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The ecological impact of rock climbing on cliff-face vegetation

Diversity, functional traits, and microclimate in Freyr, Belgium

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Scientific abstract

While the world is facing an unprecedented decline in biodiversity, rock cliff ecosystems receive little scientific attention. Yet, they harbour rich biodiversity with rare and endemic plant species, uniquely adapted to the harsh conditions on vertical surfaces. Their geomorphological heterogeneity creates diverse microclimates, potentially acting as microrefugia under global change. Inaccessibility has protected cliffs largely from human disturbance, but with the rising popularity of rock climbing, a potential threat to cliff biodiversity is emerging, although its impact remains unclear.

Most studies only focus on species diversity and abundance, often overlooking functional traits that provide a more nuanced ecological understanding. This study investigates how rock climbing and abiotic cliff characteristics shape vegetation communities and their functional composition. Specifically, it assesses the effects of climbing on species richness, vegetation cover, Shannon index, Grime CSR strategies, pH, and temperature affinity. The seasonal microclimate differences between north- and south-facing cliffs were also measured.

Vegetation data were collected from 248 subplots of one m² across 13 transects on Freyr's limestone cliffs in Belgium, with varying climbing intensities (unclimbed, low, and high). Climbing intensity was estimated using an expert-based survey approach. Functional traits were calculated at the subplot level using community-weighted means. Microclimate data were recorded over four seasons using temperature loggers.

Climbing impacts were nuanced, and vegetation patterns were largely mediated by abiotic cliff features. High species richness was associated with low climbing intensity and high microtopographic heterogeneity, which is consistent with the intermediate disturbance hypothesis. Community trait composition shifted under climbing pressure towards more ruderal species. Stress-tolerant species dominated overall. Vegetation cover and diversity were higher on north-facing cliffs, but no shift in temperature affinity was observed, despite differences in the microclimate.

Understanding these dynamics is essential for sustainable climbing management and the conservation of cliff ecosystems.

Public summary

Biodiversity is disappearing faster than ever because of global warming and other human activities. Some unique and valuable ecosystems, such as rock cliffs, are often overlooked in ecological research. At first glance, these steep rocky surfaces may seem lifeless, but they actually harbour a rich diversity of plant life and serve as refuges for rare species. These plants are adapted to survive in harsh vertical environments with little soil or water and large variations in temperature. Because of their steepness and inaccessibility, cliffs have been largely protected from humans. However, with the growing popularity of rock climbing, this may change and create a potential risk to biodiversity.

This research explores how climbing affects cliff vegetation, not only in terms of how many plant species grow there or how much rock is covered by vegetation but also how the traits and ecological strategies of these plant communities shift. This study took place on the limestone cliffs of Freyr, which is Belgium's largest climbing spot. Vegetation was surveyed across areas with different climbing intensities (unclimbed, low, high), based on input from local climbers. Temperature differences between north and south faces were measured using sensors on the wall.

The results show that the impact of climbing on cliff vegetation is complex. The amount of plant species was highest in areas with low climbing intensity and a lot of cracks, pockets, surface ridges. Climbing favoured ruderal species, plants that thrive under disturbance. Overall, stress-tolerant plants were dominant. North-facing cliffs had more plant cover and diversity, and cooler temperatures, but plants growing there had no higher temperature preference.

Thus, vegetation is not simply helped or harmed by climbing, but the impact is subtle, and vegetation also shaped by features of the rock itself. Understanding this relationship is important to allow climbing and biodiversity protection to coexist.

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This thesis and all the people involved, let me grow from a clueless climber, looking for a thesis topic in biology –a field where I often wondered if I belonged– to a very enthusiastic researcher in cliff ecology, realising rocks are fascinating, and not only to climb on.

I could easily exceed the word count limit by listing the endless things everyone did. This is just a glimpse of my immense gratitude. And I can only feel very humble and grateful for the community I can rely on.

Research is like climbing, it is not done alone!

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1. Introduction

1.1. Biodiversity in cliff ecosystems

The world is facing an unprecedented climate and biodiversity crisis driven by anthropogenic factors such as greenhouse gas emissions, land-use changes, pollution, and invasive species. These pressures contribute to biodiversity loss and disrupt ecosystem functioning (Calvin et al., 2023; Hooper et al., 2012; IPBES, 2019; Meyer et al., 2014).

Cliffs receive limited attention in ecological research, but serve as biodiversity hotspots. They host a rich diversity of vascular plants, including both generalists and many rare and endemic species, uniquely adapted to harsh, vertical environments (Datar & Watve, 2018; García et al., 2020; Kuntz & Larson, 2006b; Larson et al., 2000; March-Salas et al., 2023; Rusterholz et al., 2011). According to Ellenberg (2009), cliffs may harbour 35-40 % of world's endemic species. Their steep and fragmented nature creates isolated habitats where environmental stressors filter species and limit competitors from surrounding environments (Capó et al., 2023).

However, their spatial isolation and limited connectivity restrict species migration in response to climate change, increasing the risk of extinction. In addition, cliffs may experience shifts in local stress regimes due to warming, reducing the availability of suitable microhabitats. This makes cliffs inherently vulnerable to climate change and biodiversity loss (Capó et al., 2023; Cartwright, 2019).

1.2. Microclimatic variation

Cliff ecosystems have unique environmental characteristics, particularly their vertical orientation, which create distinctive and highly variable 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., 2000).

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., 1995; Larson et al., 2000).

Radiation absorption and dissipation primarily drive the energy balance at the cliff surface. With limited vegetation, evapotranspiration plays a minor role, and 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., 2000).

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 & Larson, 2006b; Larson et al., 2000; Lembrechts & Nijs, 2020; Speziale & 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.

1.3. The effects of slope and microtopography on vegetation

In addition to microclimate, slope and microtopography strongly shape plant communities (Boggess et al., 2021; Holzschuh, 2016). Steep cliffs are often well-drained and nutrient-poor due to gravity-driven erosion and low soil accumulation. These conditions favour desiccation-tolerant and stress-tolerant plant species. Shallower slopes tend to trap more debris and moisture, creating spots that are more suitable for plant establishment and growth (Bartlett et al., 1990; Clark & Hessel, 2015; Harrison et al., 2022; Kuntz & Larson, 2006b; Larson et al., 2000).

Microtopography -such as crevices, pockets, fractures, and surface irregularities- provide possible microsites for soil and water retention, creating places for propagule catchment and plant growth (Larson et al., 2000; Nuzzo, 1996). It may reduce bryophyte and lichen diversity but enhance species richness in vascular plants (Harrison et al., 2022; Kuntz & Larson, 2006b).

1.4. Rock climbing as an ecological disturbance

Cliffs are largely protected from anthropogenic disturbances due to their inaccessibility. They also experience limited herbivory and other natural disturbances, resulting in ecosystems dominated by disturbance-sensitive plants (Larson et al., 2000; Sangüesa-Barreda et al., 2022). Although overall competition and predation pressures are less prominent than in many other ecosystems, the scarcity of soil and suitable rooting sites can lead to localised competition for space. The physical separation of root systems, safe sites, and minimal canopy cover reflect reduced intra- and interspecific competition and herbivory. Therefore, cliff ecosystems are more shaped by abiotic stressors than competition or disturbance (Larson et al., 2000).

However, the increasing popularity of rock climbing has resulted in new disturbances 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, October 10, 2024). Rock climbing can cause both mechanical and chemical disturbances. Mechanical disturbance occurs during route development, maintenance, and climbing. When new routes are established, unstable rocks, vascular plants, and bryophytes are removed. Bolts are installed by drilling into the rock. Maintenance of existing routes may include trimming of vegetation such as ivy (*Hedera helix* L.), brambles (*Rubus* spp.), and trees growing at the cliff foot or on ledges. Smaller herbaceous plants and grasses are often left in place (D. Léduc, personal communication, June 3, 2024).

Additionally, climbers can cause chemical disturbance when using climbing chalk –magnesium carbonate hydroxide hydrate ($1-4\text{MgCO}_3 \cdot \text{Mg}(\text{OH})_2 \cdot 3-5\text{H}_2\text{O}$)– which is used to reduce hand moisture and improve grip. Chalk can increase local pH, potentially affecting nutrient availability and plant growth. Even in the absence of visible traces, chalk residues can persist and alter substrate chemistry. The degree of impact depends on the local rock buffering capacity, which could mitigate pH changes (Hepenstrick et al., 2020).

Research suggests that the greatest impact on vegetation occurs during initial route development rather than during regular climbing activity (Morales-Armijo et al., 2024). Research on vascular plants reveals inconsistent patterns in impact. While several studies have documented decreases in species richness and cover (Bogges et al., 2021; Camp & Knight, 1998; Clark & Hessler, 2015; Lorite et al., 2017; March-Salas et al., 2018; Müller et al., 2004;

Schmera et al., 2018; Tessler & Clark, 2016), others have found no significant effect (Boggess et al., 2017; Harrison et al., 2022; Kuntz & Larson, 2006b; Nuzzo, 1996). The inconsistencies may be due to variations in the site characteristics or methodological approaches (Boggess et al., 2021; Kuntz & Larson, 2006a).

An additional complication arises from climber route selection (Boggess et al., 2017). Climbers often prefer less vegetated, drier cliffs, leading to uncertainty about whether differences in vegetation abundance are a consequence of climbing or reflect inherent site characteristics (Farris, 1998; Kuntz & Larson, 2006a; Müller et al., 2004). A study in Mexico revealed that on cliffs that were already sparsely vegetated before the development of climbing routes, no significant differences in vegetation were observed after route opening (Morales-Armijo et al., 2024). This complex interaction indicates the need for an accurate estimation of climbing intensity in the research methodology.

Climbing intensity is a crucial variable for assessing the ecological impact. In previous studies, paired or unpaired transects were used to compare climbed and unclimbed zones (Boggess et al., 2021). However, in some climbing areas, accessing enough unclimbed zones is difficult or unsafe. In such cases, a gradual climbing intensity metric is more appropriate. Exact route data are not available and are difficult to collect; thus, proxies must be used. One method, the Climbing Use Index (CUI) combines star ratings from the guidebook and approach time (Clark & Hessel, 2015). In smaller climbing areas with similar approach times, this method may be less effective. Various other indicators from guidebooks, online ascent log platforms, or expert estimates can assess climbing intensity, but each of these has limitations. In this study a multifaceted approach was used to estimate the climbing intensity.

