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**Changes of Plant Diversity and Composition over the Past 22 Years Assessed with the
Z9 Data of the Swiss Biodiversity Monitoring (BDM)**

Bachelor Thesis

by
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Bachelor's degree programme in Applied Digital Life Sciences

Submission Date: 3rd July 2025
Specialisation: Digital Environment

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Abstract

Understanding long-term biodiversity dynamics is crucial for assessing ecosystem responses to global change. This study investigates changes in vascular plant diversity and community composition in Switzerland over the past 22 years (2001–2023) based on the Z9 indicator dataset of the Swiss Biodiversity Monitoring programme (BDM). Drawing on more than 6,200 vegetation surveys from 10 m² plots across all major land-use types, biogeographic regions, and elevation zones, temporal trends in species richness, mean ecological indicator values, and species occurrence frequencies were assessed.

Linear mixed-effects models reveal a modest but significant increase in national plant species richness, with stronger gains in the Central Plateau, high alpine zones, and extensively managed grasslands. In contrast, forests, settlements, and mid-elevation areas show little or no change. Mean ecological indicator values indicate consistent shifts toward thermophilic and drought-tolerant plant assemblages, suggesting climate warming and decrease in moisture availability. At the species level, significant increases in occurrence frequency were observed for 139 taxa, while 82 taxa declined, suggesting ongoing compositional turnover and possible environmental filtering.

Together, these findings highlight strong spatial contrasts and suggest that plant diversity in Switzerland may be recovering in some regions. Gains in species richness are likely driven by milder winters, longer growing seasons, and land-use changes such as the expansion of biodiversity promotion areas. While high-elevation and extensively managed grasslands show positive trends, stagnation in mid-elevation and urban areas points to persistent ecological constraints. These patterns offer valuable insights for future conservation and monitoring strategies under global change.

Table of Contents

Introduction	4
Materials and methods	5
BDM Indicator Z9 dataset	5
Data preparation	6
Calculation of community data	7
Statistical analyses	8
Results	10
Species richness.....	10
Mean ecological indicator values	13
Species level.....	14
Discussion	15
Species richness.....	15
Mean ecological indicator values	17
Species level.....	17
Conclusion	18
Acknowledgements	19
References.....	20
Appendix	22
Appendix 1: Description of 2000_Z9_Kopfdaten.xlsx	22
Appendix 2: Description of 2000_Z9_Pflanzen.xlsx	22
Appendix 3: Variable Definitions in BDM Z9 Files	23
Appendix 4: Coding of CSR-strategies.....	24
Appendix 5: Decreasing Species from 2001-2023	25
Appendix 6: Increasing Species from 2001 to 2023	27

Introduction

Biodiversity loss is one of the most pressing environmental challenges of the 21st century, with far-reaching consequences for ecosystem functioning, human wellbeing, and global sustainability (IPBES, 2019). Among the many facets of biodiversity, vascular plant species richness plays a key role as an indicator of ecosystem integrity and is widely used to assess changes in terrestrial environments over time (Measuring Biodiversity, 2022).

To better understand how biodiversity is changing in the face of global pressures, it is essential to examine these dynamics at national and regional scales. In Switzerland, plant communities are shaped by various drivers. Land-use intensification, abandonment of traditional agricultural practices, urban expansion, and forestry have substantially altered the extent and quality of natural and semi-natural habitats (Lachat et al., 2010). At the same time, climate change, particularly in Alpine regions, has led to shifts in temperature and precipitation regimes, influencing species distributions and community composition (Steinbauer et al., 2018). These interacting drivers are expected to change biodiversity patterns across the country's varied landscapes.

These conditions make Switzerland an ideal setting to investigate how vascular plant diversity is responding to multiple global change drivers across space and time - provided that adequate long-term data are available. The systematic assessment of such long-term biodiversity trends requires robust monitoring data covering large spatial and temporal scales. The Swiss Biodiversity Monitoring Programme (BDM), established in 2001, provides such a well maintained dataset by repeatedly surveying vascular plants and bryophytes on permanent sampling plots distributed across the entire country and across a wide range of habitats (BDM Coordination Office, 2014). The BDM indicator Z9 focuses on vascular plant and moss species richness recorded on 10 m² plots, providing a unique opportunity to assess temporal trends in species richness over more than two decades (BDM Coordination Office, 2014).

Several studies have utilised BDM Z9 data to analyse biodiversity trends in selected habitat types. For example, Häberlin and Dengler (2025) investigated changes in species richness and ecological indicator values in Swiss grasslands between 2001 and 2023, revealing evidence of thermophilisation and shifts in community composition (Häberlin & Dengler, 2025). Their work, however, focused exclusively on grasslands and did not extend to other major land-use types (Häberlin & Dengler, 2025).

While such studies provide valuable insights, a comprehensive analysis of plant diversity trends across the full range of land-use types, biogeographic regions, and elevation zones over the last 20 years covered by the Z9 dataset has not yet been published. This study expands on previous efforts by providing a national-scale assessment of vascular plant biodiversity dynamics across environmental gradients using BDM Z9 data from 2001 to 2023. It combines analyses of species richness, ecological indicator values, and species-specific trends to deliver an integrated picture of recent biodiversity change in Switzerland. Based on the BDM-Z9 data, a central aim of this study is therefore to quantify how vascular plant species richness has changed over time at the national scale and how these changes vary depending on environmental gradients such as land use, biogeographic region, and elevation.

In addition to species richness, the study investigates how community-level ecological indicator values have shifted over time. Finally, species-level analyses were conducted to explore which specific species show strong increases or declines over the monitoring period.

Answering these questions should provide a comprehensive overview of recent biodiversity dynamics in Swiss plant communities and help to better understand how multiple global change drivers interact across space and time. By combining analyses of species richness, ecological indicator values, and species-specific trends across Switzerland's diverse landscape, this study aims to deliver an integrated picture of recent plant community changes and support a better understanding of biodiversity responses to multiple global change drivers.

Materials and methods

BDM Indicator Z9 dataset

This study is based on the national Z9 dataset from the Swiss Biodiversity Monitoring programme (BDM), which quantifies vascular plant species richness in 10 m² circular plots distributed across Switzerland's main land-use types (BDM Coordination Office, 2014). Sampling is based on a fixed 5 × 5 km grid covering the entire country, with 1'650 terrestrial plots (Figure 1). In each grid cell, one plot is in a dominant land-use type and surveyed every five years using a rotating scheme. This staggered design, design in which approximately one fifth of the plots are surveyed each year, ensures consistent temporal comparisons while minimising the influence of short-term weather variability (BDM Coordination Office, 2014).



Figure 1: Locations BDM Z9 Plots across Switzerland and their land use type.

