slope	**-0.458 (p=0.002)**	**-0.478 (p<0.001)**	**-0.175 (p=0.01)**
Aspect (North/South)	-0.730 (p=0.18)	**-1.196 (p=0.01)**	**-0.321 (p=0.02)**
Low climbing intensity	-0.290 (p=0.30)	-0.050 (p=0.86)	-0.126 (p=0.30)
Unclimbed intensity	0.372 (p=0.34)	0.640 (p=0.13)	0.054 (p=0.73)
Microtopography : low climbing	**0.331 (p=0.04)**	0.291 (p=0.10)	**0.305 (p<0.001)**
Microtopography : unclimbed	**-0.573 (p=0.03)**	**-0.428 (p=0.010)**	-0.175 (p=0.20)
R^2_{Marginal}	0.542	0.369	0.337
$R^2_{\text{Conditional}}$	0.797	0.579	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 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 the explanatory power of this was low ($R^2 = 0.13$).

Responses of community-weighted means to climbing intensity and abiotic conditions differed among strategies (tab. 2, fig. 3). Competitive plants were more abundant on unclimbed subplots than in highly intensity climbed plots and were more present on south-facing than on north-facing cliffs. Their relative abundance was higher with increasing microtopographic heterogeneity and lower with steeper slope (fig 3A-C). Stress-tolerant plants showed a similar but weaker response to climbing intensity. Their relative abundance was higher in unclimbed than in highly climbed plots, with only a marginal, non-significant positive effect under low climbing intensity. In contrast to competitive species, stress-tolerant plants increased with slope, while microtopography and aspect had no detectable effects (fig. 3D-F). Ruderals showed the opposite pattern with climbing. Their relative abundance was lower in unclimbed than in highly climbed plots. Ruderal plants were more abundant on steeper cliffs, declined with increasing microtopographic heterogeneity, and were less common on south-facing cliffs (fig.G-I).

Table 2: Drivers of Community-weighted means (CWM) of CSR plant strategies. Fixed-effect estimates from separate generalised linear mixed models (GLMMs) with zero-inflated Tweedie distribution for each strategy-specific CWM. Cells show the estimate, its p-value (in parentheses). Significant values are bolted. Marginal and conditional R² 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	**2.578 (p < 0.001)**	**3.343 (p < 0.001)**	**3.731 (p < 0.001)**
Microtopography	**0.121 (p=0.05)**	0.023 (p = 0.55)	**-0.161 (p = 0.01)**
Slope	**-0.225 (<0.001)**	**0.105 (p = 0.008)**	**0.161 (p = 0.02)**
Aspect (north/south)	**0.850 (p <0.001)**	0.219 (p = 0.11)	**-0.681 (p=0.002)**
Low climbing intensity	-0.180 (p=0.16)	**0.177 (p = 0.07)**	0.255 (p = 0.12)
Unclimbed intensity	**0.707 (p <0.001)**	**0.273 (p = 0.04)**	**-0.894 (p=0.002)**
$\mathbf{R^2}_{\textbf{Marginal}}$	0.226	0.129	0.208
$\mathbf{R^2}_{\textbf{Conditional}}$	0.226	0.189	0.245

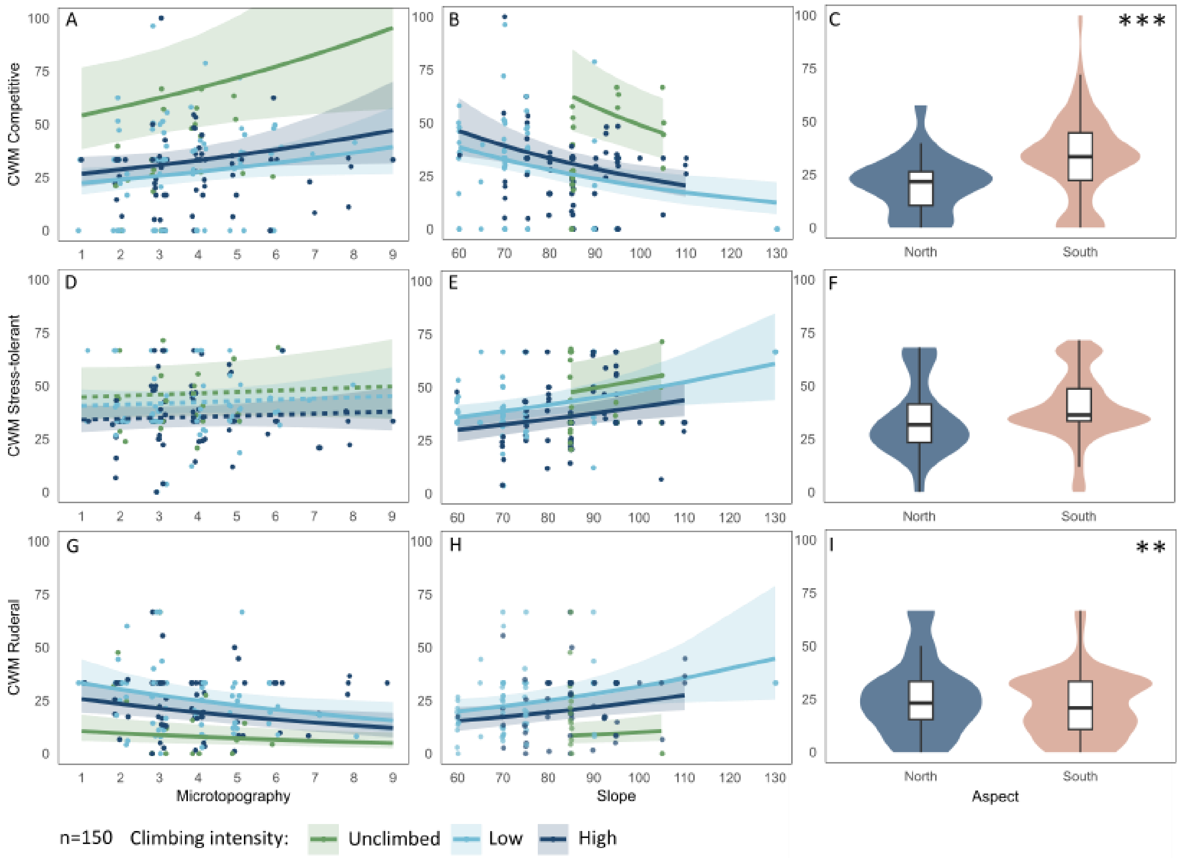

Figure 3: Effects of climbing intensity and abiotic cliff characteristics on the community-weighted mean (CWM) of Grime plant strategies. Competitive (A–C), Stress-tolerant (D–F), and ruderal (G–I) strategies are shown in relation to microtopography (A, D, G) and slope (B, E, H). Points represent observed 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

Community composition differed among climbing intensities and abiotic cliff characteristics. Climbing intensity ($R^2 = 0.06$, $p = 0.001$), North–South aspect ($R^2 = 0.05$, $p = 0.001$), slope ($R^2 = 0.03$, $p = 0.001$), and microtopography ($R^2 = 0.02$, $p = 0.001$) each explained a significant portion of variation in community composition (PERMANOVA tests, fig 4). Together, these attributes explained 15.5% of the total variation. Multivariate dispersion differed between North- and South-facing aspects ($p < 0.001$) but not among climbing categories ($p = 0.15$). This means that aspect effects reflect both shifts in centroid and variability, whereas climbing intensity effects are limited to centroid shifts (Beta dispersion analysis, Figure 4).

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.