1.5. Functional traits of plants

While existing studies on the ecological impact of climbing mainly focus on species richness and abundance, functional traits provide a more nuanced understanding of ecological responses. According to Grime's (1977) CSR theory, plant species adopt strategies to cope with environmental constraints. Stress—such as limited water or nutrient availability—reduces growth and productivity, whereas disturbance involves biomass removal by herbivores or human activity. In response, species develop competitive (C), stress-tolerant (S), or ruderal (R) strategies. Most plants combine these strategies to mitigate local stress and disturbance.

Limestone cliffs, often associated with nutrient-poor calcareous grasslands, experience low levels of disturbance due to inaccessibility. Thus, stress-tolerant species are expected to dominate. However, disturbance from climbing may shift communities towards ruderal strategies with high seed production, rapid nutrient uptake, short life cycles, and efficient dispersal mechanisms (Rusterholz et al., 2011).

These ruderals are also often associated with higher temperature affinities (Randelović & Jovanović, 2023). Disturbance may therefore favour species with higher temperature preference, thereby accelerating thermophilisation—the shift in community composition towards more warm-adapted species (Borderieux et al., 2023; De Frenne et al., 2025; Wiegmans et al., 2024). Although primarily driven by climate warming, thermophilisation can also be facilitated by anthropogenic disturbances such as climbing.

2. Research questions and hypothesis

Despite the growing interest in cliff ecosystems, they remain understudied (Fitzsimons & Michael, 2017; Harrison et al., 2024; March-Salas et al., 2023). Most research has focused on species richness and abundance, whereas changes in community composition and functional traits—such as CSR strategies, temperature, and pH affinity—are rarely addressed. Although climbing impacts have been studied in Spain, Switzerland, the USA, and Canada (Boggess et al., 2021), no such research existed already in Belgium. Furthermore, measurements of cliff microclimates are extremely limited.

This study addresses these gaps by examining how climbing intensity and abiotic factors influence vegetation diversity and functional traits and by monitoring temperature differences between north- and south-facing cliffs across seasons.

2.1. Research questions

1. How can climbing intensity be reliably estimated in the absence of empirical ascent data and paired comparisons?
2. How do climbing intensity and abiotic factors (aspect, slope, and microtopography) interact and shape rock cliff vegetation?
 - a. How are species richness, total vegetation cover, and the Shannon index affected?

- b. How are community shifts in functional traits (CSR strategies, temperature and pH affinity) affected?
- 3. How do north- and south-facing cliffs differ in microclimate temperatures across seasons?

2.2. Hypotheses

H1: A reliable proxy for climbing intensity can be obtained by combining guidebook data and online ascent logs.

H2:

H2a: Species richness, vegetation cover, and Shannon index will decrease with higher climbing intensity and steeper slope, but increase with more microtopographic complexity.

H2b: Extreme conditions in cliff environments are expected to favour stress-tolerant species, although climbing may promote ruderal species. pH- and temperature affinity will increase with climbing.

H3: South-facing cliffs exhibit warmer temperatures than north-facing cliffs, with the largest differences in summer and the smallest differences in winter.

3. Materials and methods

3.1. Study site

This study was conducted at the Freyr climbing site, located in the valley of La Meuse in the temperate climate zone of Belgium (50.223697, 4.895386) (fig. 2). The site is located in a Natura 2000 area and characterised by massive limestone cliffs and calcareous grasslands with high conservation value owing to high plant species richness (Newton et al., 2012).

Freyr's cliffs have been climbed since 1930 and form Belgium's largest climbing crag (Bott & Deneyer, 2022), where climbing occurs year-round. The Club Alpin Belge (CAB) manages access and maintenance of the area.

3.2. Quantifying the climbing intensity

The study site of Freyr was inspected for the possibility of assessing climbed and unclimbed cliff zones in paired or unpaired transects, as mentioned as guideline in the MIREN Rocks

protocol (*MIREN Rock Survey Protocol*, n.d.). In Freyr, unclimbed transects were difficult to sample due to their limited availability and the challenges of safe access. As result, a paired comparison of climbed and unclimbed transects was not feasible. Due to this lack of possibilities, alternative options to accurately assess the impact of climbing in Freyr were sought, including a metric or estimation of climbing intensity using a multifaceted approach.

First, the Climbing Use Index proposed by Clark and Hessel (2015) was applied according to the formula:

$$CUI = \text{Log}_{10} \left([S + 1] * \left(\left[\frac{1}{T} \right] * 100 \right) \right)$$

In this formula, S represents the star ratings of the climbing routes, which were sourced from 8a.nu (*Freyr • Belgium - Sportclimbing - Vertical-Life Climbing Crags*, n.d.), since the Freyr guidebook lacks star ratings. T stands for the walking approach times, which were taken from the guidebook (Bott & Deneyer, 2022).

This index was developed in New River Gorge, a national park in the USA, which covers a larger area than Freyr. Approaching times and route accessibility vary more. Given these differences between Freyr and New River Gorge, additional indicators for climbing intensity were collected: guidebook data (year of route opening, classification as ‘classic’ or ‘patiné’, indicating that the route is polished due to frequent climbing), logs from 8a.nu, an online platform where climbers can share their achievements and evaluation of routes (number of ascents, recommendation percentage, and star ratings), and estimation by the guardian of the area. Principal Component Analysis (PCA) was performed to combine different indicators into a climbing intensity score.

To validate this approach, an expert-based ranking was obtained from eight experienced local climbers familiar with the routes in Freyr. Kendall’s coefficient of concordance (W) was used to test the agreement among expert climbing intensity rankings. This non-parametric test measures the consistency of rankings given by multiple observers and is particularly suited for ordinal data. A value of W close to one indicates strong agreement, whereas a value near zero suggests low agreement. The average rank was calculated from all the expert rankings.

To evaluate the relationship between expert rankings and both CUI values and PCA-derived scores on climbed routes, Kendall rank correlation was used. This test was chosen because it

is appropriate for comparing ordinal and continuous variables, especially with small sample sizes ($n = 18$ for CUI, $n = 14$ for PCA). As these rankings did not align, the climbing intensity was categorised into three levels: unclimbed, low, and high climbing intensity, based on the average of the expert rankings.

3.3. Acquisition and analysis of vegetation data

Data collection was performed following the guidelines of the international MIREN Rocks protocol (*MIREN Rock Survey Protocol*, n.d.). Fieldwork was conducted from the fourth of June until the fifth of July 2024, during the peak flowering period for most plants, facilitating optimal species identification. Vegetation data were collected using a hierarchical sampling structure: (site>zone>transect>plot>subplot) (fig.1). In this study was Freyr (fig. 2) the site with distinct zones representing different cliff sections. Vegetation data were collected at the following zones: Jeunesse, Welcome; Jeunesse, Face Nord; Al Lègne, Pilastre; Al Lègne Esperanza; Al Lègne, Le Rab; La Tête De Lion, La Sirène; Le Mérinos, Gamma; Le Mérinos, Cubitus, and a nameless unclimbed cliff. In total, 13 transects were surveyed, including parts of 18 different climbing routes (Appendix, tab. A1), and for each transect, transect length was measured, which varied depending on cliff topography. In total 62 plots of four m^2 , composed out of four subplots of one m^2 (248 subplots) were observed. Different abiotic factors were measured at the plot level, such as height above the base of the cliff, aspect (measured with a compass), and slope (measured with an inclinometer). At the subplot level, microtopography was estimated with a scale for surface heterogeneity from one (smooth rock) to 10 (high surface heterogeneity with many fissures, cracks, crevices, pockets) (Boggess et al., 2017, 2021; Harrison et al., 2022). At the subplot level, total vegetation cover and vegetation cover of each present vascular plant species was investigated by visually estimating cover percentages. Data analysis was conducted in RStudio.

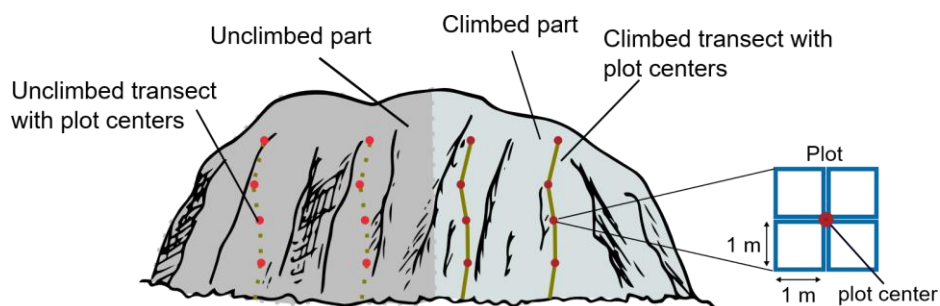


Figure 1: Sampling design for cliff faces with climbed and unclimbed zones. The vegetation was surveyed along vertical transects, with each plot composed of four $1 m^2$ subplots.

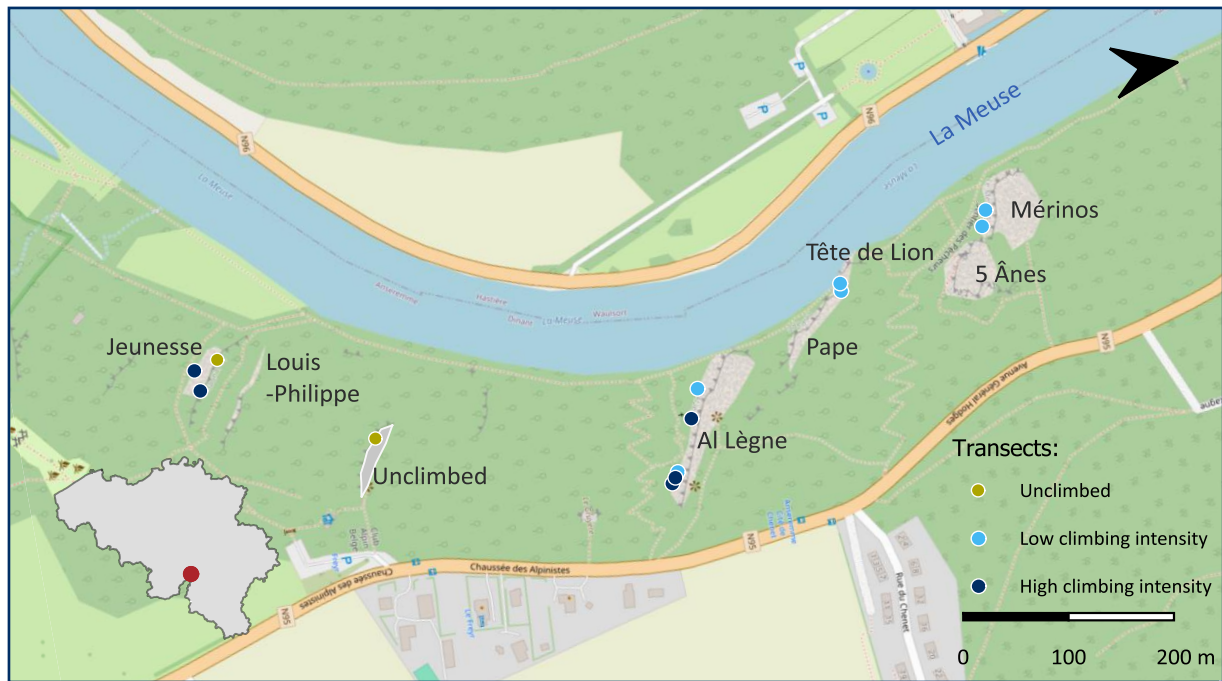


Figure 2: Map of the Freyr study area, showing different cliffs. Each dot represents a transect; colours indicate dominating climbing intensity level of the transect.