Field surveys follow standardised presence/absence protocols (BDM Coordination Office, 2014). Although species cover was estimated in later years, only presence data from 2001 to 2023 were used in this study. The small plot size was chosen to ensure clear land-use classification, facilitate detection of widespread species, and enable efficient, high-quality surveys (BDM Coordination Office, 2014). Aggregated across the national grid, these data provide robust estimates of mean alpha-diversity across major land-use types: Arable land, alpine pastures, non productive areas, settlements, forests, and grasslands. Repeated surveys allow detection of biodiversity trends related to land use, climate change, and agricultural policy (BDM Coordination Office, 2014).

Data preparation

Prior to statistical analysis, extensive data preparation was conducted to ensure consistency and reproducibility. Raw data files containing plot metadata, vascular plant observations, were imported and checked for completeness. Records missing essential information such as survey year or plot identifiers were excluded to avoid biases in temporal or spatial analyses. For vascular plants, all observations dated before 2001 were removed, as these correspond to pilot studies conducted under a different sampling regime. This step ensured that only data from the standardized monitoring period with consistent five-year resurvey intervals were included.

A central aspect of the preparation involved taxonomic harmonisation, which was critical for generating meaningful temporal trends. Over multi-decade timespans, species concepts and naming conventions often change, and different observers may apply taxon names inconsistently. Without harmonisation, these variations can introduce artificial gains or losses of species, obscuring real ecological patterns. To prevent this, all vascular plant names were matched to a national reference list. Subspecies, varieties, forms, and hybrids were aggregated to their corresponding species-level or aggregate concept. For example, all microspecies within the *Taraxacum officinale* complex were reassigned to a common aggregate. This ensured that trends reflect ecological rather than taxonomic turnover.

Following taxonomic harmonisation, the datasets were transformed into presence–absence matrices by plot and year. These matrices provided the basis for calculating species richness, and community-level trait metrics. By systematically aggregating and aligning taxonomic identities across time, the analysis was made robust to naming inconsistencies and compatible with trait datasets. All processing steps were scripted to ensure full transparency and reproducibility, with final outputs exported as cleaned CSV files for further analysis.

Calculation of community data

Species richness was calculated for each plot and survey year as the total number of unique vascular plants, species observed. Mean ecological indicator values were calculated to assess shifts in environmental conditions inferred from the plant community composition. Ecological indicator values were obtained from *Flora indicativa* (Landolt et al., 2010), which provides ordinal scores ranging from 1 to 5 for various environmental gradients such as temperature, light, moisture, reaction, nutrients, mowing tolerance, and hemeroby. Additionally, Grime's CSR strategy components (Grime, 1973) were incorporated as functional trait proxies. These components include competition, stress and ruderality and range from 0 to 3 and together, they always sum up to 3 (Appendix 4: Coding of CSR-strategies). Community-means (CMs) for each trait were then calculated for every plot with using function "functcomp" of the "FD" (Laliberté et al., 2023) package (unweighted by abundance, i.e. each species present contributes equally).

Since the taxon names in the BDM dataset differ slightly from those in (Landolt et al., 2010), taxonomic harmonisation was necessary. Species names were manually matched to the corresponding indicator taxa using a combination of fuzzy matching algorithms, expert corrections, and manual validation. When multiple sources of matching information were available, expert-validated matches were prioritized, followed by manually reviewed suggestions and automatic matches. Unmatched species were excluded from CM calculations for the corresponding trait. Community means for each plot and survey year were calculated using unweighted presence-absence data, thus reflecting the average ecological indicator value of the species present in the community. This approach enables detecting directional shifts in environmental preferences of the community, independent of species richness changes.

Statistical analyses

All statistical analyses were performed using R version 4.5.0 (R Core Team, 2025). The following significance levels were used throughout the study: *** $p < 0.001$, ** $p < 0.01$ and * $p < 0.05$. Data processing and statistical modelling were carried out using workflows based on the tidyverse package (Wickham et al., 2019) and a combination of linear and generalised linear mixed models. Visual inspections of diagnostic plots and residual simulations were used throughout to ensure that model assumptions were reasonably met. All plots were surveyed within a repeated sampling design, and models accounted for this with random effects on plot level.

To analyse temporal changes in species richness, linear mixed-effects models with a Gaussian error distribution were applied. The response variable was the number of unique vascular plant species recorded per 10 m² plot in a given survey year. The main predictor was time, expressed as a continuous variable (year_index) representing the number of years since 2000 (e.g. 2001 = 1). To account for repeated measurements on the same plots, a random intercept for plot ID (aID_STAO) was included in all models. A baseline model was first fitted to test the overall temporal trend in species richness across Switzerland. Building on this, several interaction models were specified to test whether temporal trends varied depending on key site characteristics. These included interactions between year and (i) the six main biogeographic regions (UFAM, 2022), (ii) dominant land use type, and (iii) elevation, modelled as categorical 400 m elevation bands (from 200 m to 3100 m). For each model, diagnostic checks of simulated residuals were performed using the DHARMA package (Hartig et al., 2024) to assess model validity. Group-wise predictions and marginal trends were visualised using functions from the ggeffects (Lüdtke, 2018) and emmeans packages (Lenth et al., 2025). Temporal slopes (year_index) from the interaction models were extracted per group using the emtrends() function and assessed for effect size and statistical significance.

This allowed the identification of regions, land-use types or elevation zones with steeper or weaker changes in species richness over time. In addition, and key statistics (year effects, significance) were summarised in a comparison table. For the elevation models, an additional Gamma GLMM with log-link was tested as a robustness check for skewed data, but the Gaussian model proved more appropriate.

To test whether the ecological affinities of plant communities have shifted over the monitoring period, we first constructed a presence–absence matrix (6 283 plots × 1 381 species) and a matching trait matrix containing mean ecological indicator values (EIVs) from Flora indicative (Landolt et al., 2010) for temperature, light, moisture, reaction, nutrients, hemeroby, mowing tolerance and Grime's C, S and R scores (Grime, 1973). These ecological indicators were merged with plot metadata and enriched with a continuous time index ($\text{year_index} = \text{year} - 2001$). For each trait, we fitted a Gaussian linear mixed-effects model of the form $\text{CM} \sim \text{year_index} + (1 \mid \text{plot})$ using `glmmTMB` (Brooks et al., 2017), thereby quantifying the annual change in community preference while accounting for repeated sampling of plots. Prior to modelling, records with missing values for the focal trait were omitted; on average > 6 250 plots per trait were retained. Model validity was evaluated with simulated residual diagnostics in `DHARMA` (Hartig et al., 2024). For each model, the estimated yearly change (slope), its standard error, and the corresponding p-value were extracted. Marginal trends and predictions were obtained using `emtrends()` from the `emmeans` package (Lenth et al., 2025) in combination with `ggemmeans()` from `ggeffects` (Lüdtke, 2018), to visualise temporal trajectories. Finally, all slope estimates were compiled into a summary table, annotated with significance levels, and rounded for reporting.