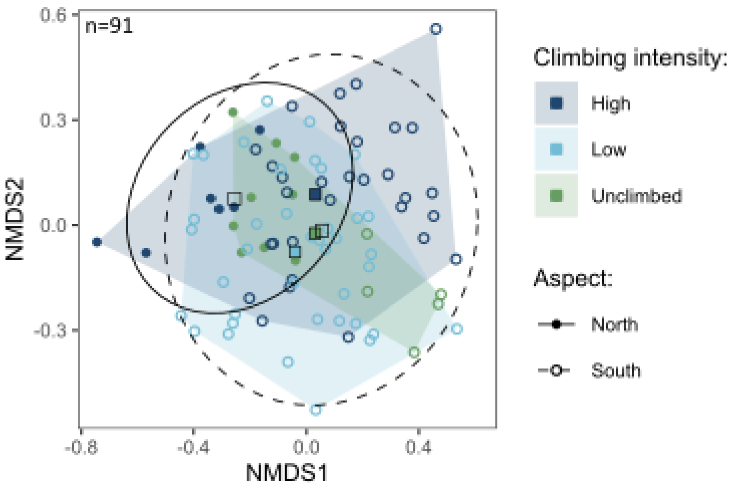

Figure 4: NMDS ordination (3D, stress = 0.18) of species composition across subplots with different climbing intensities and cliff aspects. Points represent subplots with at least three species, colored by climbing intensity and filled by aspect. Colored convex hulls illustrate the range of sites for each climbing category, while ellipses show 95% confidence intervals for North- and South-facing aspects. Squares indicate group centroids; coloured for climbing intensity, empty for aspect.

Microclimate

The cliff aspect strongly influenced microclimatic temperatures. 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.2).

DISCUSSION

We surveyed vascular plant communities on Freyr's limestone cliffs in Belgium to examine how recreational rock climbing influences cliff vegetation 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 ecological effects of rock climbing can be subtle, expressed primarily through species turnover rather than reductions in vegetation cover, and strongly shaped by abiotic constraints.

Effects of rock climbing on vegetation diversity, functional structure, and species composition

Rock climbing did not lead to uniform reductions in richness, cover, or diversity; instead, it primarily altered community composition and functional structure. The observed changes in diversity patterns due to climbing intensity were underpinned by shifts 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 both a higher relative abundance of competitors (C-strategy) and stress-tolerant (S-strategy) species in comparison with low and high level intensity climbed cliffs. Within this low-disturbance context, competitive species may dominate locally, leading to reduced diversity through competitive exclusion, while stress-tolerant species persist in harsher micro-sites (e.g., steeper slope, less microtopography). Competitive 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., which were not significantly associated as indicator species with 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. Moderate disturbance reduced local competitive dominance and resulted in a peak in species richness, while 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 climbing can potentially reduce community uniqueness.

Highly climbed cliffs supported disturbance-driven communities, where frequent biomass removal created open space for ruderal and opportunistic species. Indicator species associated with high climbing intensity, such as *Taraxacum sp*., demonstrated that these communities favor disturbance-adapted taxa. This is similar to literature, potentially at the expense of more specialised taxa, which are replaced (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. (Radujković et al. 2025). However, the three climbing intensity levels were unevenly represented (unclimbed = 28; low = 116; high = 104). The lower number of unclimbed plots may have reduced within-group variation, increasing the likelihood of detecting significant indicator species. However, overall species richness did not differ among climbing levels. Overall, stress-tolerant species dominated in cliff ecosystems due to harsh conditions (Larson et al. 2005). These shifts in functional strategies explained the observed patterns in alpha-diversity, showing that climbing primarily affects species composition rather than vegetation cover.

Abiotic constraints

Abiotic factors remained the dominant constraint on cliff vegetation, shaping patterns of richness, cover, diversity, and functional composition.

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. These effects were consistent across climbing intensities, suggesting that slope constraints vegetation more strongly than climbing disturbance. This finding is similar to existing studies (Bartlett et al. 1990; Clark and Hessl 2015; Larson et al. 2005). Ruderal and stress-tolerant plants were more abundant on steeper slopes, while competitive plants declined, consistent with the expectation that steep, harsh environments favour disturbance- and stress-adapted species (Kraft et al. 2015), and competitive plants are disadvantaged in resource-poor, stressful environments (Grime 1977).

Aspect did not affect species richness, 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 and more humid microclimatic conditions that promote greater plant growth and biomass accumulation. NMDS results further indicated that north-facing communities were compositionally less variable, suggesting stronger environmental filtering under cooler, moister conditions. These findings align with Müller et al. (2004), who reported higher plant cover on shaded cliffs. South-facing cliffs, by contrast, are warmer and drier, which constrains plant growth and likely results in lower overall cover and more patchy vegetation, thereby reducing evenness 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. 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. 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 Hessl 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, as indicated by the positive relationship between microtopography and the community-weighted mean of competitive plant strategies. 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 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.

Shannon diversity did not vary with microtopography, 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

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 indicates that the ecological effects of climbing depend strongly on underlying habitat heterogeneity. These patterns are consistent with the Intermediate Disturbance Hypothesis (Connell 1978; Fox 1981), but only under structurally heterogeneous conditions, suggesting that habitat complexity mediates whether disturbance promotes coexistence. Together, our results indicate that climbing does not impose a uniform pressure across cliffs, but instead interacts with abiotic constraints that already structure these ecosystems.

Future directions

Although climbing and abiotic variables significantly influenced diversity and species composition, most variation in community composition remained unexplained. Climbing disturbance and abiotic cliff characteristics explained only ~15.5% of variation in community composition, with climbing intensity explaining 6% specifically. This low explanatory power suggests that cliff plant communities may additionally be shaped by factors not captured in this study, potentially finer-scale spatial processes than we assessed.

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 ecological impacts of climbing in Freyr were complex and context-dependent. Climbing influenced species and community composition under certain habitat conditions rather than causing an overall loss of vegetation cover or decline in species richness. Low-intensity climbing was associated with higher biodiversity under highly heterogeneous microtopography, potentially through reduced competitive dominance and increased representation of ruderal strategies. However, we also observed a lower abundance of stress-tolerant and vulnerable plant species in climbed areas.

Vegetation was further shaped by microhabitat availability determined by abiotic cliff characteristics. 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 can 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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Supplementary materials

A.1. MIREN Rocks Survey protocol

A.2. Climbing intensity

A central challenge of this study was to quantify climbing intensity in a way that allows an accurate assessment of its ecological impacts. In previous studies, climbing impacts were often evaluated by comparing climbed and unclimbed areas using paired or unpaired transects (Boggess et al. 2021). At Freyr, however, identifying a sufficient number of comparable unclimbed control zones was either impractical or unsafe. Consequently, a gradient-based measure of climbing intensity was considered more appropriate than a binary climbed/unclimbed classification.

Exact empirical data on how much each route is climbed were not available and are difficult to collect. Therefore, climbing intensity had to be estimated using indirect indicators (proxies). Several such proxies have been proposed in previous research, including the Climbing Use Index (CUI) (Clark and Hessl 2015), guidebook information, online ascent logs, and expert judgement. Each of these approaches has inherent limitations. To address this, a multifaceted approach was adopted to evaluate and compare different indicators and to identify the most suitable method for estimating climbing intensity at the study site.

Climbing use index (CUI)

As a first step, the Climbing Use Index (Clark and Hessl 2015) was calculated for the routes in Freyr. The CUI combines route popularity, expressed as guidebook star ratings, with walking approach time (Formula X). Because the Freyr guidebook does not provide star ratings, ratings were obtained from the online platform 8a.nu (Freyr • Belgium - Sportclimbing - Ver...). Approach times were taken from the most recent Freyr guidebook (Bott & Deneyer, 2022).

This index was developed in a large area (New River Gorge, USA) with substantial variation in approaches (2-50 min on foot). In such settings, longer approach times are expected to generally correspond to lower visitation. However, in Freyr, a compact site with more uniform approach times (8–18 min), CUI ranged from 1.02 to 1.78 (range = 0.76) only, a substantially more narrow range than in New River Gorge (0.31-2.22; range = 1.91) (fig. 3). Unlike New River Gorge, the distribution of CUI values in Freyr was also not normal, as indicated by the Shapiro-Wilk test (W=0.840, p < 0.001). This narrower range and non-normal distribution limited its effectiveness as a climbing intensity proxy. Furthermore, the star ratings, either from guidebooks or 8a.nu, are a rather arbitrary estimate because they reflect climber's appreciation of a route rather than usage intensity. The correlation between appreciation and intensity is uncertain, and these ratings lack clear, objective criteria as well as transparency regarding who assigned them. Both components of the CUI—approach time and star ratings—are thus either questionable or unsuitable for Freyr, necessitating alternative measures of climbing intensity.