3.3.1. Species richness

Species richness, defined as the number of different vascular plant species recorded in each plot, is a discrete count variable. Due to overdispersion in the data, a negative binomial generalised linear mixed model (GLMM) was used to examine the effects of climbing intensity and environmental variables on species diversity.

Fixed-effects in the model included climbing intensity (categorical factor: unclimbed, low, and high), aspect (categorical factor representing north- or south-facing orientation), slope (continuous, standardised variable), and microtopography (discrete, standardised variable). A quadratic term of microtopography was included to test for non-linear effects. The interaction between climbing intensity and microtopography was also included to investigate whether the effect of climbing varied with the microtopography.

A nested random-effects structure was incorporated with plots nested in transects, nested within zones (Zone > Transect > Plot), accounting for spatial hierarchy and variance partitioning. The analysis was conducted at the subplot level using a dataset comprising 248 subplots across 62 plots nested within 13 transects and 8 zones. This full random-effects structure was used by default across all vegetation models; however, when convergence or

singularity issues arose, a simpler structure was applied, as specified in individual model descriptions.

The species richness model was fitted using the *nbinom2* family in the *glmmTMB* package, which is suitable for overdispersed count data. The figures in this report were generated using the *ggplot2* and *ggpredict* packages.

3.3.2. Total vegetation cover

The total vegetation cover was defined as the proportion of a subplot covered by vascular plants. These continuous proportions, bounded between zero and one, were analysed using a beta regression generalised linear mixed model (GLMM). The model included the same fixed-effects structure as the species richness model, with a nested random-effects structure of plots within transects (Transect > Plot).

3.3.3. Shannon's diversity index

The Shannon index (H) is a biodiversity metric that accounts for species richness and relative abundance. It was calculated using the *vegan* package, based on the following formula (Shannon, 1948):

$$H = - \sum_{i=1}^S P_i \ln P_i$$

where P_i is the proportional abundance (cover percentage) of species i , and S the total number of species in the subplot. Because Shannon values are continuous and positive and include many zeros, a GLMM with a Tweedie distribution and zero-inflation was applied. The model used the same fixed-effects structure as the species richness model, except that it excluded the quadratic term for microtopography and included only plots as a random effect.

3.3.4. Simpson's diversity 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):

$$D = \frac{1}{\sum_{i=1}^S P_i^2}$$

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.

3.3.5. Red list species

The response variable in this model was the number of distinct species per subplot that are either legally protected in Wallonia or appear on the regional red list (*Liste Rouge de La Flore de Wallonie*, n.d.; *Liste-Especies-Vegetales-Protegees-Wallonie-201202.Pdf*, n.d.). The count data was analysed using a negative binomial GLMM with climbing intensity as the only fixed effect and by applying the full nested random-effects structure (Zone > Transect > Plot).

3.3.6. Plant strategies

Plant strategies were classified following Grime's CSR framework using the three-letter code from Konkurrenz-Stress-Ruderal (KS) index codes (C = competitive, S = stress-tolerant, R = ruderal) obtained from Flora Indicativa (Ivanova & Zolotova, 2023). For each species, the relative contribution of each strategy was determined by calculating the percentage of each letter within the KS index. When species-level KS values were missing, genus-level averages were used, but only if the standard deviation was smaller than one. For each subplot, a representative value was calculated by dividing the sum of the cover percentages of the species with known CSR values by the total cover of all present species. Only subplots with at least 70% representation were included in the analysis; 16 subplots did not meet this threshold and were excluded.

$$Representative = \frac{\sum \text{cover of species with known CSR}}{\text{Total cover}}$$

For each subplot, the community-weighted mean (CWM) of each strategy was calculated using the following formula:

$$CWM = \frac{\sum P_i * C_i}{\sum C_i}$$

where P_i represents the proportion of a given strategy for species i , and C_i is the cover percentage of species i . The denominator corresponds to the total vegetation cover in each subplot. Subplots without vegetation cover ($n = 96$) were also excluded from the analysis, resulting in 136 subplots, nested in 51 plots, 13 transects, and 8 zones.

To determine which plant strategy was dominant overall, a linear model was fitted with CWM as the response variable and strategy (C, S, R) as a fixed effect. Pairwise comparisons between the strategies were performed using the *emmeans* package and Tukey-adjusted p-values.

To evaluate the effects of climbing intensity and abiotic factors on the community-weighted mean (CWM) of each plant strategy, zero-inflated Tweedie GLMMs were fitted, as the response variables were positive, continuous data with the presence of zeros. The fixed-effects structure of the previous models was retained, except that the interaction term was excluded. For the stress-tolerant strategy model, the fully nested random-effects structure was included. The competitive plant strategy model excluded zone from the random effects, and the ruderal strategy model only included plots as random effects.

3.3.7. pH affinity

The community-weighted mean (CWM) of pH affinity for each subplot with vegetation cover was calculated based on soil reaction (R) values for niche position from the European Indicator Values for Europe (EIVE) dataset (Dengler et al., 2023). However, soil reaction may differ in cliff environments compared to ground level, on which these values are based, as soil on cliffs is typically sparse and accumulates in microtopographic features. If species-level EIVE values were unavailable, genus-level means were used, provided the standard deviation was less than one. To account for other missing species values, subplots were only included in the analysis if at least 70% of the vegetation cover was attributable to species with known values. However, 15 subplots did not reach this threshold and were excluded from the analysis. This resulted in data points for 137 subplots located in 51 plots, 13 transects, and 8 zones.

The response variable, CWM pH, was positive, continuous, and left-skewed. Given these characteristics, a Tweedie generalised linear mixed model (GLMM) was fitted with random effects nested at the plot level. For the fixed effects, climbing was included, as well as slope and microtopography to account for their potential influence on chalk powder retention on rock surfaces.

3.3.8. Temperature affinity

The same procedure as described for pH affinity was applied to calculate the community-weighted mean (CWM) of temperature preference using EIVE niche position temperature values (Dengler et al., 2023). A generalised linear mixed model (GLMM) with a Tweedie

distribution was fitted with only plot level as a random effect. Fixed effects included the climbing intensity and aspect. The full model could not include the interaction effect of aspect and climbing due to the lack of unclimbed north-facing plots. Therefore, two additional submodels were run: one to test the effect of climbing only on south-facing cliffs and another to test the effect of aspect on climbed plots only. Both models included plot as random effect. Post hoc analysis was performed using estimated marginal means (*emmeans* package) for pairwise comparisons with Tukey's adjusted p-values. The Emmeans test was used because of the non-normal distribution of the CWM values, which was confirmed by the Shapiro-Wilk test for normality.

3.4. Measurement and analysis of microclimate temperatures

Microclimate data were collected by recording the temperature of air just in front of the rock (6 cm) with 15 TOMST thermologgers 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 a totally unclimbed cliff, which is unmanaged and uncleaned, one on the north face and one on the south face. In total, six sensors are 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 Lolly software.

Daily mean temperatures were calculated for each thermologger and used as the response variable in a linear mixed-effects model 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.

All of the models described above, for both the microclimate and vegetation data were evaluated for assumptions and diagnostics, including residuals, overdispersion, and multicollinearity, to ensure their validity.

4. Results

4.1. Climbing intensity

The Climbing Use Index (CUI) in Freyr ranged from 1.02 to 1.78 (range = 0.76), narrower than in New River Gorge (0.31-2.22; range = 1.91) (fig. 3). Unlike New River Gorge, the CUI distribution in Freyr was not normal, as indicated by the Shapiro-Wilk test ($W=0.840$, $p < 0.001$).

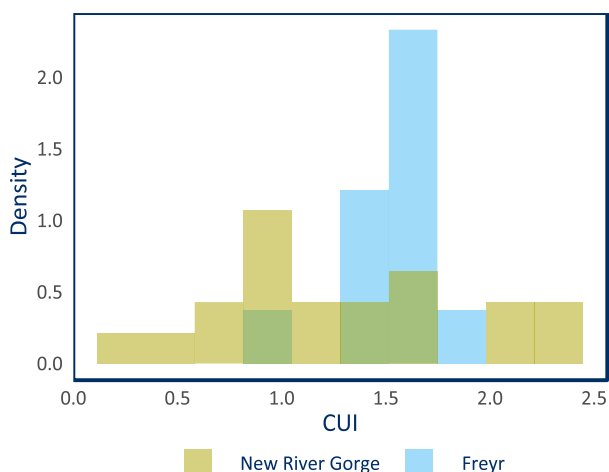


Figure 3: Histogram of Climbing Use Index (CUI) distributions for New River Gorge ($n = 20$) and Freyr ($n = 14$). The data are grouped into 10 bins with a bin width of 0.2.

Principal Component Analysis (PCA) identified two primary components that explain variations in climbing intensity. Historical popularity (30.8% of the variance), including years in use and classification as ‘classic’ and ‘patiné’; and current popularity (29.6% of variance), characterised by ascent numbers, recommendation percentages, and star ratings from 8a.nu, along with guardian estimations (fig. 4). Loadings are provided in the in Appendix (tab. A2).