To assess species-specific trends in presence frequency over time, a logistic generalised linear mixed-effects model (GLMM) was fitted individually for each vascular plant taxon. The binary response variable indicated species presence or absence in each 10 m² survey plot, while the predictor variable was a continuous year index ($\text{year} - 2000$). Plot identity was included as a random intercept to account for repeated measures across years (Zuur et al., 2009). Species were only analysed if they occurred in at least ten plots and showed both presences and absences across the study period. This threshold was applied to ensure sufficient variation in the response variable, which is essential for reliable model convergence and meaningful estimation of temporal effects (Bolker et al., 2009). Species with consistently high or low occurrence rates (i.e., near-constant presence or absence) were excluded, as such cases typically result in separation issues or unstable coefficient estimates in logistic models (Bolker et al., 2009).

This modelling approach is appropriate for analysing presence/absence trends in ecological monitoring data, as GLMMs allow for binary responses while accounting for repeated measurements and hierarchical data structures (Bolker et al., 2009). By including plot identity as a random intercept, the model controls for non-independence among observations from the same location, which is essential for avoiding pseudoreplication (Bolker et al., 2009).

For each species, the slope coefficient of the fixed effect (year_index) was extracted along with the standard error and p-value. From the estimated slopes, we calculated the average annual relative change in occurrence probability (%). Species were assigned to significance categories based on their p-values, and trends were classified as increasing, decreasing, or non-significant. This analysis provides a species-level complement to the community-wide assessments, identifying taxa with particularly strong directional changes in distribution over time.

Results

Species richness

The linear mixed-effects model with year as the only fixed effect showed a significant increase in vascular plant species richness (Figure 2) across Switzerland from 2001 to 2023 ($\beta = 0.0585$, $p < 0.001$). Fixed effects explained 0.1% of the variance in species richness ($R^2m = 0.001$).

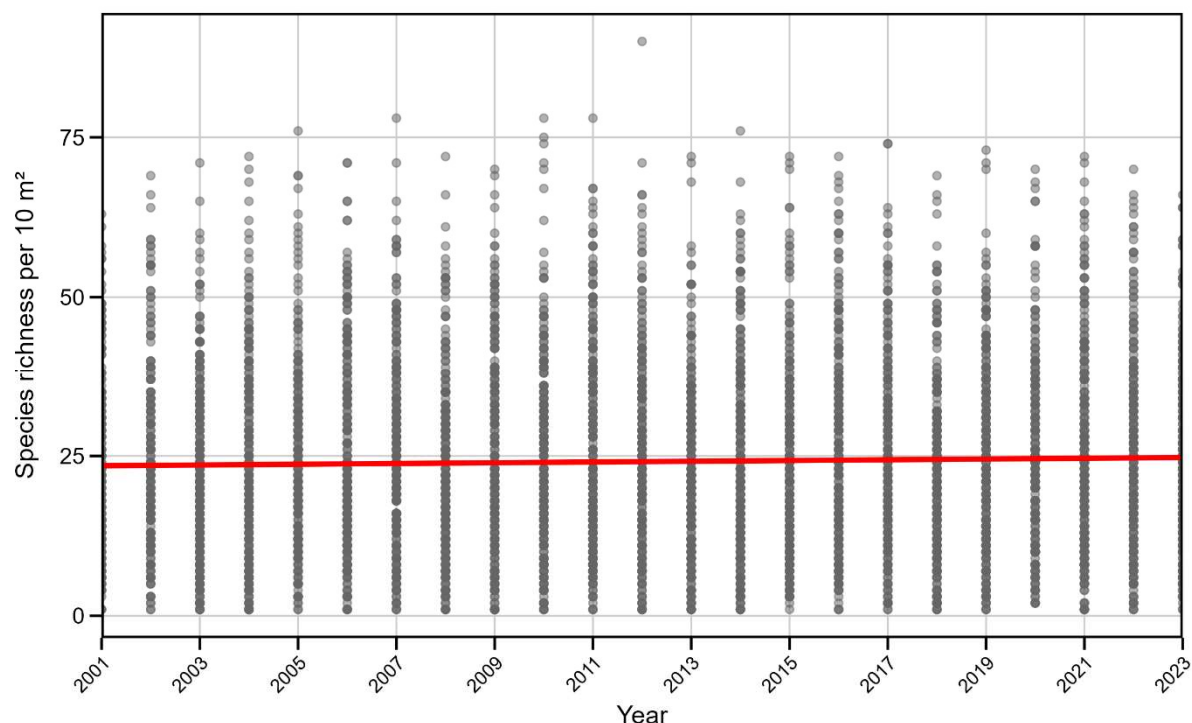


Figure 2: Trend Species richness 2001 - 2023 in Switzerland in this study. The grey dots represent the observations, the redline the fitted curve of the LMM.

When including an interaction between year and biogeographic region the interaction term was significant ($p = 0.0006$), indicating that temporal trends in species richness varied significantly between regions (Figure 3; Table 1). The strongest increases were observed in the Central Plateau and the Eastern Central Alps, while other regions showed weaker or non-significant changes. Fixed effects explained 12.1% of the variance in species richness ($R^2m = 0.121$).