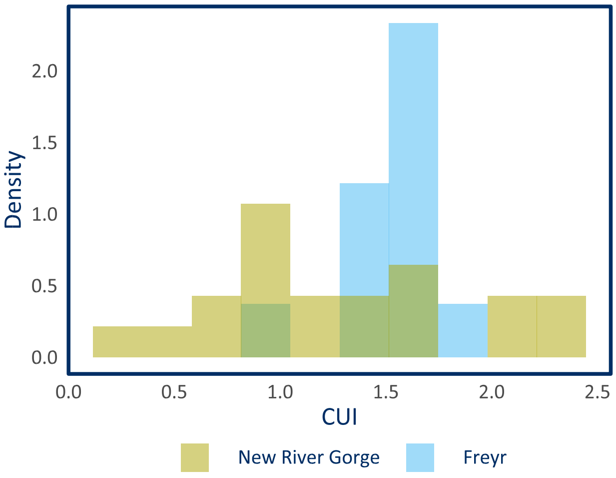


Figure A.2.1: *Histogram of Climbing Use Index (CUI) distributions for New River Gorge (n = 20) and Freyr (n = 14). The data are grouped into 10 bins with a bin width of 0.2.*

$$CUI = LOG10\left([S+1] * \left(\left[\frac{1}{T}\right] * 100\right)\right)$$

Indicators for climbing intensity

Given the limitations of the CUI, additional indicators of climbing intensity were compiled. These included guidebook information (year of route opening; classification as *classique* (indication as "must climb" popular route) or *patiné* (indicating surface polishing due to frequent climbing)), ascent logs from 8a.nu (number of ascents, recommendation percentage, and star ratings), and climbing intensity estimates provided by the site guardian.

To combine these indicators, a Principal Component Analysis (PCA) was conducted to derive composite measures of climbing intensity. Two main components explaining variation in climbing intensity were identified (Fig. 4). The first component, interpreted as historical popularity, explained 30.8% of the variance and was primarily associated with years in use and classification as *classique* or *patiné*. The second component, interpreted as current popularity, explained 29.6% of the variance and was characterised by ascent numbers, recommendation percentages, star ratings from 8a.nu, and guardian estimates. Together, these components explained 60.4% of the total variance. Variable loadings are provided in Table A2.

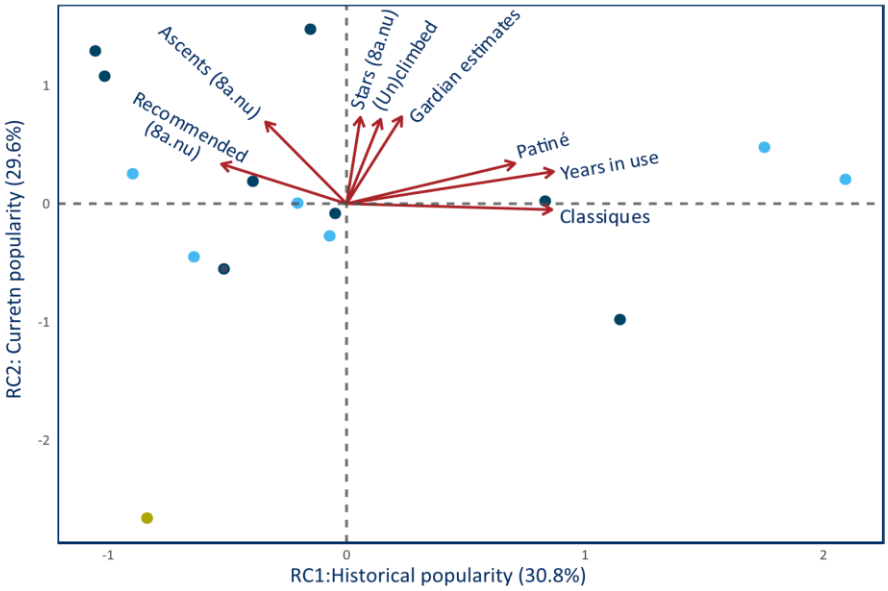


Figure A2.2: Biplot from Principal Component Analysis (PCA) showing two primary components explaining variation in climbing intensity. The x-axis represents RC1 (historical popularity), while the y-axis represents RC2 (current popularity). Arrows indicate the contribution of different variables to each principal component, and dots represent the analysed climbing routes with colour depending on climbing intensity based on expert rank (green: unclimbed; light blue: low intensity; dark blue: high intensity).

Despite this explanatory power, the PCA approach appeared to underestimate the intensity of frequently climbed low-grade routes and overestimate the intensity of higher-grade routes. For example, some low-graded routes (e.g. 4c, 5c) that were ranked by experts as frequently climbed, had a low PCA scores because they were not marked as *classiques* or *patiné* in the guidebook and had relatively few ascent logs on 8a.nu. This could reflect a logging bias, as climbers may selectively log more prestigious ascents, thus introducing a bias towards higher-graded climbs. Other similar platforms to log ascents like 'the Crag' (www.thecrag.com) (Rochers de Freyr, Sport climbing) and 27crags (27crags.com) (Freyr) would suffer the same issue.

Table A2: Loadings of climbing intensity indicators on the first two rotated principal component axes (RC1 and RC2) from a Principal Component Analysis (PCA). Loadings indicate the contribution of each indicator to the rotated components, with higher absolute values representing stronger influence on the corresponding axis.

Variable	RC1: Historical Popularity	RC2: Current Popularity
Gardian estimates	0.347	0.347
Ascents (8a.nu)	0.119	0.517
Recommended (8a.nu)	-0.106	0.415
Stars (8a.nu)	0.315	0.356
Patiné	0.456	-0.143
Classiques	0.371	-0.419
(Un)climbed	0.396	0.280
Years in use	0.502	-0.253

Expert-based approach

To validate these approaches, an expert-based ranking was obtained from eight experienced local climbers familiar with the routes in Freyr. Agreement among experts was assessed using Kendall's coefficient of concordance (W), a non-parametric statistic suitable for ordinal data. Values of W close to one indicate strong agreement, whereas values close to zero indicate weak agreement. An average rank was calculated across all expert rankings for each route.

To examine the relationship between expert rankings and both CUI values and PCA-derived scores, Kendall's rank correlation (τ) was used. This test is appropriate for comparing ordinal and continuous variables, particularly with small sample sizes (n = 18 for CUI; n = 14 for PCA).

Agreement among experts was moderate but statistically significant (W = 0.510, p = 0.001). However, correlations between expert rankings and proxy-based metrics were weak and non-significant. The correlation between expert rankings and PCA-derived current popularity scores was τ = 0.221 (p = 0.273; Fig. 5B), while the correlation with the CUI was τ = 0.156 (p = 0.441; Fig. 5A). According to local experts, neither the CUI nor the PCA-based ranking accurately reflected actual climbing intensity at Freyr.

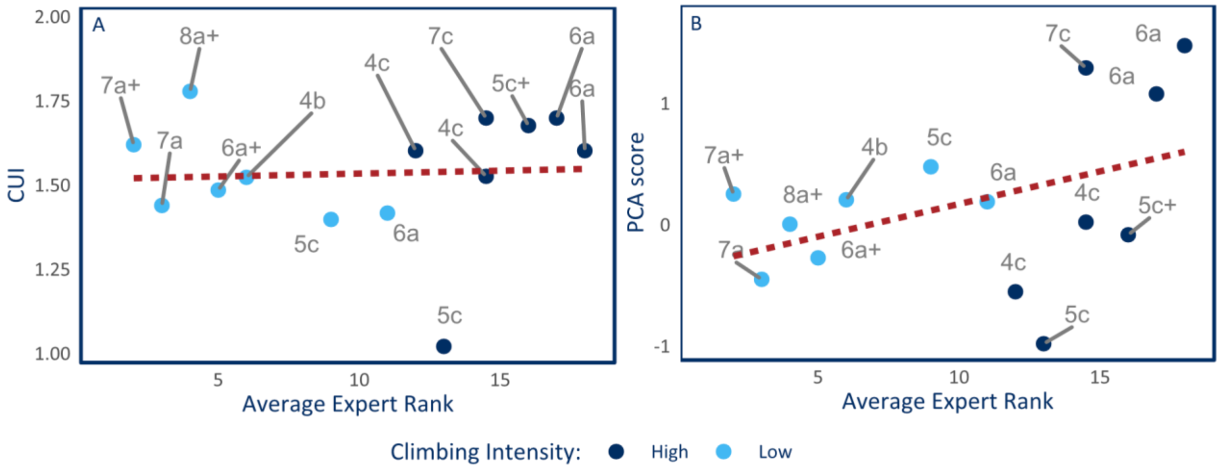


Figure A2.3: Scatterplots showing the relationship between (A) Climbing Use Index (CUI); (B) PCA score and expert rankings for climbing routes. Each point represent a route, labelled whit its grade and is coloured according to its final climbing intensity category. Dashed correlation lines indicate the absence of a significant association between the two ranking methods. (n = 14)

Final classification of climbing intensity

Given the weak correspondence between proxy-based metrics and expert judgement, climbing intensity was ultimately categorised into three classes based on the average expert rankings: unclimbed (n = 28), low climbing intensity (n = 116), and high climbing intensity (n = 104). This categorisation allowed the inclusion of four additional routes lacking 8a.nu data, increasing the total number of routes included in the analysis across the 36 subplots.