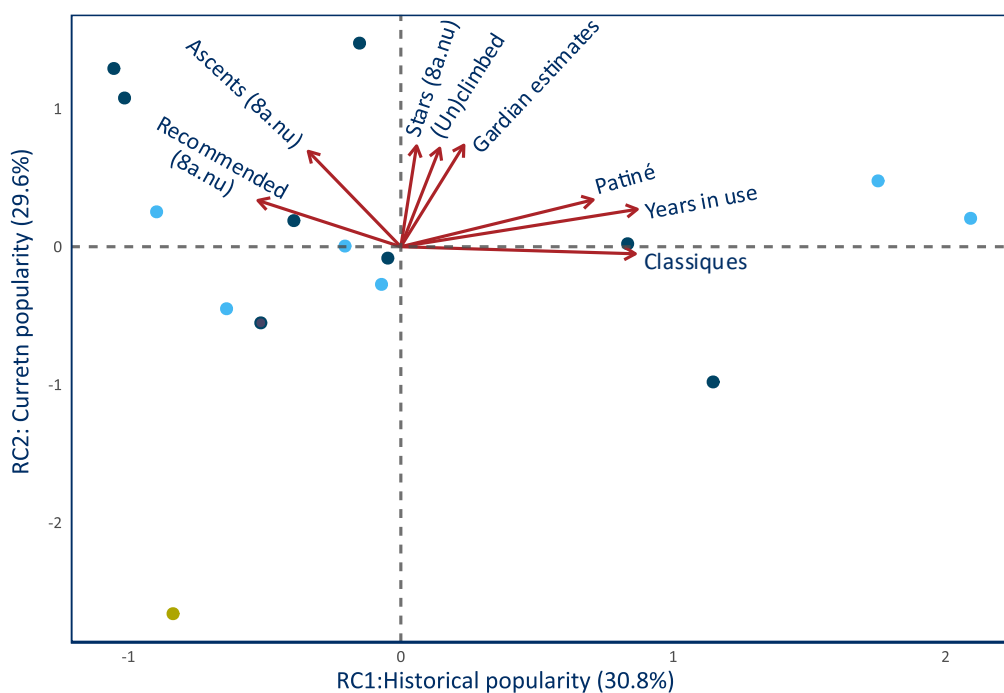


Figure 4: Biplot from Principal Component Analysis (PCA) showing two primary components explaining variation in climbing intensity. The x-axis represents RC1 (historical popularity), while the y-axis represents RC2 (current popularity). Arrows indicate the contribution of different variables to each 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).

Together, these two components explain 60.4% of the total variance, suggesting that most variation in climbing popularity can be explained by these two factors.

A moderate but significant association was found between the rankings provided by experts ($W=0.510$, $p=0.001$), as indicated by the concordance index, a measure of association. However, Kendall's rank correlation test showed only a weak non-significant correlation between the average expert ranking and the PCA-based ranking of current popularity ($\tau = 0.221$, $p = 0.273$; fig. 5B).

Further testing of the expert rankings with the climbing use index (CUI) revealed a very weak, non-significant correlation ($\tau = 0.156$, $p = 0.441$; fig. 5A).

In light of the weak correlation between CUI, PCA scores and expert rankings, climbing intensity was categorised into three groups based on the average expert rankings: unclimbed ($n=28$), low climbing intensity ($n=116$), and high climbing intensity ($n=104$). This categorisation allowed for the inclusion of four additional routes that lacked data on 8a.nu ($n=36$), increasing the number of climbing routes included in the analysis of the 36 subplots.

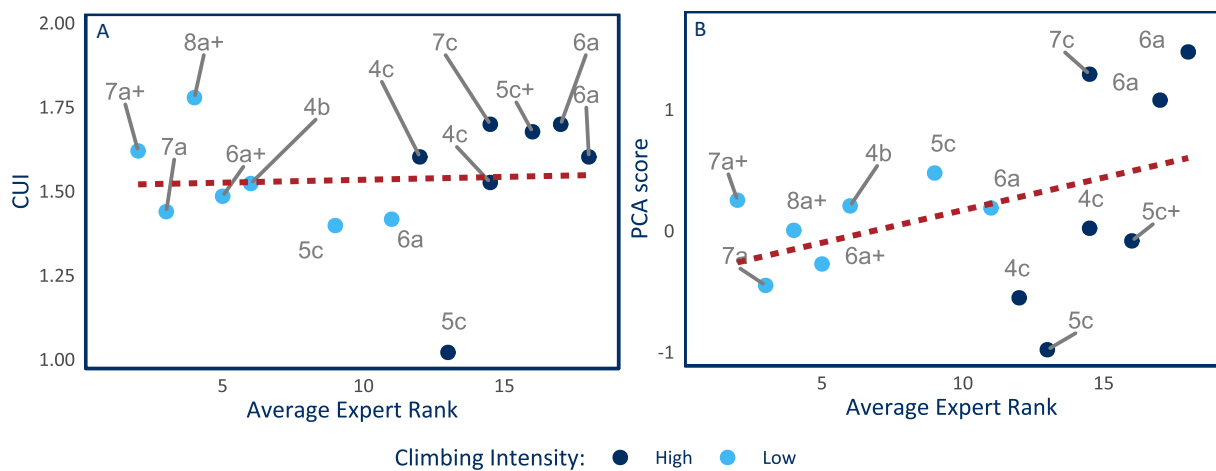


Figure 5: Scatterplots showing the relationship between (A) Climbing Use Index (CUI); (B) PCA score and expert rankings for climbing routes. Each point represent a route, labelled with its grade and is coloured according to its final climbing intensity category. Dashed correlation lines indicate the absence of a significant association between the two ranking methods. ($n = 14$)

4.2. Vegetation patterns

4.2.1. Species richness

The negative binomial generalised linear mixed model (GLMM) revealed a significant quadratic effect of microtopography on species richness, following a bell-shaped curve: richness initially increased with microtopography before declining. Further, slope had a

significant negative effect, indicating lower species richness on steeper cliffs at all climbing intensities. In contrast, north-south orientation was not significant. The interaction between climbing and microtopography was important: species richness peaked at intermediate-to-high microtopography levels under low climbing intensity, but declined in similarly structured unclimbed areas. High-intensity climbed plots showed intermediate richness. At low microtopography levels, species richness was uniformly low across all climbing intensities (tab. 1, fig. 6A-B). The GLMM explained a substantial portion of the variance in species richness ($R^2_{\text{marginal}} = 0.533$, $R^2_{\text{conditional}} = 0.803$).

Table 1: Summary of the fixed effects from the negative binomial generalised linear mixed model (GLMM) testing the effects of climbing and abiotic factors on species richness per subplot on cliffs. Displayed are the estimated coefficients, p-values, and significance levels for the predictors: $p < 0.1$ (.), $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***).

Predictor	Estimate	p-value	Significance
Intercept	1.447	0.015	*
Microtopography (linear)	0.876	< 0.001	***
Microtopography (quadratic)	-0.277	< 0.001	***
Slope	-0.408	0.005	**
Aspect (north/south)	-0.735	0.235	
Low climbing intensity	-0.101	0.137	
Unclimbed intensity	0.358	0.366	
Microtopography x Low climbing	0.348	0.0311	*
Microtopography x Unclimbed	-0.571	0.032	*

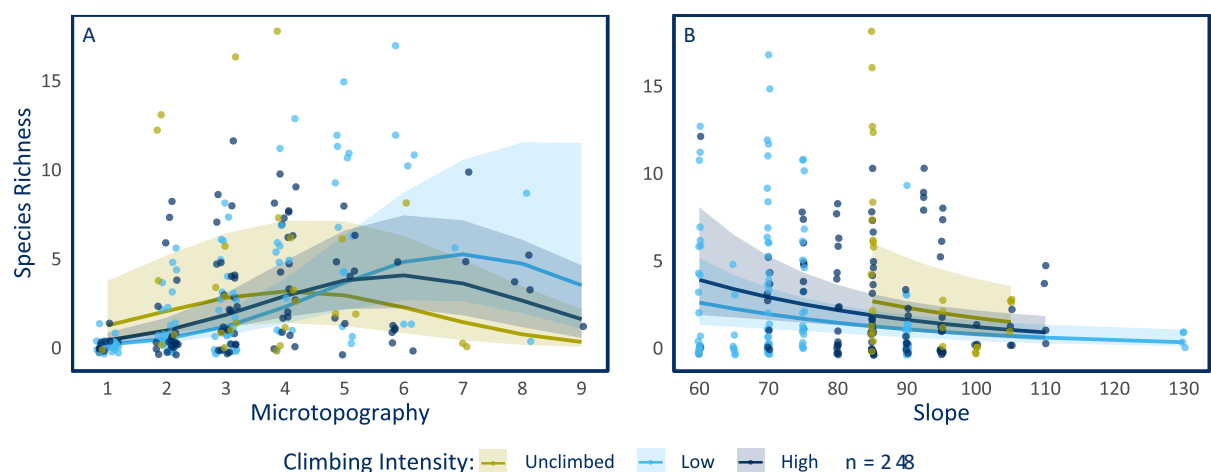


Figure 6: Relationship between species richness and microtopography (A), and slope (B), across different levels of climbing intensity. The observed data points are displayed alongside regression lines fitted from the model, with shaded areas representing 95 % confidence intervals.

4.2.2. Total vegetation cover

The generalised linear mixed model (GLMM) using beta regression revealed a significant quadratic effect of microtopography on total vegetation cover, with cover increasing with microtopographic complexity up to a plateau. Slope had a strong negative effect across all levels of climbing intensity, with steeper cliffs supporting less vegetation. Additionally, south-facing cliffs had significantly lower vegetation cover than north-facing cliffs, particularly at higher levels of microtopography. The climbing intensity had no significant main effects. Interaction terms between climbing intensity and microtopography were marginally non-significant, indicating weak trends: vegetation cover tended to increase slightly more with microtopography in low-intensity plots and slightly less in unclimbed plots. However, no clear or statistically significant differences in vegetation cover were observed between the climbing intensity categories across the microtopography gradient (fig. 7A-C, tab.2). The model explained a moderate amount of variance in vegetation cover ($R^2_{\text{marginal}} = 0.369$, $R^2_{\text{conditional}} = 0.579$).