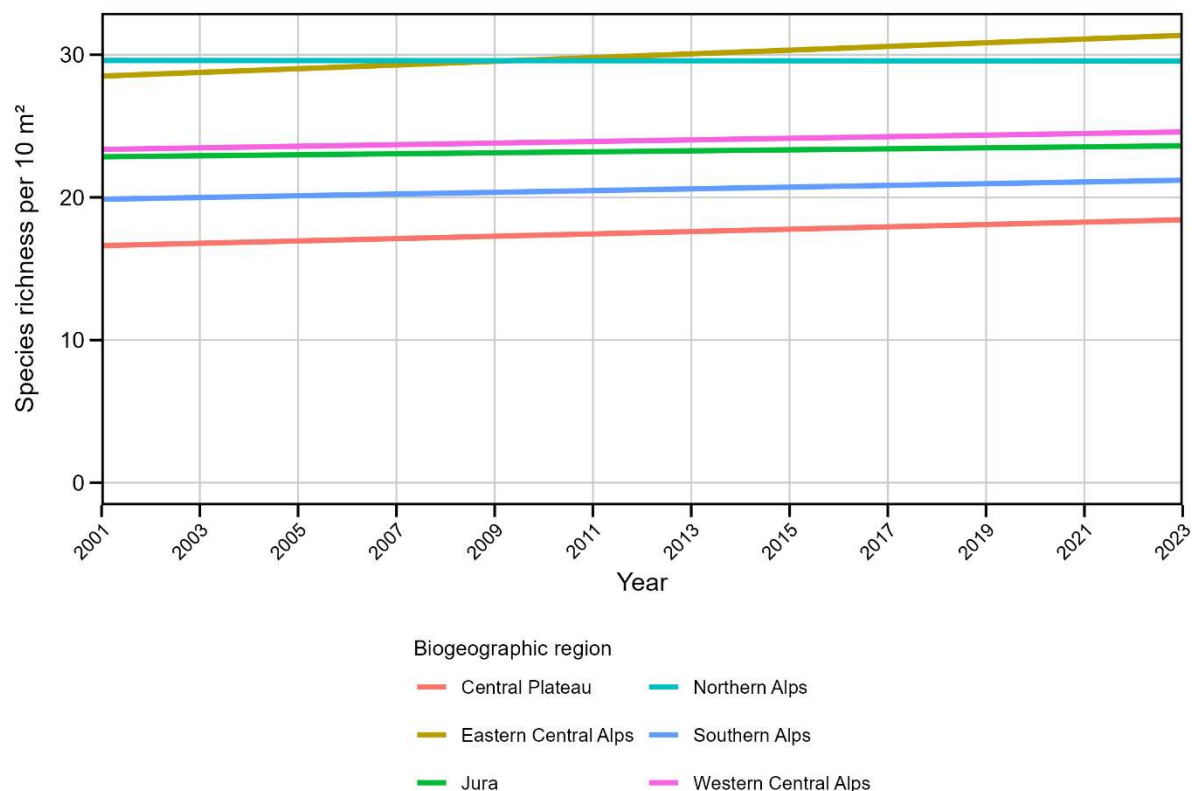


Figure 3: Temporal trends in vascular plant species richness from 2001 to 2023 in 10 m² permanent plots across Swiss biogeographic regions. Lines show linear model predictions.

Table 1: Estimated temporal trends in vascular plant species richness for different biogeographic regions between 2001 and 2023. Values represent linear trend coefficients (change per year) with 95% confidence intervals. A trend is considered significant if the confidence interval does not include zero.

Biographic Region	Trend	Lower CI	Upper CI	Significant
Northern Alps	-0.00196	-0.0390	0.0351	No
Southern Alps	0.06059	-0.0001	0.1213	No
Jura	0.03476	-0.0213	0.0908	No
Central Plateau	0.08234	0.0463	0.1184	Yes
Eastern Central Alps	0.13002	0.0838	0.1762	Yes
Western Central Alps	0.05575	-0.0060	0.1175	No

An interaction model with dominant land use type revealed clear differences in temporal trends among land use categories as shown in Figure 4 and Table 2. Species richness increased most strongly on unused land, alpine pastures, and meadows/pastures, while no significant change was detected in forest and settlement areas. The interaction was statistically significant overall ($p < 0.001$). Fixed effects explained 17.7% of the variance in species richness ($R^2m = 0.177$).

Table 2: Estimated temporal trends in vascular plant species richness for different land use types (HN classification) between 2001 and 2023. Values represent linear trend coefficients (change per year) with 95% confidence intervals. A trend is considered significant if the confidence interval does not include zero.

Land Use	Trend	Lower CI	Upper CI	Significant
Arable land	0.07470	0.0198	0.1296	Yes
Alpine pastures	0.14120	0.0774	0.2050	Yes
Non-productive areas	0.18210	0.1262	0.2380	Yes
Settlements	0.03460	-0.0513	0.1205	No
Forests	-0.02360	-0.0538	0.0066	No
Grasslands	0.08980	0.0528	0.1269	Yes

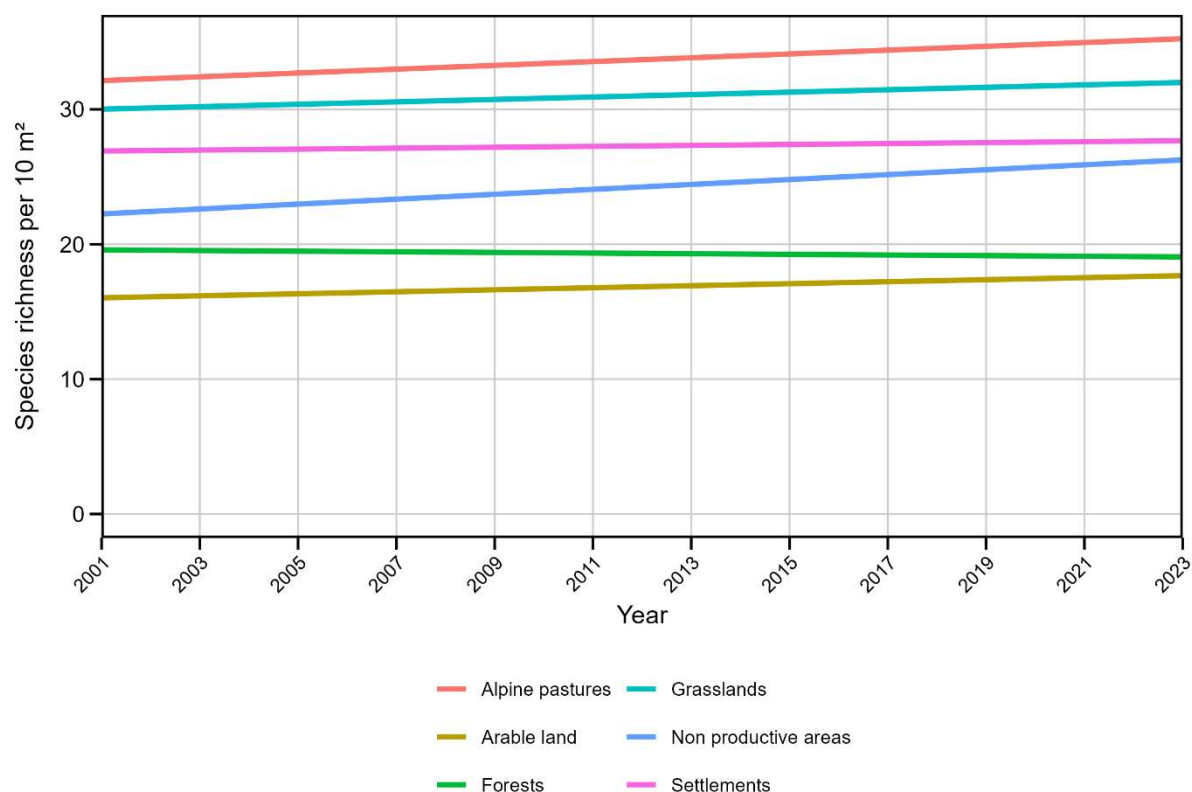


Figure 4: Temporal trends in vascular plant species richness from 2001 to 2023 across major land-use types. Lines show linear model predictions.

When using elevation bands, the model revealed a significant interaction between year and elevation ($p < 0.001$), indicating that temporal trends in species richness varied across elevation bands as shown in Figure 5. Species richness increased significantly in both lowland areas (200–1000 m) and high elevations above 1800 m, with the strongest trend observed in the 2200–2600 m band. In contrast, mid-elevation zones between 1000 and 1800 m showed no significant change. Fixed effects explained 13.9% of the variance in species richness ($R^2_m = 0.139$).