While a continuous measure of climbing intensity would retain more nuance, the categorical approach was considered more robust given the limitations of the available proxies. Expert-based classification also made it possible to incorporate local knowledge not captured by online platforms. Although expert rankings are inherently subjective and may reflect shared perceptions within the climbing community, the moderate level of agreement among experts and high agreement with the final classification suggests that this approach provides a reasonable representation of relative climbing intensity at Freyr. Categorisation into broader classes further helped to reduce the influence of inconsistencies among individual expert estimates.

However, such expert-based rankings are site-specific and not directly transferable across regions or climbing areas. For broader comparisons, indicators such as online ascent logs, guidebook sales, or surveys about perceived crowding can be used. Future research should also consider more precise monitoring, like targeted logbooks, observations or movement sensors, but these approaches have to be implemented carefully to ethically handle privacy concerns.

A.3. Microclimate

Introduction

Cliff ecosystems are characterised by a vertical structure that generates distinctive and highly heterogeneous microclimates. These fine-scale conditions can differ substantially from standardised weather station measurements and are influenced by the aspect, slope, and solar exposure (Bartlett et al. 1990; Bramer et al. 2018; Larson et al. 2005). Such fine-scale microclimatic variation will likely play a key role in shaping cliff vegetation by filtering species according to their thermal and moisture tolerances.

South-facing slopes in the Northern Hemisphere generally receive more solar radiation, making them warmer and drier, while north-facing slopes are cooler and more humid (Suggitt et al. 2011). However, cliff surfaces exhibit more complex radiation dynamics than horizontal or gently sloped surfaces. Because of their steep angles, south-facing cliffs may receive less direct solar radiation during summer in comparison to horizontal surfaces, when the sun is high in the sky, but more radiation during winter, when the sun's angle is lower. In contrast, north-facing cliffs consistently receive less solar radiation because they are oriented away from sun's path, resulting in persistently cooler microclimates throughout the year (Geiger et al. 2012; Larson et al. 2005). Radiation absorption and dissipation primarily drive the energy balance at the cliff surface. With limited vegetation, evapotranspiration often plays only a minor role, whereas albedo is a determining factor. Due to their low water content compared to soils, rocks require less energy for heating, making them more susceptible to rapid temperature fluctuations (Larson et al. 2005). The geomorphological heterogeneity of cliffs creates a variety of microclimates, some of which can buffer extreme climate conditions, while others amplify them. As a result, cliffs can serve as microrefugia for climate-sensitive species within a broader unfavourable climate, while also potentially acting as stepping stones for warm-adapted species, allowing them to extend their distribution (De Frenne et al. 2013; Dobrowski 2011; Kuntz and Larson 2006; Lembrechts and Nijs 2020; Speziale and Ezcurra 2015). Despite the ecological importance of cliff microclimates in-situ microclimatic temperature measurements are rare. This study contributes to this knowledge gap by comparing the temperature of north- and south-facing cliffs over the four seasons.

While the number of sensors was necessarily constrained by logistical and safety considerations, the resulting data represent some of the few in situ measurements of cliff-face microclimates and offer an important empirical baseline for future studies.

Methods

Microclimate data were collected by recording the temperature of air just in front of the rock (6 cm) with 15 TOMST thermologgers (Wild et al. 2019) placed on different cliffs with variations in height and aspect. Two sets of three sensors were placed at different heights on both a north-facing cliff (Jeunesse) and a south-facing cliff (Le Mérinos). Two sensors were placed on an unclimbed cliff, which was unmanaged and uncleaned, one on the north face and one on the south face. In total, six sensors were placed on north faces, nine on south faces. Sensors were installed in spring (10 April 2024-24 June 2024) and read out in winter 2025 (20 January 2025- 21 February 2025) using TOMST's Lolly software. Daily mean, minimum, and maximum temperatures were calculated for each thermologger and used as the response variables in three separate linear mixed-effects models to assess differences in temperature between north and south-facing cliffs across seasons. The model included season (spring, summer, fall, winter) and aspect as fixed effects, along with their interaction. Aspect was treated as a categorical fixed effect distinguishing between north- and south-facing cliffs, as the aspects were clustered into high and low values for northness (i.e., the cosine of aspect), and variation across the full compass circle was not available. Thermologger identity and date were included as random effects to account for spatial and temporal variations. Afterwards, post hoc pairwise comparisons were conducted using the emmeans package. Note that thermologgers are not well suited for measuring temperature under direct solar radiation, due to heating of the sensor itself. We thus recommend against interpreting the observed differences as absolute values (Maclean et al. 2021).

Results

Cliff aspect strongly influenced microclimatic temperatures, as expected. South-facing cliffs were generally warmer than north-facing cliffs, but the magnitude of the difference varied seasonally. For daily mean temperature, differences 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 across all seasons, and highly significant in all except winter. For daily minimum temperatures, south-facing cliffs were significantly warmer than north-facing cliffs in summer. See table A.3 for estimated marginal means, differences, p-values, and model R^2.

Table A3: Summary of linear mixed model (LMM) analysis of daily minimum, mean and maximum microclimate temperature. Estimated marginal means (emmeans) are shown for north- and south-facing plots across four seasons. The table includes the difference between aspects, corresponding p-values, and significance levels: < 0.1 (.), p < 0.05 (*), p < 0.01 (**), p < 0.001 (***).

Daily mean temperature:

Season	North (°C)	South (°C)	Difference (°C)	p-value	Significance
Spring	13.08	16.79	-0.710	0.007	**
Summer	18.26	19.46	-1.197	< 0.001	***
Fall	9.34	9.97	-0.626	0.018	*
Winter	3.20	3.60	-0.398	0.133	

$R^2_{marginal} = 0.718$, $R^2_{conditional} = 0.994$

Daily maximum temperature:

Season	North (°C)	South (°C)	Difference (°C)	p-value	Significance
Spring	16.91	19.13	-2.23	< 0.001	***
Summer	22.71	26.03	-3.32	< 0.001	***
Fall	11.88	13.94	-2.05	< 0.001	***
Winter	5.57	7.03	-1.46	0.016	*

$R^2_{marginal} = 0.673$, $R^2_{conditional} = 0.73$

Daily minimum temperature:

Season	North (°C)	South (°C)	Difference (°C)	p-value	Significance
Spring	9.52	9.80	-0.279	0.2145	
Summer	14.42	14.91	-0.495	0.0274	*
Fall	7.05	7.36	-0.315	0.1609	
Winter	1.11	1.27	-0.160	0.1609	