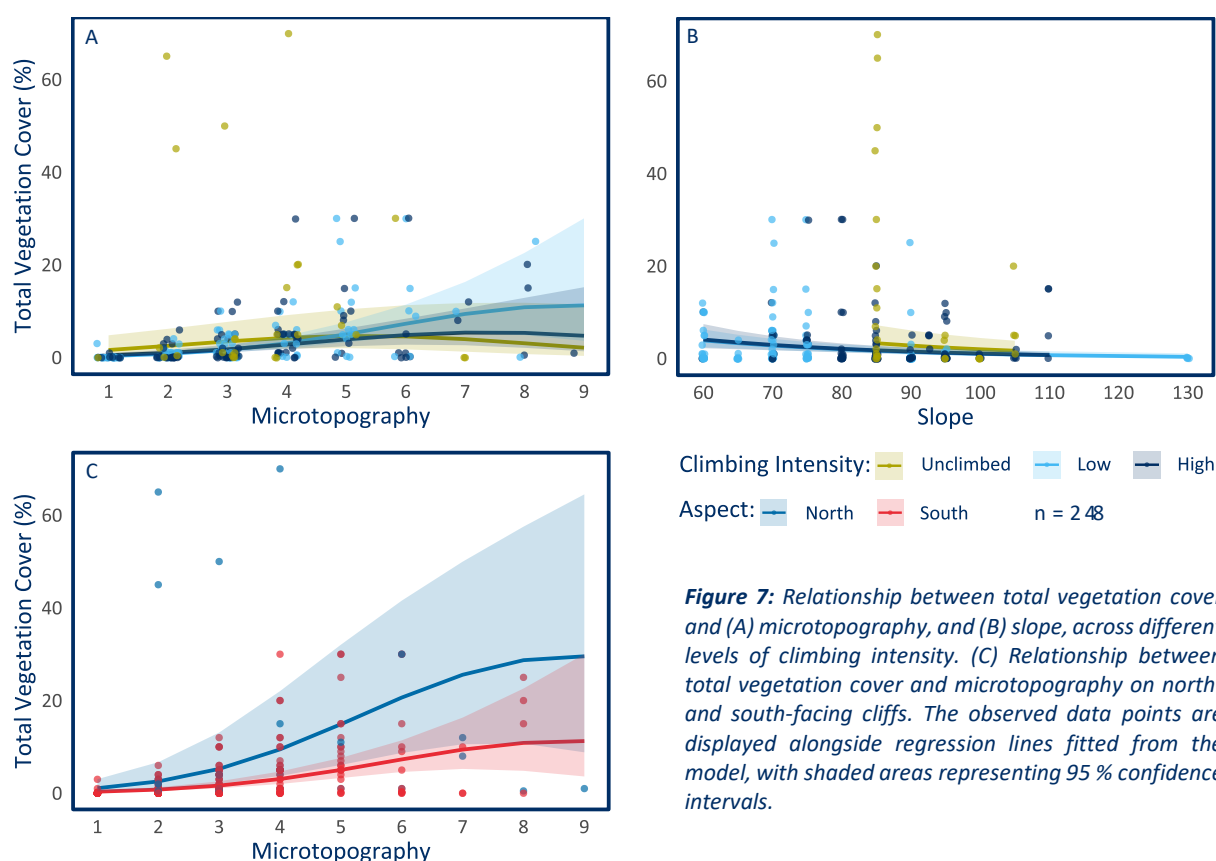


Figure 7: Relationship between total vegetation cover and (A) microtopography, and (B) slope, across different levels of climbing intensity. (C) Relationship between total vegetation cover and microtopography on north- and south-facing cliffs. The observed data points are displayed alongside regression lines fitted from the model, with shaded areas representing 95 % confidence intervals.

Table 2: Summary of the fixed effects from the beta regression generalised linear mixed model (GLMM) testing the effects of climbing and abiotic factors on total vegetation cover per subplot on cliffs. Displayed are the estimated coefficients, p-values, and significance levels for the predictors: $p < 0.1$ (.), $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***).

Predictor	Estimate	p-value	Significance
Intercept	-2.718	< 0.001	***
Microtopography (linear)	0.853	< 0.001	***
Microtopography (quadratic)	-0.172	0.003	**
Slope	-0.478	< 0.001	***
Aspect (north/south)	-1.196	< 0.001	***
Low climbing intensity	-0.050	0.855	
Unclimbed intensity	0.640	0.133	
Microtopography x Low climbing	0.291	0.095	.
Microtopography x Unclimbed	-0.428	0.096	.

4.2.3. Shannon's diversity index

The GLMM using a zero-inflated Tweedie distribution revealed a significant negative effect of slope on the Shannon index, indicating that steeper slopes support lower vegetation diversity. South-facing cliffs had significantly lower diversity than north-facing cliffs, with the difference consistent across the microtopography gradient. While microtopography and climbing intensity had no significant main effects, their interaction was important. In particular, in areas with low climbing intensity, vegetation diversity increased significantly with microtopography. No such relationship was found in the unclimbed plots (tab.3, fig.8). The model explained a moderate proportion of variance in diversity patterns ($R^2_{\text{marginal}} = 0.337$, $R^2_{\text{conditional}} = 0.575$).

Similar patterns were found for the Simpson index, reported in the Appendix (tab. A7).

Table 3: Summary of the fixed effects from the generalised linear mixed model (GLMM) with zero-inflated Tweedie distribution testing the effects of climbing and abiotic factors on the Shannon index per subplot on cliffs. Displayed are the estimated coefficients, p-values, and significance levels for the predictors: $p < 0.1$ (.), $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***).

Predictor	Estimate	p-value	Significance
Intercept	0.439	0.002	**
Microtopography	-0.027	0.657	
Slope	-0.175	0.010	**
Aspect (north/south)	-0.321	0.024	*
Low climbing intensity	-0.126	0.304	
Unclimbed intensity	0.054	0.731	
Microtopography x Low climbing	0.305	< 0.001	***
Microtopography x Unclimbed	-0.175	0.203	

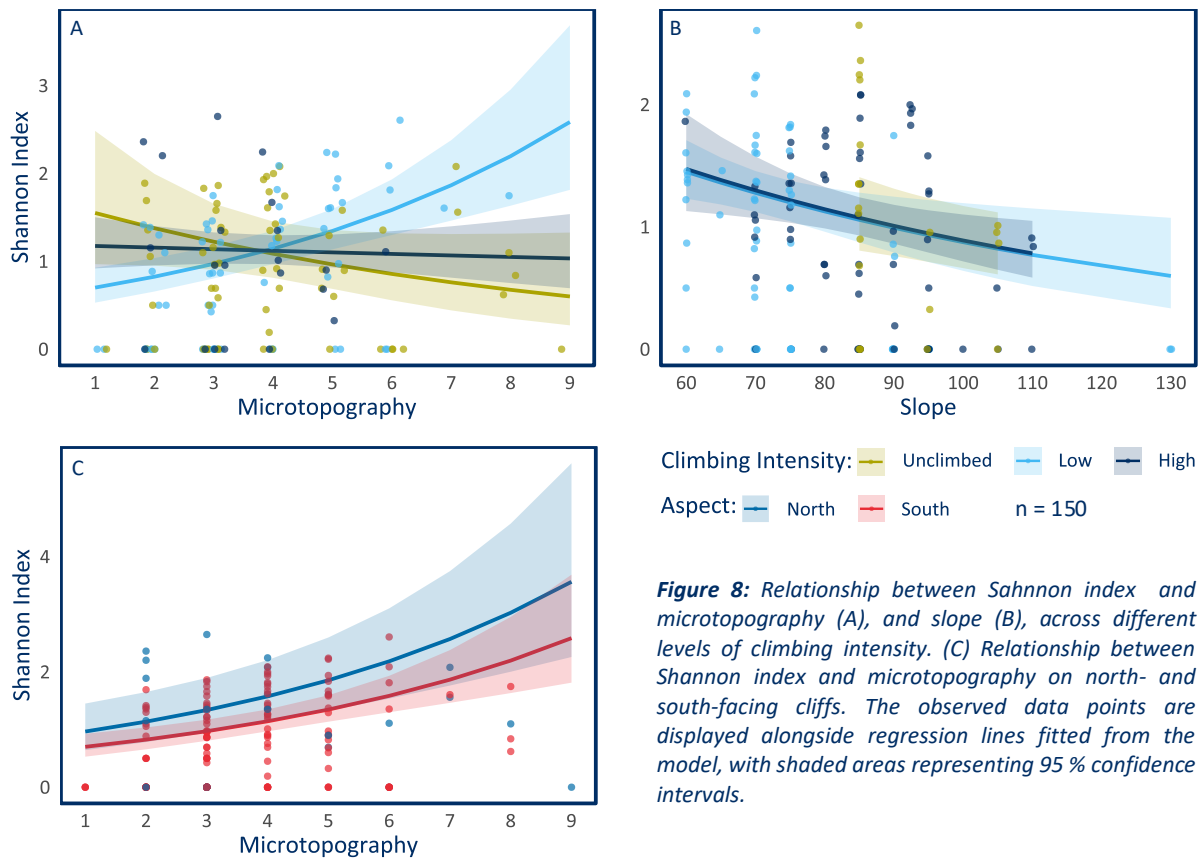


Figure 8: Relationship between Shannon index and microtopography (A), and slope (B), across different levels of climbing intensity. (C) Relationship between Shannon index and microtopography on north- and south-facing cliffs. The observed data points are displayed alongside regression lines fitted from the model, with shaded areas representing 95 % confidence intervals.

4.2.4. Red list species

Climbing intensity did not significantly affect red list species richness per subplot, as indicated by the negative binomial generalised linear mixed model (GLMM), with no significant differences between high, low and unclimbed plots (tab. 4). Most of the variation was explained by the random effects, with fixed effects alone accounting for little variation ($R^2_{\text{marginal}} = 0.056$, $R^2_{\text{conditional}} = 0.593$).

Table 4: Summary of the fixed effects from the negative binomial generalised linear mixed models (GLMM) testing the effect of climbing on red list species richness per subplot on cliffs. Displayed are the estimated coefficients, p-values, and significance levels for the predictors $p < 0.1$ (.), $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***).

Predictor	Estimate	p-value	Significance
Intercept	-1.589	< 0.001	***
Low climbing intensity	-0.558	0.348	
Unclimbed intensity	0.664	0.421	

4.2.5. Plant strategies

The linear model revealed significant differences in community-weighted mean (CWM) values among the three Grime plant strategies. Stress-tolerant species exhibited the highest values, followed by competitive species, whereas ruderal species had the lowest (fig. 9, tab. 5). All pairwise differences were statistically significant (Tukey-adjusted $p < 0.001$). The model explained a small amount of variation ($R^2 = 0.158$).

Generalized linear mixed models with a zero-inflated Tweedie distribution revealed that climbing and abiotic factors affected each plant strategy differently (tab. 5). The competitive strategy (C) showed significantly higher community-weighted mean (CWM) values in unclimbed and south-facing plots (fig. 10A-B). For the stress-tolerant strategy (S), slope had a significant positive effect, with steeper cliffs supporting higher CWM

values (fig. 10C). In contrast, the ruderal strategy (R) was strongly influenced by climbing intensity and abiotic factors. CWM values were significantly lower in unclimbed areas compared to highly climbed cliffs, while low climbing intensity plots did not differ significantly from highly climbed ones. Additionally, ruderal CWM values were significantly lower on south-facing cliffs, decreased with increasing microtopographic heterogeneity, and increased with slope (fig. 10D-E). Variation explained by fixed effects and full models varied by strategy, highest for ruderal, then competitive, lowest for stress-tolerant (tab. 5).