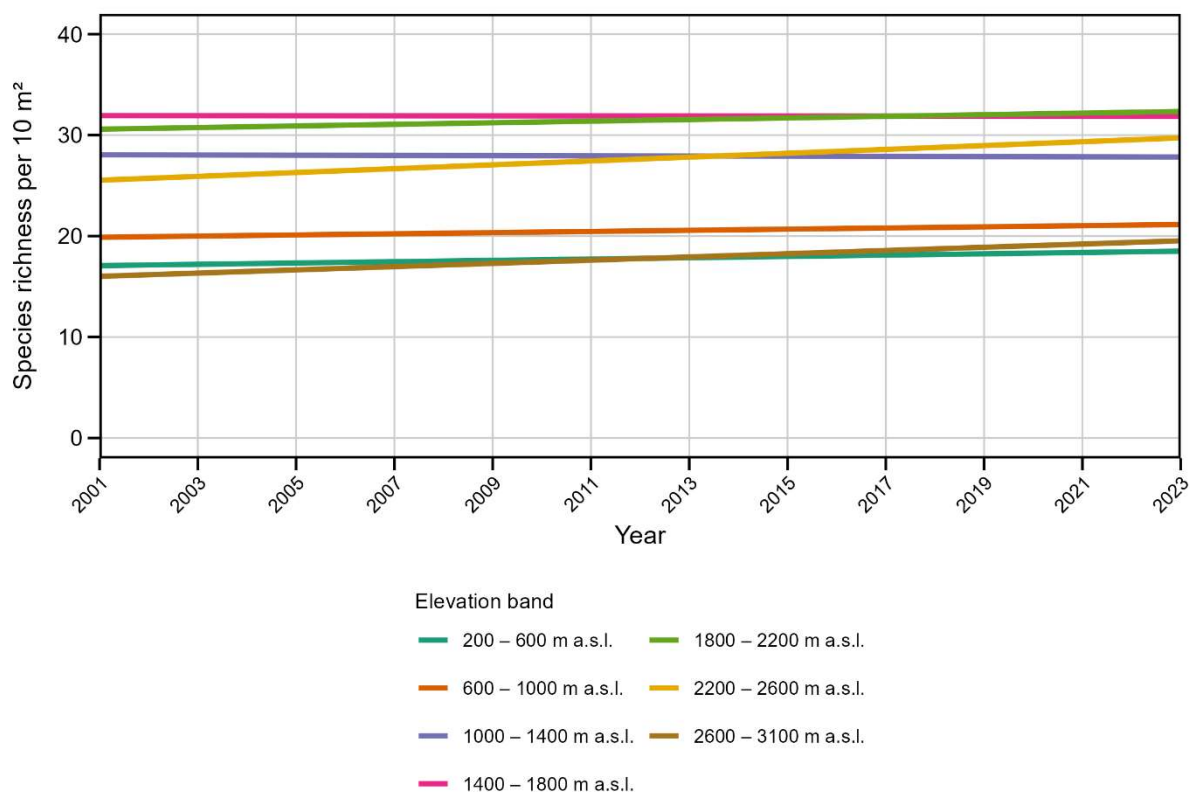


Figure 5: Temporal trends in vascular plant species richness from 2001 to 2023 across different elevation belts. Lines show linear model predictions.

Mean ecological indicator values

Temporal trends in mean ecological indicator values of vascular plants are summarised below and detailed in Table 3. Temperature preference and moisture showed significant positive and negative trends, respectively. Temperature indicator value increased by 0.00208 units per year ($p < 0.001$), while the moisture indicator value decreased by 0.00076 units per year ($p < 0.001$). Light declined slightly over time (-0.00077 units per year, $p = 0.006$), whereas hemeroby increased significantly by 0.00250 units per year ($p < 0.001$).

Several other traits also showed significant trends: The moving tolerance declined (-0.00141 per year, $p = 0.007$), the stress indicator decreased (-0.00132 , $p < 0.001$), and the ruderal increased (0.00107 , $p = 0.0013$). No significant temporal trends were found for reaction, nutrients, or the competitor scores.

Table 3: Temporal trends in mean ecological indicator values of vascular plants from 2001 to 2023.

Trait	Yearly Change	Std. Error	z-value	p-value	Significance
Temperature	+0.00208	0.00021	9.94	<0.001	***
Light	-0.00077	0.00028	-2.74	0.006	**
Moisture	-0.00076	0.00020	-3.77	<0.001	***
Reaction	-0.00009	0.00024	-0.39	0.696	n.s.
Nutrients	+0.00001	0.00024	0.06	0.955	n.s.
Hemeroby	+0.00250	0.00032	7.72	<0.001	***
Mowing Tolerance	-0.00141	0.00052	-2.69	0.007	**
Competitors	+0.00026	0.00029	0.89	0.372	n.s.
Stress	-0.00132	0.00022	-5.96	<0.001	***
Ruderals	0.001066	0.00033	3.21	0.001	**

Species level

Of the 1,381 vascular plant taxa included in the analysis, 876 species were successfully modelled. A total of 505 species were excluded due to low variation or fewer than 10 occurrences. Among the modelled species, 221 showed statistically significant temporal trends in their presence across the survey years 2001–2023 ($p < 0.05$), with 139 species increasing (Appendix 6: Increasing Species from 2001 to 2023) and 82 decreasing (Appendix 5: Decreasing Species from 2001–2023).

Out of the vascular plant species successfully modelled, several exhibited pronounced temporal trends in their occurrence between 2001 and 2023 as shown in (Figure 6: Estimated temporal trends in presence probability of the 20 most significantly changing vascular plant species in Switzerland (2001–2023). Bars represent the average yearly change in odds of occurrence (%), derived from model coefficients. The number of presence records per species is indicated in parentheses. (*) Asterisk denotes species for which the actual estimated change exceeded the plotting limits ($\pm 130\%$) and was truncated for visual clarity. Figure 6), which highlights the 10 strongest winners and losers based on the slope of presence–absence trends derived from logistic GLMMs. Notably, *Asplenium adiantum-nigrum*, *Bupleurum stellatum*, and *Salix hastata* showed the steepest positive trends, whereas *Mentha aquatica*, *Ranunculus flammula*, and *Asperula taurina* experienced the strongest declines.