$R^2_{marginal} = 0.658$, $R^2_{conditional} = 0.997$

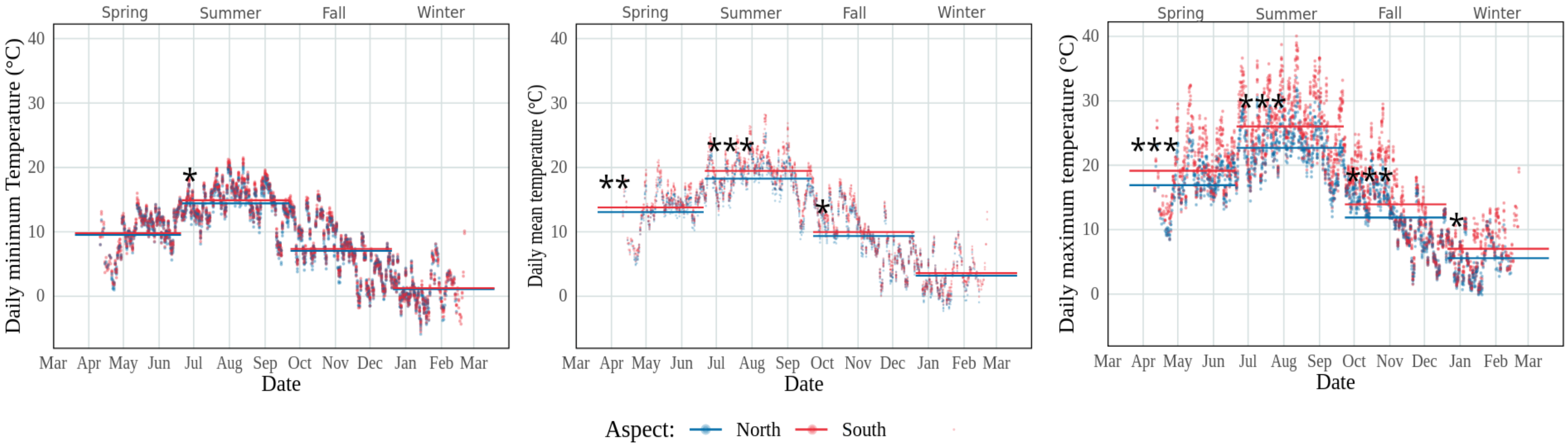


Figure A3: Daily minimum, mean, and max microclimate temperature over a time span of nearly one year (April 2024-February 2025) for north (blue) and south (red) faces. Dots represent raw daily mean temperature; solid lines show estimated marginal means based on the linear mixed interaction model between aspect and season.

Discussion

Microclimate measurements confirmed that south-facing cliffs are generally warmer than north-facing cliffs, reflecting their greater exposure to direct solar radiation throughout the day (Geiger et al. 2012). Temperature differences between aspects varied seasonally: in summer, long photoperiods and high solar angles result in intense midday radiation on south-facing cliffs, while north-facing slopes receive only oblique, low-angle sunlight during mornings and evenings. Notably, daily minimum temperatures were still higher on south-facing cliffs in summer, indicating that cliffs retain heat overnight. Spring and autumn showed intermediate differences, while winter differences were small and non-significant (Geiger et al. 2012; Suggitt et al. 2011).

However, the measurement of microclimate faced several limitations. First, only 15 thermologgers were deployed for approximately one year, recording temperature alone. Second, as mentioned above, TOMST thermologgers can overestimate temperatures under direct solar radiation, due to radiative heating. Daily maximum values on exposed south-facing cliffs are affected most by it; shielding reduces but does not eliminate this bias. Nevertheless, the general trends captured by the microclimate model likely remain valid, as the processes causing these measurement errors - primarily solar radiation - are also the main drivers of actual temperature differences. Still, specific quantitative values may be unreliable. Future research could address this limitation by using ultra-fine wire thermocouples, which provide more accurate measurements due to their small size, high reflectivity, and thermally isolated data storage and housing (Maclean et al. 2021).

Third, due to the small sample size, the linear mixed model included only a simple interaction between aspect and season. Future studies with expanded sensor networks could include additional variables such as radiation, humidity, and wind. Such studies would also benefit from employing IoT systems for efficient data collection in difficult-to-access cliff environments (De Frenne et al. 2025), although to our knowledge no accurate, low-cost, robust IoT-sensor exists at this point. High-resolution UAV-based thermal imagery and digital elevation models (DEMs) could further improve spatial modelling and integration with topography and vegetation (Bramer et al. 2018). Comparative analyses across MIREN Rocks sites worldwide would allow exploration of microclimatic patterns across latitudes, elevations, and climates.

A.4. GLMM Species richness without high microtopography subplots (max. 6)

Predictor	**Species richness with all data points (n=248**	**Species richness without high microtopgraphy subplots above 6 (n=237)**
Intercept	1.440 (p=0.007)	1.580 (p=0.007)
Microtopography (linear)	**0.880 (p<0.001)**	**0.741 (p<0.001)**
Microtopography (quadratic)	**-0.276 (p<0.001)**	**-0.495 (p<0.001)**
Slope	**-0.458 (p=0.002)**	**-0.425 (p=0.004)**
Aspect (North/South)	-0.730 (p=0.18)	-0.780 (p=0.19)
Low climbing intensity	-0.290 (p=0.30)	-0.256 (p=0.37)
Unclimbed intensity	0.372 (p=0.34)	0.392 (p=0.35)
Microtopography : low climbing	**0.331 (p=0.04)**	**0.559 (p=0.005)**
Microtopography : unclimbed	**-0.573 (p=0.03)**	-0.189 (p=0.52)
$R^2_{Marginal}$	0.542	0.574
$R^2_{Conditional}$	0.797	0.822

Predictor effects were largely comparable between models. Both the direction and significance of the main effects remained unchanged. The only notable difference was the interaction between microtopography and unclimbed plots, which was no longer significant after excluding high microtopography subplots.

Explained variance was only slightly higher in the GLMM without the high microtopography subplots.

Overall, these results indicate that the small number of subplots with very high microtopography values did not drive or inflate the observed trends, despite their low representation in the dataset.

A.5. Simpson index

Simpson's diversity index (D) incorporated species richness and relative abundance. The vegan package was also used, based on the following formula (Simpson, 1949): D = 1 ∑ Pi S 2 i=1 where Pi is the proportional cover of species i in each subplot. Since Simpson's diversity index is a proportion bounded between zero and one but includes a substantial number of zeros, a 16 zero- inflated beta regression generalised linear mixed model (GLMM) was fitted. The model used the same fixed-effects and full random-effects structure as described for the species richness model, except that it excluded the quadratic term for microtopography.

Simpson's diversity index (D) incorporated species richness and relative abundance. The *vegan* package was also used, based on the following formula (Simpson, 1949):

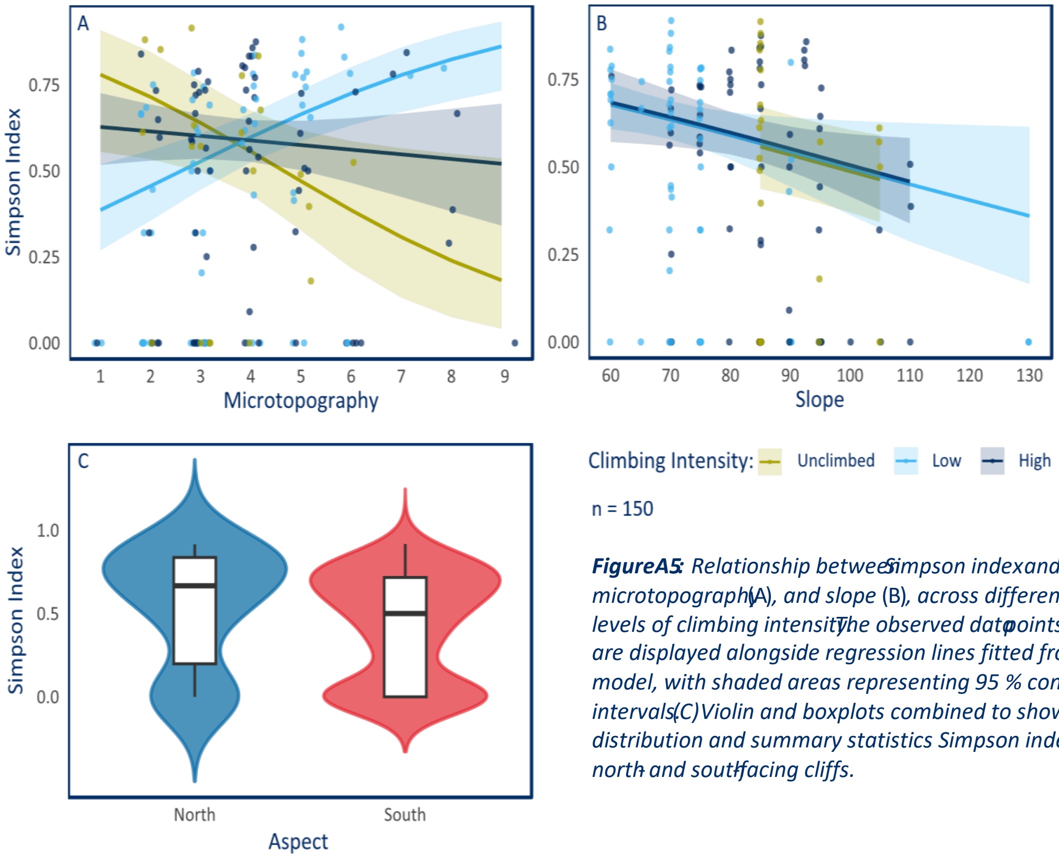
$$D= \frac{1}{i=1} \sum SPi2$$

where P_i is the proportional cover of species i in each subplot. Since Simpson's diversity index is a proportion bounded between zero and one but includes a substantial number of zeros, a zero-inflated beta regression generalised linear mixed model (GLMM) was fitted. The model used the same fixed-effects and full random-effects structure as described for the species richness model, except that it excluded the quadratic term for microtopography.