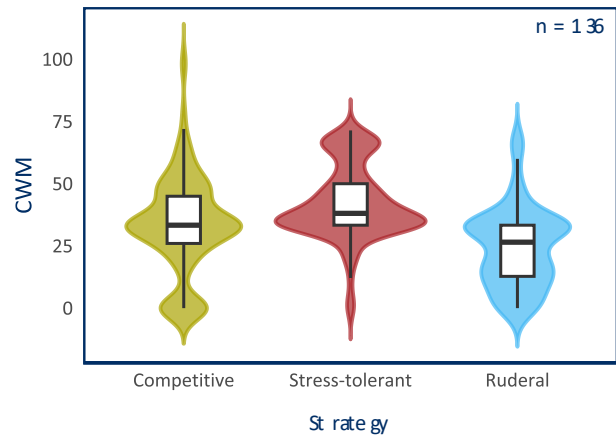


Figure 9: Violin and boxplots combined to show both distribution and summary statistics of community-weighted mean (CWM) values across the three plant strategies (competitive, stress-tolerant, ruderal).

Table 5: Community-weighted means (CWM) of Grime's plant strategies.

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

Middle panel: 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), and significance levels of the predictors: < 0.1 (.), $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***).

Bottom panel: Marginal and conditional R^2 values from the GLMMs indicating the proportion of variance explained by fixed effects and by both fixed and random effects, respectively.

	Competitive (C)	Stress-tolerant (S)	Ruderal (R)
LM estimate	33.313	8.941	-8.881
CWM (emmean)	33.3	42.3	24.4
Tukey-adjusted p-value	< 0.001***	< 0.001***	< 0.001***
Predictor			
Intercept	3.134 ($p < 0.001$) ***	3.744 ($p < 0.001$) ***	3.015 ($p < 0.001$) ***
Microtopography	0.048 (0.164)	0.004 ($p = 0.914$)	-0.173 ($p = 0.007$) **
Slope	-0.052 (0.331)	0.072 ($p = 0.040$) *	0.144 ($p = 0.027$) *
Aspect (north/south)	0.393 ($p = 0.010$) **	0.063 ($p = 0.606$)	-1.107 ($p < 0.001$) ***
Low climbing intensity	0.170 (0.184)	-0.026 ($p = 0.830$)	0.219 ($p = 0.106$)
Unclimbed intensity	0.400 ($p = 0.004$) **	-0.093 ($p = 0.423$)	-1.229 ($p < 0.001$) ***
R²			
Marginal	0.205	0.050	0.330
Conditional	0.448	0.123	0.400

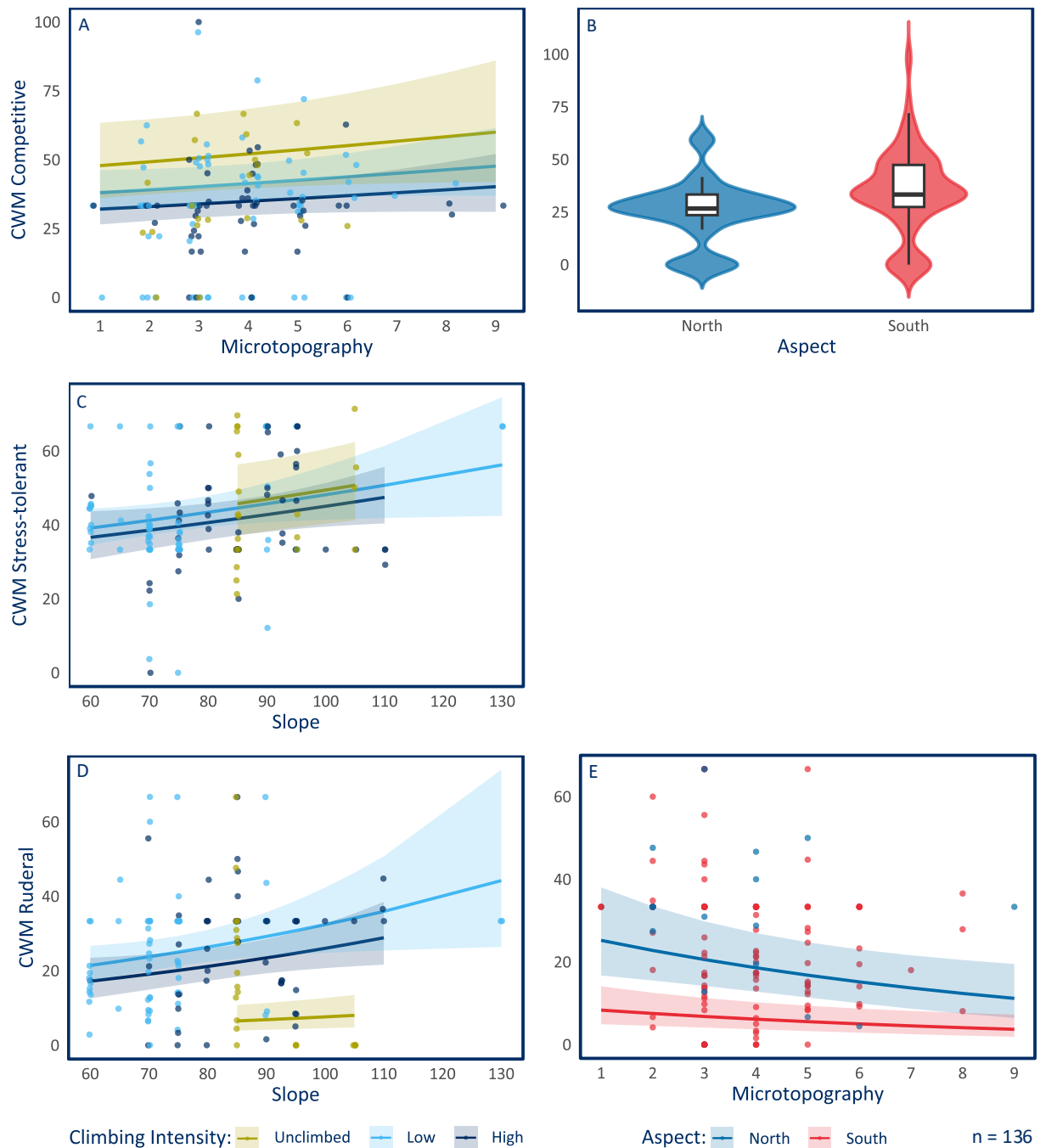


Figure 10: Effects of climbing intensity and abiotic cliff features on the community-weighted mean (CWM) of Grime plant strategies.

(A) Competitive strategy along the microtopography gradient across different levels of climbing intensity.

(B) Competitive strategy distribution on north- and south-facing cliffs, violin and boxplot combined.

(C) Stress-tolerant strategy plotted against slope across different levels of climbing intensity.

(D) Ruderal strategy plotted against slope across different levels of climbing intensity.

(E) Ruderal strategy plotted against microtopography across north and south-facing cliffs.

The observed data points are displayed alongside regression lines fitted from models, with shaded areas representing 95 % confidence intervals.

4.2.6. pH affinity

The generalized linear mixed model (GLMM) with a Tweedie distribution revealed a small but significant positive effect of slope on the community-weighted mean (CWM) of pH affinity. In contrast, microtopography had no significant effect. Climbing intensity showed a small, marginally non-significant trend, with slightly higher CWM values in unclimbed and low-intensity plots compared to high-intensity plots. However, overlapping confidence intervals indicate that climbing intensity does not meaningfully affected the pH affinity (fig. 11, tab. 6). The model explained a moderate proportion of the total variation ($R^2_{\text{conditional}} = 0.239$), while fixed effects alone explained a smaller proportion ($R^2_{\text{marginal}} = 0.083$).

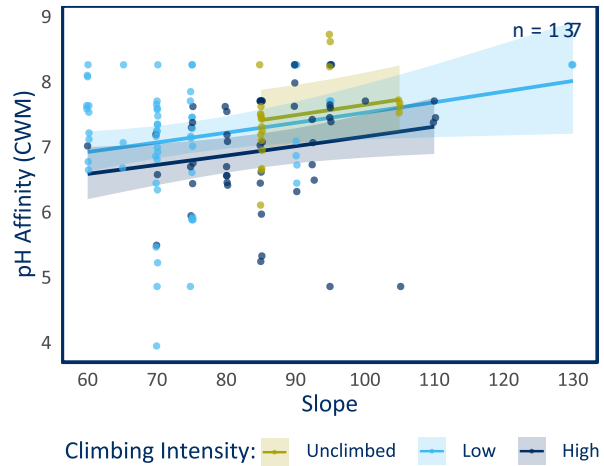


Figure 11: Relationship between slope and community-weighted mean of pH affinity and slope across different levels of climbing intensity. The observed data points are displayed alongside regression lines fitted from the model, with shaded areas representing 95 % confidence intervals.

Table 6: Summary of the fixed effects from the generalised linear mixed model (GLMM) with Tweedie distribution testing the effects of climbing and abiotic factors on community-weighted mean for pH affinity per subplot on cliffs. Displayed are the estimated coefficients, p-values, and significance levels for the predictors: < 0.1 (.), $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***).

Predictor	Estimate	p-value	Significance
Intercept	1.930	< 0.001	***
Microtopography	0.003	0.791	
Slope	0.029	0.028	*
Low climbing intensity	0.050	0.067	.
Unclimbed intensity	0.066	0.072	.

4.2.7. Temperature affinity

The full generalised linear mixed model using Tweedie distribution showed a significant effect of climbing on community-weighted mean (CWM) of temperature affinity (fig. 12, tab. 7). Unclimbed plots exhibited higher CWM values compared to highly climbed plots, while low-intensity plots showed a similar but non-significant trend. Post hoc

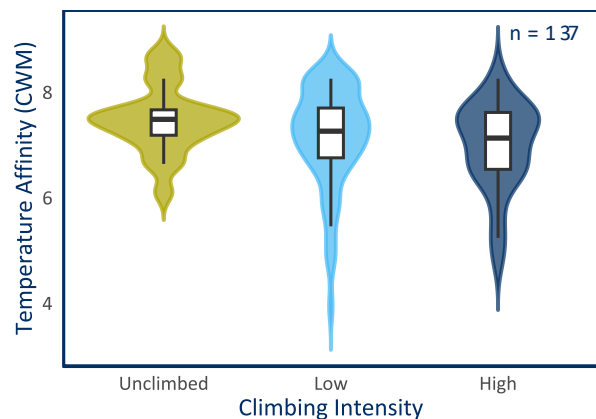


Figure 12: Violin and boxplots combined to show both distribution and summary statistics of community-weighted mean (CWM) values for EIVE temperature affinity across different levels of climbing intensity.

comparisons, including p-values, are reported in the Appendix (tab. A3) and confirmed that only the difference between high and unclimbed plots was statistically significant. No significant effect of aspect (north vs. south-facing cliffs) on temperature affinity was detected. The model accounted for a moderate amount of total of variation ($R^2_{\text{conditional}} = 0.207$) with fixed effects explaining only a small proportion ($R^2_{\text{marginal}} = 0.054$). Similar results were found in the two submodels: one restricted to south-facing cliffs to assess the robustness of the climbing intensity effect, and one limited to climbed plots to test for the effect of aspect (Appendix, tab. A4 and A5).