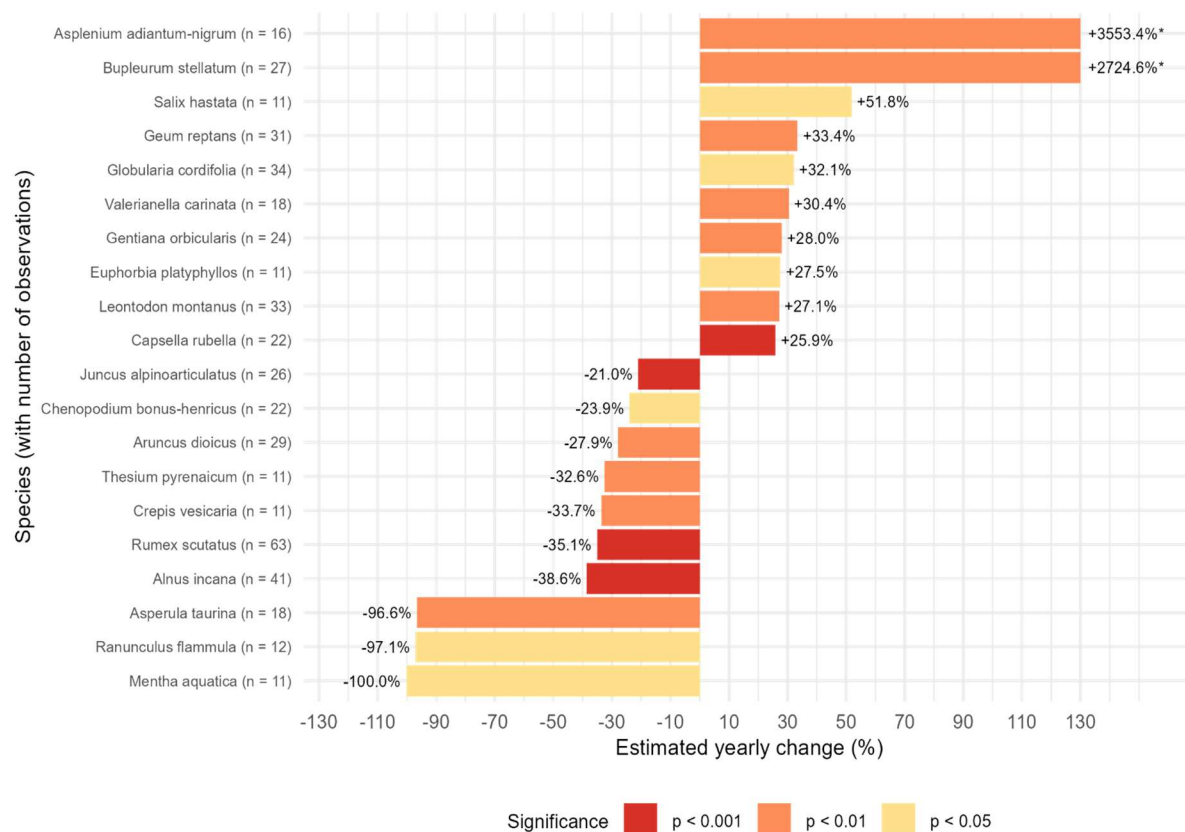


Figure 6: Estimated temporal trends in presence probability of the 20 most significantly changing vascular plant species in Switzerland (2001–2023). Bars represent the average yearly change in odds of occurrence (%), derived from model coefficients. The number of presence records per species is indicated in parentheses. (*) Asterisk denotes species for which the actual estimated change exceeded the plotting limits ($\pm 130\%$) and was truncated for visual clarity.

Discussion

Species richness

The observed nation-wide rise in vascular plant richness ($\approx +0.06$ species yr^{-1}) aligns with earlier assessments from the Swiss Biodiversity Monitoring (BDM): based on the 2005–2015 panel, a minor but statistically significant increase in the average number of vascular-plant species for Switzerland as a whole and, more specifically, for the Central Plateau has been noticed (Federal Office for the Environment (FOEN), 2016). Together, these findings indicate that the modest upswing detected in the present study has persisted for almost two decades, suggesting that large-scale drivers most plausibly milder winters, longer growing seasons and steady reductions in sulphur deposition continue to favour a gradual enrichment of common species at the 10 m^2 scale.

Yet the biogeographic interaction highlights pronounced spatial heterogeneity. The strongest gains occurred in the Central Plateau and the Eastern Central Alps, mirroring the BDM report (Federal Office for the Environment (FOEN), 2016) that singled out the Central Plateau for significant increases while noting far weaker trends in Jura and parts of the Alps. In the lowland agricultural matrix, recent agri-environmental schemes (e.g. Biodiversity Promotion Areas) have expanded extensively managed field margins and fallows, which are known to boost plot-scale diversity (Knop et al., 2006). Conversely, the alpine signal likely reflects ongoing thermophilisation: Long-term summit resurveys in the Swiss Alps (e.g. Piz Linard) document an accelerated influx of lower-montane species at high elevations since the 1980s consistent with the positive slope observed for the Eastern Central Alps in our dataset (Rumpf et al., 2018).

The separately modelled main land uses underscore management intensity as a key determinant of temporal change. Richness increased most on unused land, alpine pastures and extensively managed meadows, echoing evidence that moderate grazing or low fertiliser inputs maintain structurally heterogeneous swards and maximise α -diversity in Swiss alpine grasslands (Roth et al., 2014). By contrast, forests and settlements showed no detectable trend, matching FOEN's conclusion (Federal Office for the Environment (FOEN), 2016) that gains in forest deadwood and urban greening have so far translated into only marginal richness changes at 10 m² scale. The stagnation in built-up areas further supports recent national indicators showing that vegetation quality in settlements remains below that of other habitat types despite local greening projects. This may, in part, be due to ongoing urban densification, which can lead to the loss of older, ecologically valuable green spaces (Lezzi, 2018). However, densification does not necessarily reduce habitat quality in all cases, particularly when accompanied by targeted measures to integrate biodiversity-promoting elements into urban development.

Finally, the elevation analyses reveal increases to the lowest (< 1000 m) and highest (> 1800 m) belts, leaving mid-elevations unchanged. Comparable four-decade resurveys of Swiss grasslands found constancy in colline belts but marked richness gains above the treeline, driven by warming and reduced snow cover (Zehnder et al., 2025). The lack of change between 1000 and 1800 m may reflect simultaneous but opposing forces: climatic amelioration that favours newcomers versus land-use abandonment leading to shrub encroachment and competitive exclusion, a mechanism also noted for abandoned pastures across the Alps (Zehnder et al., 2025).

Taken together, these comparisons indicate that the overall positive national trend masks strong regional, elevational, and management-driven contrasts. Future conservation efforts should therefore target the stagnant mid-elevation zone and intensively used lowlands, where habitat quality, not merely climate, limits further recovery of plant diversity.

Mean ecological indicator values

The analysis of community means reveals consistent shifts in plant community composition across Switzerland over the past two decades. A significant upward trend in the temperature indicator suggests ongoing thermophilisation, in line with earlier findings from alpine summit resurvey studies (Rumpf et al., 2018). Simultaneously, the decrease in moisture indicator values indicates a shift toward more drought-tolerant communities, potentially driven by rising temperatures and altered precipitation regimes, as also documented in long-term vegetation monitoring of dry grasslands (Bühler & Roth, 2011).