The generalised linear mixed model (GLMM), using a zero-inflated beta regression, revealed similar results as for Shannon index (section 4.2.3.) However, the model for Simpson index explained a lower proportion of variance ($R^2_{marginal} = 0.054$, $R^2_{conditional} = 0.078$). Additionally, a marginally non-significant negative interaction between microtopography and unclimbed subplots was observed, suggesting a negative trend between microtopography and diversity in the absence of climbing (tab. A7, fig. A7 A–C).

Table A7: Summary of the fixed effects from the zero-inflated beta regression generalised linear mixed model (GLMM) testing the effects of climbing and abiotic factors on Simpson index per subplot on cliffs. Displayed are the estimated coefficients, p values, and significance levels for the : p < 0.1 (.), p < 0.05 (*), p < 0.01 (**), p < 0.001 (***).

Predictor	Estimate	p-value	Significance
Intercept	1.046	< 0.001	***
Microtopography	-0.093	0.425	
Slope	-0.261	0.032	*
Aspect (north/south)	-0.656	0.011	*
Low climbing intensity	-0.240	0.270	
Unclimbed intensity	0.108	0.715	
Microtopography × Low climbing	0.582	< 0.001	***
Microtopography × Unclimbed	-0.496	0.095	.



***FigureA5**: Relationship between Simpson index and microtopography (A), and slope (B), across different levels of climbing intensity. The observed data points are displayed alongside regression lines fitted from the model, with shaded areas representing 95 % confidence intervals. (C) Violin and boxplots combined to show both distribution and summary statistics Simpson index on north- and south-facing cliffs.*

A.6. Results table indicator species analysis

Table A6: Species significantly associated with each climbing-intensity level identified by indicator species analysis. Locally threatened (Red List) species are shown in bold. The indicator statistic reflects the strength of association between species occurrence and a given climbing-intensity level, and p-values indicate statistical

significance based on permutation tests. The KS value from Flora Indicativa represents the species' ecological strategy according to the CSR framework (competitor–stress tolerator–ruderal), indicating relative dominance along this gradient (Ivanova and Zolotova 2023).

Group	Species	Indicator Statistic	P-value	KS (Flora indicativa)
Unclimbed	Umbilicus rupestris	0.316	0.001***	css
	Saxifraga tridactylites	0.305	0.001***	rrs
	Carex humilis	0.272	0.001***	css
	Erysimum cheiri	0.256	0.001***	rss
	Jacobaea vulgaris	0.250	0.002**	NA
	Scabiosa columbaria	0.172	0.04*	csr
	Unknown shrub	0.221	0.002**	NA
	Cardamine sp.	0.221	0.02*	NA
	Hieracium murorum	0.218	0.009**	crs
	Festuca pallens	0.205	0.009**	css
	Asplenium trichomanes	0.205	0.01*	rrs
	Sedum album	0.198	0.008**	sss
	Geranium robertianum	0.196	0.01*	crr
	Sesleria caerulea	0.190	0.03*	ccs
	Silene nutans	0.168	0.05*	ccs
	Centaurea scabiosa	0.153	0.05*	ccs
Low	Seseli libanotis	0.194	0.02*	ccs
High	Arenaria serpyllifolia	0.170	0.03*	rrs
	Taraxacum sp.	0.154	0.04*	csr

A.7. Community-weighted means Grime plant strategies

Detailed results on how the occurrence of Grime plant strategies differs based on a linear model.

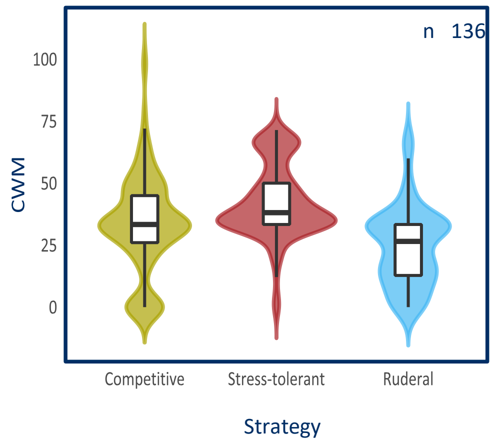


Figure *Violin and boxplots combined to show both distribution and summary statistics of community weighted mean (CWM) values across the three plant strategies (competitive,-stress tolerant, ruderal).*

Table A7: Summary of the linear model comparing CWM values among the three plant strategies, showing linear estimates, estimated marginal means (emmean), and p-values.

	Competitive (C)	Stress-tolerant (S)	Ruderal (R)
Estimate	30.5	38.9	22.7
LM estimate difference	30.464	8.405	-7.773
Tukey-adjusted p-value	< 0.001***	< 0.001***	< 0.001***

A.8. Climbing routes

Table A8: Local climbing route names where vegetation was surveyed displayed with grade of climbing difficulty, amount of subplots (n) in each route, and category of climbing intensity based on the average expert evaluation.

Route name	Grade	n subplots	climbing intensity
La Grune	4b	4	Low
L'Ascendente	4c	12	High
Arriba Bolivia	4c	12	High
Le Dernier Combat	5b	8	Low
Super-Vol-Au-Vent (L1)	5c	16	High
Les Anciens Belges	5c	20	Low
Le Rab Directe	5c+	20	High
The Wall	6a	12	High
Les Negresses Vertes	6a	12	High
L'avenue Chlorophyl	6a	12	High
La Lili	6a	12	Low
La Gamma	6a+	12	Low
La Tjetten	6b	12	Low
Mongolito	7a	8	Low
La cerise (L3)	7a+	8	Low
La Cerise départ Propagande	7b	4	Low
Troucage	7c	20	High
Cool Cat	8a+	16	Low

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 m^2, composed out of 4 subplots of 1 m^2. 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 & m^2 subplots).

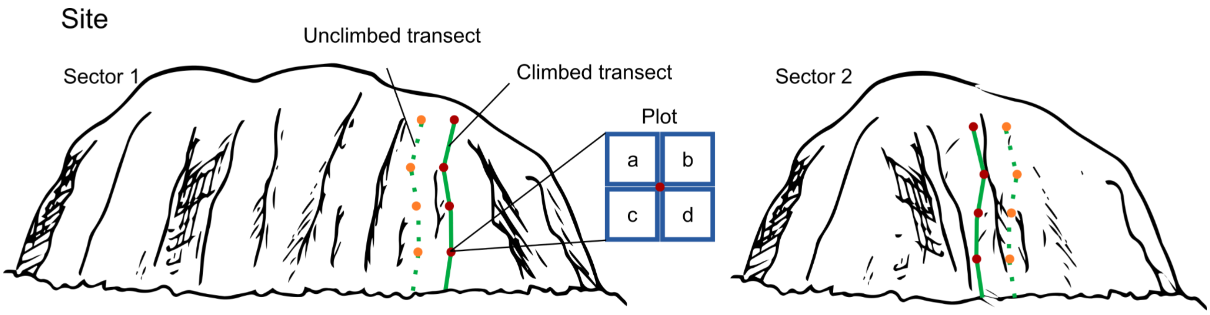


Figure 1: A rock climbing site with 2 paired transects (in total 2 climbed and 2 unclimbed transects). The vegetation is recorded in a plot of 2 m x 2 m, consisting of 4 subplots of 1 m² (a, b, c, d)

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 & Hessl, 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.