Table 7: Summary of the fixed effects from the generalised linear mixed model (GLMM) with a Tweedie distribution testing the effects of climbing and abiotic factors on CWM for temperature affinity per subplot on cliffs. Displayed are the estimated coefficients, p-values, and significance levels for the predictors: < 0.1 (.), $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***).

Predictor	Estimate	p-value	Significance
Intercept	1.986	< 0.001	***
Aspect (north/south)	0.058	0.192	
Low climbing intensity	0.021	0.422	
Unclimbed intensity	0.099	0.016	*

4.3. Microclimate temperatures of north- and south-facing cliffs

A linear mixed model (LMM) revealed that temperature differences between north- and south-facing plots varied significantly across seasons. South-facing plots exhibited consistently higher temperatures than north-facing ones, with a significant interaction indicating that the magnitude of this difference depended on the season (tab. 8, fig. 13, Appendix tab. A6). The contrast was most pronounced and highly significant in summer, moderately significant in spring and fall, and small and non-significant in winter. The model explained a large proportion of the variation ($R^2_{\text{marginal}} = 0.718$, $R^2_{\text{conditional}} = 0.994$).

Table 8: Summary of linear mixed model (LMM) analysis of daily mean 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 (.), $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***).

Season	Emmean north (°C)	Emmean 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	

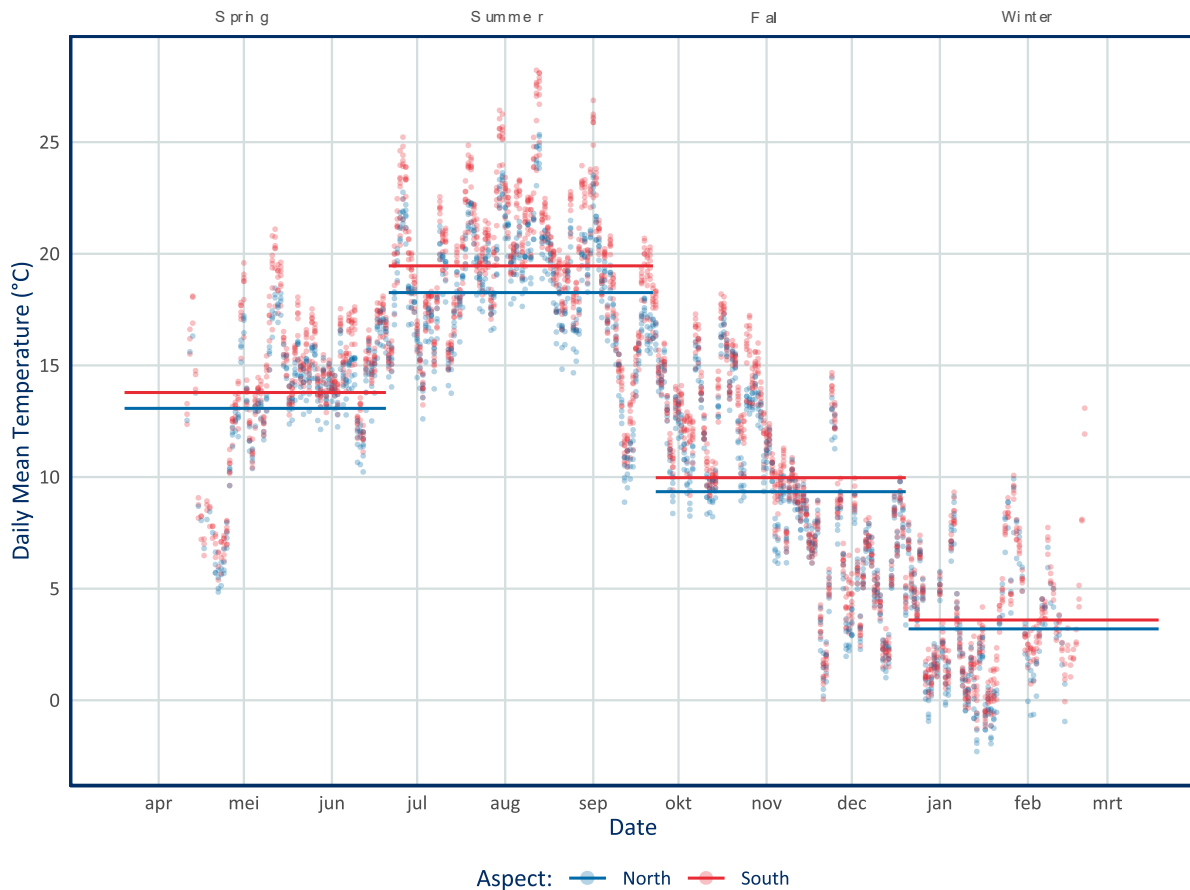


Figure 13: Daily mean microclimate temperature over a time span of nearly one year (April 2024-February 2025) for north (blue) and south (red) faces. Dots represent raw daily mean temperature; solid lines show estimated marginal means based on the linear mixed interaction model between aspect and season.

5. Discussion

5.1. Effects of rock climbing as a disturbance

The observed species richness patterns support the Intermediate Disturbance Hypothesis (Connell, 1978; Fox, 1981; Graham & Duda, 2011), which posits that diversity peaks at intermediate disturbance levels. In this study, species richness was highest at low climbing intensity level combined with high microtopographic heterogeneity, while both unclimbed and high intensively climbed areas exhibited lower diversity.

In unclimbed areas, low disturbance levels may allow competitive exclusion, favouring competitive species and reducing diversity. This is reflected by the higher community-weighted means (CWM) for competitive strategy in unclimbed areas with species like *Fraxinus excelsior* L., *Clematis vitalba* L., *Sambucus nigra* L., *Centaurea scabiosa* L., and *Seseli libanotis* (L.) Koch, all exhibiting strong competitive traits (Grime, 1977; Ivanova & Zolotova, 2023). In contrast, climbed areas showed lower CWM values for competitive strategy and higher for

ruderal strategy with plants such as *Asplenium trichomanes* L., *Geranium robertianum* L., and *Saxifraga tridactylites* L., which thrive under frequent disturbance (Grime, 1977; Ivanova & Zolotova, 2023). These patterns suggest that climbing inhibits competitive dominance and filters for ruderal traits. At intermediate disturbance levels, i.e. low climbing intensity in this study, competitive exclusion is reduced without severe habitat degradation, allowing coexistence of a broader set of species (Graham & Duda, 2011). Across all conditions, stress-tolerant strategies maintained high CWMs, confirming that cliff environments impose strong abiotic stress on plant communities (Larson et al., 2000).

No significant effect of climbing was found on the richness of red list species (*Liste Rouge de La Flore de Wallonie*, n.d.; *Liste-Especies-Vegetales-Protegees-Wallonie-201202 .Pdf*, n.d.). The six observed red list species (*Festuca pallens* Host, *Lactuca perennis* L., *Scabiosa columbaria* L., *Melampyrum arvense* L., *Hieracium glaucinum* Jord., and *Thymus praecox* Opiz) were dominantly stress-tolerant plants and not especially vulnerable for disturbance (Ivanova & Zolotova, 2023).

Finally, no significant effect of climbing was detected on pH affinity, suggesting that climbing chalk does not strongly altered cliff plant communities in Freyr. This is likely due to limestone's natural alkalinity buffering capacity (Hepenstrick et al., 2020; Newton et al., 2012). The slight positive relationship between slope and pH affinity may reflect reduced rainfall wash-off on steeper slopes, or increased chalk use on more physically demanding routes. Contrary to expectations, no relationship was found between microtopography and pH affinity, although surface heterogeneity was hypothesised to promote local chalk accumulation (Hepenstrick et al., 2020).

5.2. Influence of abiotic cliff factors on vegetation

Microtopography increased species richness and total cover. On smooth cliff surfaces, space limits plant establishment, while higher microtopography provides microhabitats with soil, nutrients, moisture, and propagule accumulation (Kuntz & Larson, 2006b, 2006a; Larson et al., 2000), supporting the habitat heterogeneity hypothesis. Environmental complexity promotes species coexistence through niche differentiation, as species with differing requirements can exploit varying conditions (Graham & Duda, 2011; Stein et al., 2014). Richness followed a bell-shaped curve in relation to microtopography, suggesting a threshold beyond which

competitive exclusion may reduce diversity—though community-weighted mean values (CWM) for competitive strategy did not increase.

Slope acted as a strong environmental filter. Steeper cliffs had significantly lower richness, cover, and diversity, likely due to gravitational instability, low water retention, soil and nutrient scarcity (Bartlett et al., 1990; Clark & Hessler, 2015; Larson et al., 2000). CWMs for ruderal and stress-tolerant strategies increased with slope, consistent with the expectation that steep, harsh environments favour disturbance- and stress-adapted species (Kraft et al., 2015).

Aspect strongly influenced the microclimate of cliffs, which may shape their vegetation structure. However, in this study, species richness did not significantly differ between north and south-facing cliffs, suggesting that both aspects offer sufficient habitat heterogeneity and appropriate conditions for species survival. In contrast, vegetation cover and Shannon index were significantly higher on north-facing cliffs, likely reflecting higher moisture availability. Functional trait composition also differed between aspects: community-weighted means (CWM) for competitive strategy were higher on south-facing cliffs, while ruderal species were more abundant on north-facing cliffs. Stress-tolerance strategy showed no significant differences between both aspects, indicating that cliffs create harsh conditions, despite their aspect. These patterns are reflected in the species composition. Competitive species such as *Fraxinus excelsior* L., *Sesleria caerulea* (L.) Ard., and *Clematis vitalba* L. were exclusively found on south-facing cliffs. In contrast, ruderal species including *Asplenium trichomanes* L., *Saxifraga tridactylites* L., and *Geranium robertianum* L. were more common on north-facing cliffs. The occurrence of these species likely contributes to the observed functional differences across aspects. Further research is needed to unravel the ecological mechanisms driving these patterns.