The decline in light indicator values may reflect increased canopy closure or encroachment by competitive species in certain habitats, a phenomenon also observed in abandoned meadows and forest edge plots (Helm et al., 2006). Hemeroby values increased, indicating a shift toward species more tolerant of anthropogenic disturbance and habitat modification. This trend may reflect increasing urbanisation, infrastructure development, or changes in agricultural practices that favour disturbance-tolerant taxa. Notably, the slight decrease in moving tolerance suggests a reduction in land-use intensity, possibly linked to an increasing share of extensively managed biodiversity promotion areas. Meanwhile, changes in functional scores such as a decline in stress and an increase in ruderality suggest that plant communities are becoming less associated with typical urban or highly managed habitats but include more disturbance-adapted taxa possibly due to increased extreme events or intermittent land-use intensity (Roth et al., 2014). No significant trends were observed for soil reaction, nutrients, or species competitive score, implying that these conditions have remained relatively stable at the 10 m² scale. Overall, the EIV analysis supports the notion that Swiss plant communities are responding to climate-related drivers and management changes through gradual but directionally consistent trait shifts (Bühler & Roth, 2011).

Species level

The species-level models revealed significant temporal trends in the occurrence of 221 vascular plant taxa between 2001 and 2023. These results highlight clear shifts in presence frequency over time for a subset of the flora captured by the BDM Z9 surveys.

However, extremely high or low slope values should not be overinterpreted, especially for rare species with few presences (Puhr et al., 2017). Logistic regression models (including bias-corrected approaches such as Firth-type logistic regression) are known to produce distorted effect sizes and predicted probabilities when outcome imbalance is strong (Puhr et al., 2017). This issue can similarly affect GLMMs when species with few occurrences are modelled individually (Puhr et al., 2017). Nonetheless, the analysis provides a useful overview of species-specific dynamics and serves as a starting point for identifying taxa with consistent long-term increases or declines.

When contextualised within longer temporal trajectories, these findings may indicate a turning point. In Switzerland, previous decades were marked by steep biodiversity losses, especially during and after the Third Agricultural Revolution, largely driven by land-use intensification and abandonment. However, the consistent upward trends observed here suggest that, at least for a subset of vascular plants, the lowest point in diversity may have been reached or even surpassed, hinting at a potential recovery phase in Swiss lowland and alpine ecosystems (Lachat et al., 2010).

Conclusion

The results of this study demonstrate that vascular plant diversity in Switzerland has undergone measurable change over the past two decades. While an overall increase in species richness was observed at the national scale, this pattern varied strongly across biogeographic regions, land-use types, and elevational gradients. Significant gains were particularly evident in the Central Plateau and at high elevations, especially on unused land and extensively managed grasslands. At the same time, forests, settlements, and mid-elevation zones showed no significant change, suggesting stagnation or potential degradation in these areas. Shifts in mean ecological indicator values further revealed signs of thermophilisation, increased drought tolerance, and a rise in ruderal traits, consistent with climate change and altered land-use intensity. The species-level analysis identified both increasing and declining taxa, with substantially more increasing than decreasing. Taken together, and viewed in a broader historical context, these trends may indicate the beginning of a turning point, suggesting that, for at least some vascular plant species, the long-standing decline in diversity could have slowed, stabilised, or even started to reverse.

Building on these findings, future research should seek to better disentangle the relative contributions of climate, land-use, and policy-driven factors in shaping biodiversity trends. Linking species trends to trait data or habitat preferences could help identify mechanisms behind observed changes and inform conservation priorities. Incorporating abundance data, where available, would allow a more detailed understanding of community dynamics. Additionally, integrating remote sensing data or high-resolution land-use histories could provide spatial context to plot-level observations. Finally, stagnating, or declining zones, particularly mid-elevation belts and urban landscapes, should be targeted for more detailed monitoring and restoration efforts, as they may currently fall through the cracks of existing conservation strategies.

Acknowledgements

I would like to express my heartfelt gratitude to my supervisors, Prof. Dr. Jürgen Dengler and MSc Stefan Widmer, for their invaluable support, guidance, and encouragement throughout the course of this Bachelor thesis. Their expertise, patience, flexibility, and constructive feedback have been incredibly important during this entire project. I am also thankful for their generous sharing of time, insights, and enthusiasm for biodiversity.

Furthermore, I would like to thank Thomas Miller for his valuable assistance with proofreading and language editing.

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Appendix

Appendix 1: Description of 2000_Z9_Kopfdaten.xlsx

2000_Z9_Kopfdaten.xlsx

Dieses File beinhaltet die durchgeführten Pflanzen- und Moos-Aufnahmen seit 2001.

Wichtig: Die Spalten `yearP1` und `yearMoos` beinhalten das Pflanzen- und Moosaufnahmejahr. Immer wenn es hier einen Eintrag gibt, dann ist die entsprechende Aufnahme gültig. Das ist wichtig, weil es Aufnahmen mit Null Arten gibt, aber auch einzelne Aufnahmen, die aus methodischen Gründen ungültig sind. Es kann auch sein, dass die Pflanzenaufnahme gültig, die Moosaufnahme aber ungültig war.

Die Moosproben werden von den Botanikern meistens während der 1. Begehung gesammelt. Deshalb gibt es kein eigenes Erhebungsdatum für die Moose und in der allermeisten Fällen ist das Aufnahmejahr der Pflanzen und Moose das gleiche. In Einzelfällen kann es aber Nachholer im Folgejahr geben, wenn eine Artengruppe nicht methodenkonform erhoben wurde.

Appendix 2: Description of 2000_Z9_Pflanzen.xlsx

2000_Z9_Pflanzen.xlsx

Enthält die Pflanzennachweise. Diese können mit der `aID_KD` mit den Kopfdaten verknüpft werden.

Die Deckung der Arten wird im BDM erst seit 2016 erfasst (2015 nur teilweise), davor gibt es nur Präsenz-/Absenz-Daten. Zur Umrechnung der Deckungs-Schätzklassen nach Braun-Blanquet verwenden wir die Tabelle im Anhang.