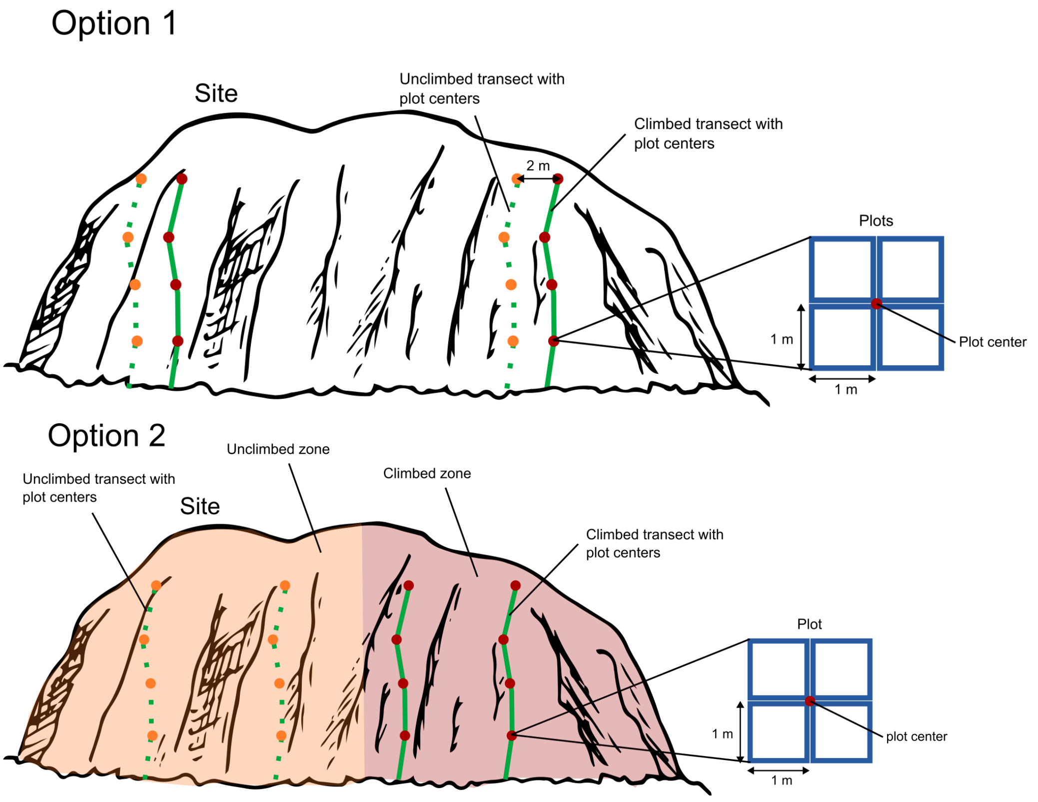


Figure 2: two options to position paired climbed and unclimbed transects within a rock site

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).


TOMST
TMS 91171134

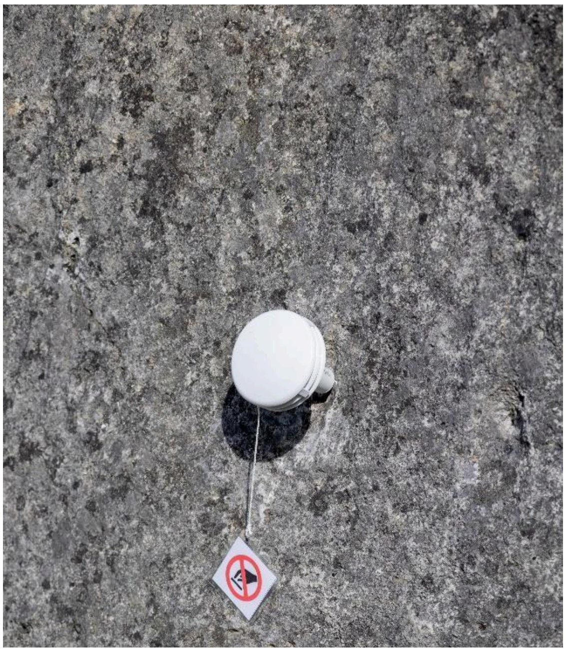


Figure 3: TOMST Thermologger can be used to measure the temperature at the rockface, as it comes with a handy screw and triple radiation shield. Pictures from https://tomst.com/, Jonas Lembrechts and Kobe Burdack

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 sprit 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

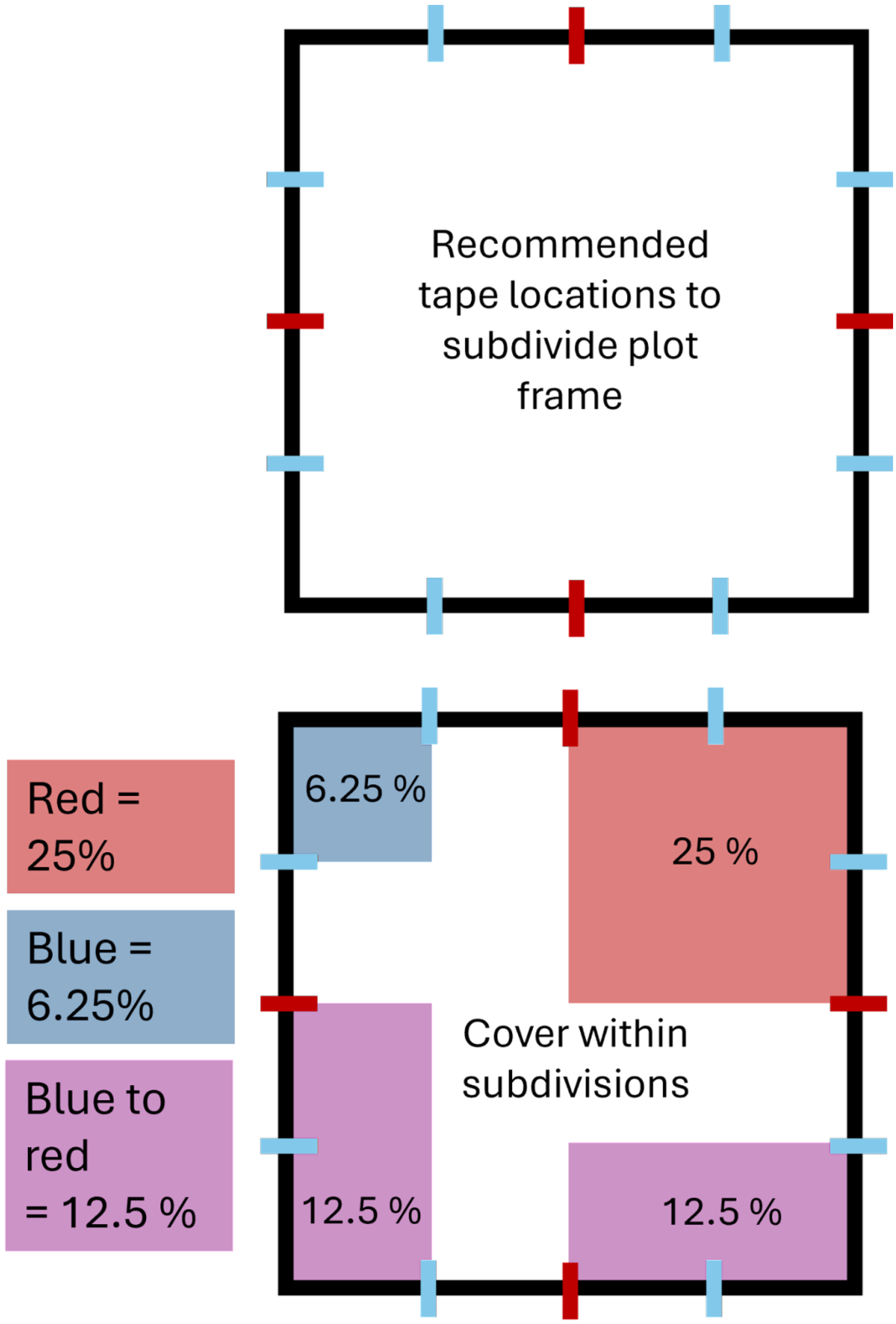


Figure 6: Recommendations for plot subdivisions to assess cover using colored guides (tape). Figure from Georgia Harrison & Laura Boggess