Contrary to the expectations that disturbance would favour warm-adapted species (Wiegmans et al., 2024), unclimbed areas showed significantly higher CWM values for temperature affinity. Moreover, despite measured temperature differences between aspects, no significant trait shift in temperature affinity was detected. This discrepancy currently lacks a clear ecological explanation. Two warm-adapted species, *Umbilicus rupestris* (Salisb.) Dandy and *Erysimum cheiri* (L.) Crantz, were exclusively found on unclimbed subplots and had relatively high EIVE values for temperature affinity (Dengler et al., 2023). However, these two

species alone are insufficient to explain the overall pattern. The pattern could be coincidental, and the sample too limited to draw general conclusions. Further species-level analysis is needed to better understand this unexpected result.

5.3. Evaluating methods to estimate climbing intensity

A central challenge of this study was quantifying climbing intensity in absence of empirical ascent data or safely accessible unclimbed control areas. The Climbing Use Index (CUI), which combines route star ratings and approach time, was developed in a large area (New River Gorge) with substantial variation in approaches (2-50 min on foot). In such settings, longer approach times would generally correspond to lower visitation. However, in Freyr, a compact site with more uniform approach times (8–18 min), the narrower CUI range limited its effectiveness as a climbing intensity proxy. The star ratings, either from guidebooks or 8a.nu, are a rather arbitrary estimate because they reflect climber's appreciation of a route 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. Moreover, neither the CUI or PCA-based ranking of routes was validated by local experts. According to the climbing community in Freyr, these estimates did not accurately reflect true patterns of use.

The PCA approach, based on different indicators, including 8a.nu logs and guidebook data—possibly underestimated the usage of easy routes and overestimated hard ones. 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 *pattiné* 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' (*Rochers de Freyr, Sport Climbing*, n.d.) and 27crag (*Freyr*, n.d.) would suffer the same issue.

While a continuous ranking of climbing intensity would retain more nuance, a categorical approach (unclimbed, low, high intensity) was ultimately more feasible and provided a more robust framework given the limitations of available proxies. Nevertheless, this method inevitably introduces a degree of simplification, potentially obscuring fine-scale variation in climbing pressure.

Expert-based assessments, used to assign categories, also made it possible to include routes with missing 8a.nu data –specifically four routes (36 subplots, 9 plots) that otherwise would have had to be excluded. The level of agreement among experts was moderate, indicating a shared –though not unanimous– understanding of local climbing patterns. They were therefore considered the most reliable source of local knowledge, although expert rankings carry inherent subjectivity and may be shaped by shared perceptions within the climbing community. Categorisation into broader classes also helped mitigate potential inconsistencies in 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 or movement sensors, but these approaches have to be implemented carefully to ethically handle privacy concerns.

5.4. Microclimate: patterns and limitations

Microclimate measurements confirmed that south-facing cliffs are generally warmer than north-facing cliffs, due to greater exposure to direct solar radiation as the sun moves through the day (Geiger et al., 1995). Temperature differences between aspects varied seasonally. In summer, with long photoperiods and high solar angles, south-facing cliffs receive intense midday radiation, while north-facing slopes receive only oblique, low-angle sunlight during mornings and evenings. Furthermore, higher vegetation cover on north faces may enhance evapotranspirative cooling, increasing contrast. In winter, low solar angles and cloud cover minimise the differences. Spring and autumn showed intermediate patterns, reflective to their transitional solar conditions (Geiger et al., 1995; Suggitt et al., 2011).

However, the measurement of microclimate faced several limitations. First, the dataset includes measurements from only 15 thermologgers, over approximately one year, and recorded temperature only. Furthermore, TOMST thermologgers have potential measurement errors due to radiative heat transfer (Maclean et al., 2021). They can warm up under direct solar radiation, which often occurs on exposed cliffs with minimal vegetation cover, potentially leading to overestimated temperature readings. Shielding the sensor reduces, but does not eliminate these errors. The bias is likely strongest on south-facing cliffs,

while errors are less pronounced in shaded zones such as north-facing cliffs. However, 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).

Additionally, the model was limited to a simple linear interaction between aspect and season. Future studies should expand sensor networks, apply IoT systems for efficient data collection—since reading out thermologgers on difficult-to-access cliff sites is time- and labour-intensive— and include additional variables such as radiation, humidity, and wind (De Frenne et al., 2025).

Finally, high-resolution UAV-based thermal imagery and digital elevation models (DEMs) could improve spatial modelling (Bramer et al., 2018). While DEMs are not yet available for Freyr, UAV mapping could enable integration with topography and vegetation. Comparative studies across MIREN Rocks sites worldwide could explore patterns across latitudes, elevation, and climates.

5.5. Methodological reflections and future recommendations

This study demonstrates the applicability of the standardised MIREN Rocks protocol. The use of permanently bolted routes ensures precise relocation of plots and creates a strong basis for future monitoring. However, the data is based on a single summer of fieldwork. To fully understand the ecological impact of sport climbing on cliff vegetation, long-term monitoring is essential. Continued observations would allow detection of delayed vegetation responses and their interaction with climate change and succession.

To better understand disturbance and succession processes, future research should combine observational studies with semi-experimental approaches. Monitoring before and after the development of new routes (Morales-Armijo et al., 2024) or conducting vegetation removal experiments could help define disturbance thresholds where biodiversity begins to decline.

While this study focused on cliff face vegetation, cliff ecosystems also include the edge and base, which host distinct vegetation communities and might be influenced differently by

climbing (Boggess et al., 2021; Larson et al., 2000). Including these zones too, would provide a more comprehensive understanding of climbing impacts on the cliff ecosystem.

In addition, expanding and refining abiotic measurements is crucial. As discussed above, fine-scale microclimate mapping using UAV-derived digital elevation models (DEMs) would improve microhabitat understanding. Furthermore, direct pH measurements on cliff surfaces could better assess chemical disturbance by climbing chalk, particularly across different rock types. Moreover, given the importance of microtopography, it is also essential to quantify soil presence and composition on cliff faces to understand plant establishment.

While this study offered detailed local insights, broader comparisons are essential to unravel patterns across regions. Applying the standardised MIREN Rocks survey protocol (*MIREN Rock Survey Protocol*, n.d.) across the growing network will enable consistent international data. In particular, comparative studies should include cliffs under different climates, rock types, and management regimes. For instance, Freyr sees limited vegetation removal, unlike other sites with intensive annual cleaning. Furthermore, research should explore whether climbers choose naturally sparse routes or if vegetation was lost through climbing (Boggess et al., 2021). Additionally, comparing natural cliffs with repurposed quarries may reveal further ecological differences related to structure and management.

Expanding research across time, environmental gradients, and geographical space, is essential for the formulation of recommendations for sustainable climbing practices and ecological conservation strategies to protect and remain unique cliff ecosystems.

6. Conclusion

This study provides the first analysis of climbing impacts on Freyr's cliff vegetation. Species richness peaked at low climbing intensity and high microtopography, supporting the intermediate disturbance hypothesis. Climbing caused a functional shift towards ruderal strategies. Abiotic cliff features, particularly microtopography and slope, influenced vegetation by determining the availability of microsites. Pioneering in-situ microclimate measurements revealed strong seasonal contrasts between warmer south- and cooler north-facing cliffs, most pronounced in summer. The results highlight the complex interplay between environmental characteristics and disturbance. Further research is essential for sustainable climbing and conservation of these biodiverse and vulnerable ecosystems.

7. References

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8. Appendix

Table A1: Local climbing route names where vegetation was surveyed, ranked from highest to lowest climbing intensity based on the average expert evaluation. Climbing grade of each route is also showed.

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

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

Table A3: Tukey post hoc comparisons of climbing intensity levels for community-weighted mean (CWM) of temperature affinity. Results are based on a generalised linear mixed model (GLMM) with a Tweedie distribution, testing the effects of climbing intensity and abiotic factors on temperature affinity. The table presents estimated differences between climbing levels (on the log scale), associated p-values, and significance levels: < 0.1 (.), $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***)

Comparison	Estimate (Log scale)	p-value	Significance
Unclimbed - Low	0.078	0.164	
Unclimbed - High	0.099	0.0433	*
Low – High	0.021	0.706	

Table A4: Summary of the fixed effects from the generalised linear mixed model (GLMM) with a Tweedie distribution, including only climbed subplots. This submodel tests the effect of aspect (north vs. south) on the community-weighted mean (CWM) of temperature affinity. Displayed are the estimated coefficients, p-values, and significance levels: < 0.1 (.), $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***). $R^2_{\text{conditional}} = 0.100$, $R^2_{\text{marginal}} = 0.004$.

Predictor	Estimate	p-value	Significance
Intercept	1.922	< 0.001	***
Aspect (north/south)	0.035	0.568	

Table A5: Summary of the fixed effects from the generalised linear mixed model (GLMM) with a Tweedie distribution, including only south-facing subplots. This submodel tests the effect of climbing intensity on the community-weighted mean (CWM) of temperature affinity. Displayed are the estimated coefficients, p-values, and significance levels: < 0.1 (.), $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***). $R^2_{\text{conditional}} = 0.181$, $R^2_{\text{marginal}} = 0.058$.

Predictor	Estimate	p-value	Significance
Intercept	1.942	< 0.001	***
Low climbing intensity	0.025	0.367	
Unclimbed intensity	0.124	0.014	*

Table A6: Summary of fixed effects from the linear mixed-effects model (LMM) testing the influence of aspect (north vs. south), season, and their interaction on daily mean microclimate temperature on cliffs. Displayed are the estimated coefficients, p-values, and significance levels for the predictors: < 0.1 (.), $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***).

Predictor	Estimate	p-value	Significance
Intercept (Spring, north)	13.075	< 0.001	***
Summer x north	5.187	< 0.001	***
Fall x north	-3.731	< 0.001	***
Winter x north	-9.878	< 0.001	***
Spring x south	0.710	0.018	*
Summer x south	0.487	< 0.001	***
Fall x south	-0.084	0.067	.
Winter x south	-0.312	< 0.001	***

A7. Simpson's diversity index

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 ($R^2_{\text{marginal}} = 0.054$, $R^2_{\text{conditional}} = 0.078$). 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 x Low climbing	0.582	< 0.001	***
Microtopography x Unclimbed	-0.496	0.095	.