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

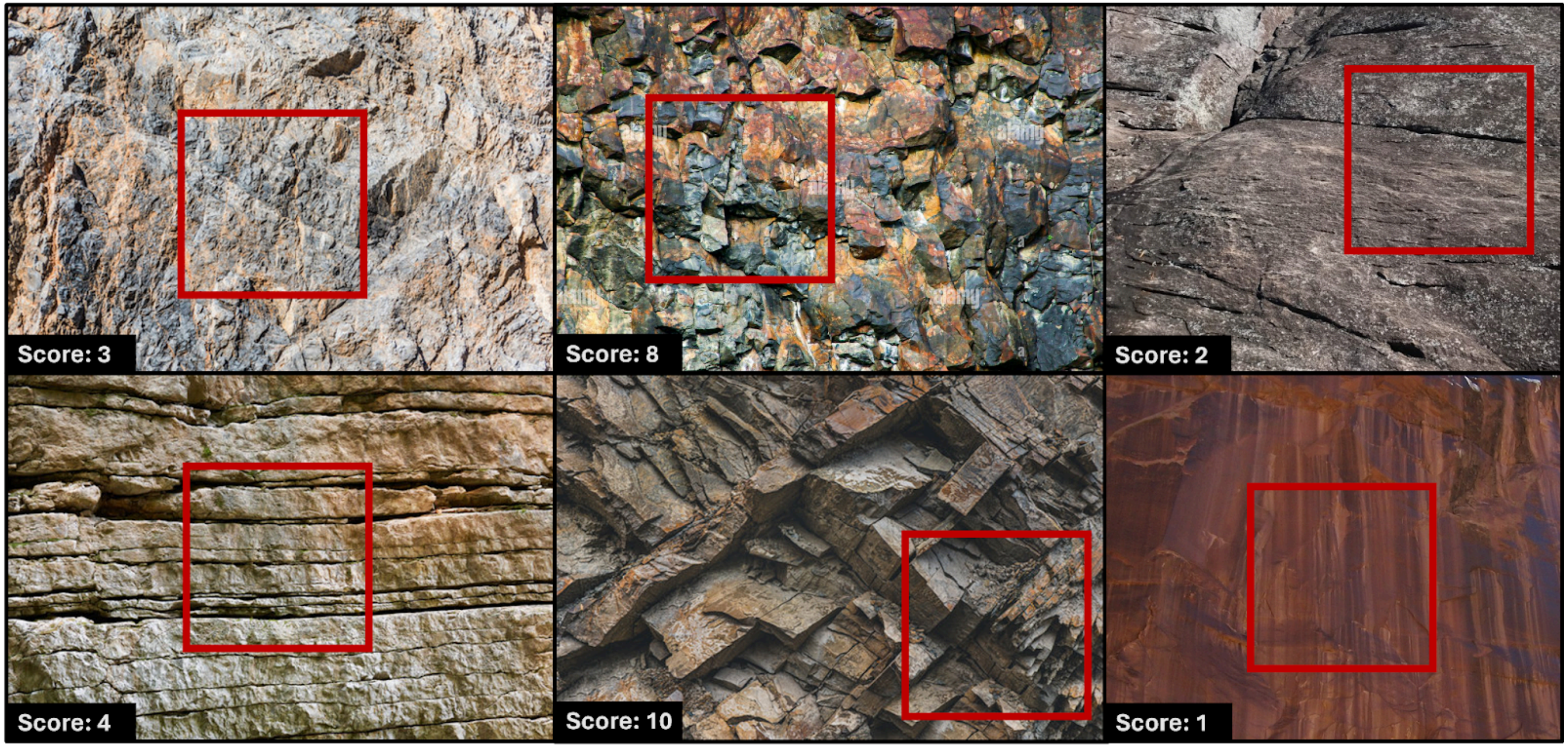


Figure 7: Example cliff face photos to score surface heterogeneity. Red box is plot frame, only score surface heterogeneity within plot frames. Not included in photos is the distinction between overhanging or non-overhanging features.

**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-power 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

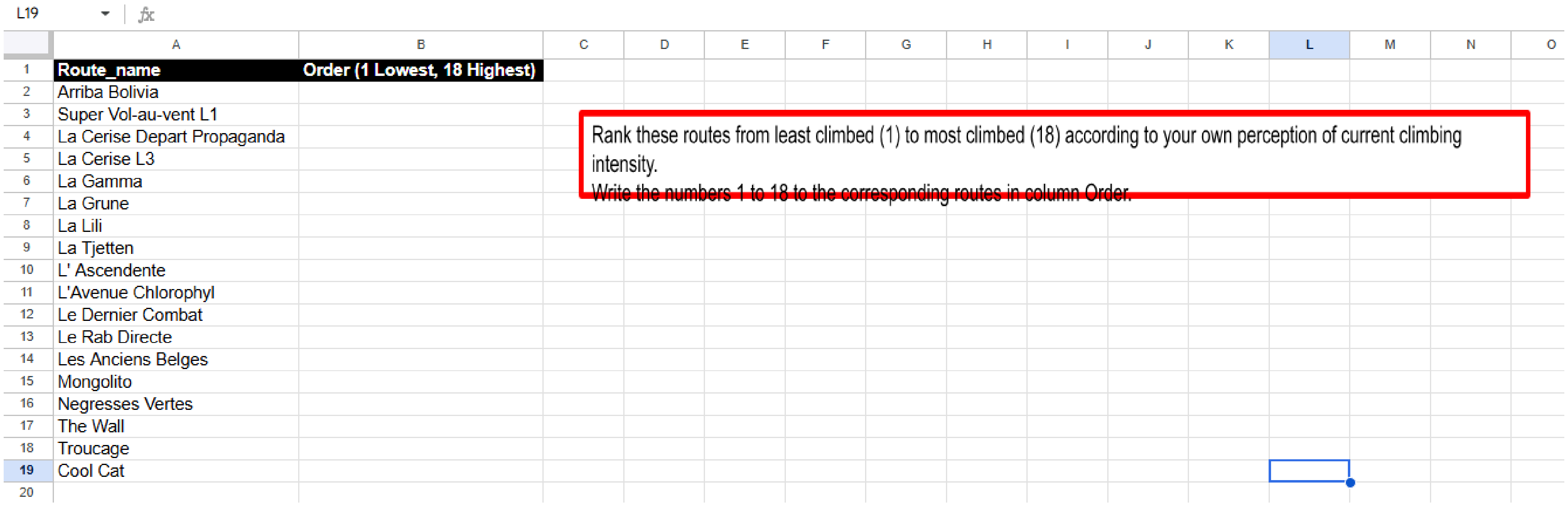
To estimate climbing intensity, prepare an Excel file (or similar spreadsheet format) and send it to around 10 local climbers who are very familiar with the site and its routes.

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.



Route_name	Order (1 Lowest, 18 Highest)
Arriba Bolivia	
Super Vol-au-vent L1	
La Cerise Depart Propaganda	
La Cerise L3	
La Gamma	
La Grune	
La Lili	
La Tjetten	
L' Ascendente	
L'Avenue Chlorophyl	
Le Dernier Combat	
Le Rab Directe	
Les Anciens Belges	
Mongolito	
Negresses Vertes	
The Wall	
Troucage	
Cool Cat	

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.

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

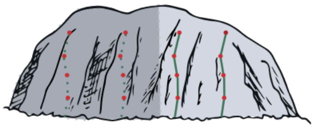
MIREN KU LEUVEN University of Antwerp Utrecht University

6.9 Summary sheet field data collection

Date of the survey

MIREN Rocks survey summary

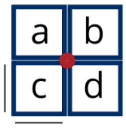
Transect



- Length
- Coordinates
- Elevation
- Overall slope and aspect

- Climbed?
  - Y - Route (+ info)
  - N - Position & distance to route

Plot



- Anchor number
- Heigh
- Aspect
- Slope

Subplot

- Microtopography

Vegetation:

Vascular plants	**Mosses**	**Lichens**
% total cover	% total cover	% total cover
Species • identification • % cover	Morphotype Harvest fragment from each cushion + %cover	Morphotype • Crustose • Foliose • Fruticose + %cover