Appendix 3: Variable Definitions in BDM Z9 Files



Kurzbeschreibung der Spalten in den Dateien

- **aID_STA0**: Eindeutige Nummer für einen Z9-Standort
- **aID_KD**: Eindeutige Nummer für eine Aufnahme (eine Aufnahme beinhaltet alle Begehungen eines Jahres). Dient als Verknüpfungsfeld
- **XKoord_LV95**: X-Koordinate gemäss neuem CH-Koordinatensystem
- **YKoord_LV95**: Y-Koordinate gemäss neuem CH-Koordinatensystem
- **HN**: Hauptnutzung (Siedlung, Wald, ...) der aufgenommenen Fläche
- **Delarze1**: Zuordnung der Fläche zur passenden Kategorie gemäss Delarze et al. 2015 während der Erstbegehung
- **Delarze2**: Zuordnung der Fläche zur passenden Kategorie gemäss Delarze et al. 2015 während der Zweitbegehung (soweit vorhanden)
- **yearP1**: Aufnahmejahr der Pflanzenaufnahmen
- **yearMoos**: Aufnahmejahr der Moosaufnahmen
- **Date_P1_1**: Aufnahmedatum der ersten Begehung (Pflanzen und Moose)
- **Date_P1_2**: Aufnahmedatum der zweiten Erhebung (nur Pflanzen, alpine Flächen werden nur einmal begangen)
- **BGR_6**: Die biogeographischen Regionen (6 Grundregionen), Stand 2020
- **Hoehe**: Höhe über Meer (m) gemäss DHM25_LV03
- **Kanton**: Kanton gemäss swissBOUNDARIES3D
- **aID_SP**: Eindeutige ArtID. Dient als Verknüpfungsfeld
- **InfoSpeciesNr**: Artnummer von InfoSpecies, soweit bekannt. Bei den Pflanzen handelt es sich um die Identifikationsnummer gemäss Synonymie-Index (Index synonymique de la flore suisse et territoires limitrophes, ISFS)
- **Gattung**: Gattungsname
- **Art**: Artname
- **ArtD**: Deutschsprachige Bezeichnung für die Art (soweit vorhanden)
- **Pr1**: Wurde die Art während der ersten Begehung nachgewiesen?
- **Pr2**: Wurde die Art während der zweiten Begehung nachgewiesen?
- **Deckung1**: Deckungsschätzung der nachgewiesenen Pflanzen-Arten bei der Erstbegehung nach Braun-Blanquet
- **Deckung2**: Deckungsschätzung der nachgewiesenen Pflanzen-Arten bei der Zweitbegehung nach Braun-Blanquet

Appendix 4: Coding of CSR-strategies

Coding of CSR-strategies in Flora Indicativa and VEGEDAZ

Strategy	C-score	S-score	R-score
CCC	3	0	0
SSS	0	3	0
RRR	0	0	3
CCS	2	1	0
CSS	1	2	0
CCR	2	0	1
CRR	1	0	2
SSR	0	2	1
SRR	0	1	2
CRS	1	1	1

Appendix 5: Decreasing Species from 2001-2023

species	yearly_change_%	p_value	trend	n_obs
Mentha aquatica	-100.0	0.026	decreasing	11
Ranunculus flammula	-97.1	0.020	decreasing	12
Asperula taurina	-96.6	0.004	decreasing	18
Alnus incana	-38.6	0.000	decreasing	41
Rumex scutatus	-35.1	0.000	decreasing	63
Crepis vesicaria	-33.7	0.007	decreasing	11
Thesium pyrenaicum	-32.6	0.002	decreasing	11
Aruncus dioicus	-27.9	0.001	decreasing	29
Chenopodium bonus-henricus	-23.9	0.017	decreasing	22
Juncus alpinoarticulatus	-21.0	0.000	decreasing	26
Sempervivum tectorum	-20.6	0.001	decreasing	39
Vinca minor	-20.5	0.028	decreasing	35
Galium palustre	-20.1	0.018	decreasing	22
Solidago canadensis	-19.1	0.014	decreasing	10
Daphne laureola	-18.6	0.030	decreasing	11
Onobrychis viciifolia	-17.7	0.012	decreasing	22
Allium oleraceum	-17.2	0.010	decreasing	18
Sedum rupestre aggr.	-17.1	0.005	decreasing	24
Viola rupestris	-17.0	0.004	decreasing	23
Lathyrus vernus	-16.6	0.003	decreasing	91
Astrantia minor	-16.5	0.000	decreasing	72
Potentilla pusilla	-14.3	0.009	decreasing	21
Crepis conyzifolia	-14.0	0.014	decreasing	26
Stellaria alsine	-13.9	0.042	decreasing	18
Galium verum	-13.6	0.006	decreasing	53
Calamagrostis epigejos	-13.4	0.043	decreasing	10
Salvia pratensis	-13.3	0.016	decreasing	58
Eriophorum latifolium	-12.7	0.040	decreasing	12
Hypericum hirsutum	-12.6	0.025	decreasing	25
Juncus bufonius	-12.5	0.041	decreasing	11
Lamium maculatum	-12.2	0.004	decreasing	37
Polygonum mite	-11.9	0.029	decreasing	15
Saxifraga stellaris	-11.4	0.001	decreasing	109
Heracleum sphondylium	-11.3	0.000	decreasing	443
Anthriscus sylvestris	-11.1	0.000	decreasing	150
Gentiana lutea	-10.1	0.021	decreasing	81
Colchicum autumnale	-10.1	0.008	decreasing	95
Gymnocarpium dryopteris	-9.8	0.017	decreasing	136
Pimpinella major	-9.7	0.001	decreasing	169
Melampyrum pratense	-9.4	0.012	decreasing	53
Sambucus racemosa	-9.3	0.003	decreasing	57
Campanula trachelium	-9.2	0.007	decreasing	67
Phleum hirsutum	-9.2	0.017	decreasing	90

<i>Arenaria biflora</i>	-8.7	0.023	decreasing	62
<i>Origanum vulgare</i>	-8.7	0.022	decreasing	51
<i>Adenostyles alpina</i>	-8.6	0.001	decreasing	139
<i>Viola tricolor</i> aggr.	-8.5	0.000	decreasing	174
<i>Rubus saxatilis</i>	-8.4	0.009	decreasing	117
<i>Veronica fruticans</i>	-7.7	0.033	decreasing	90
<i>Alchemilla vulgaris</i> bdm-aggr.	-7.7	0.000	decreasing	1285
<i>Anemone nemorosa</i>	-7.5	0.000	decreasing	460
<i>Brachypodium pinnatum</i>	-7.5	0.000	decreasing	158
<i>Saxifraga exarata</i>	-7.4	0.029	decreasing	85
<i>Hieracium villosum</i>	-7.4	0.034	decreasing	61
<i>Lysimachia nummularia</i>	-7.2	0.003	decreasing	136
<i>Huperzia selago</i>	-7.1	0.010	decreasing	139
<i>Rhinanthus minor</i>	-7.0	0.021	decreasing	47
<i>Maianthemum bifolium</i>	-6.8	0.026	decreasing	218
<i>Gentiana purpurea</i>	-6.4	0.032	decreasing	102
<i>Rumex obtusifolius</i>	-6.1	0.000	decreasing	511
<i>Quercus robur</i>	-6.1	0.003	decreasing	110
<i>Viola biflora</i>	-6.0	0.003	decreasing	502
<i>Prenanthes purpurea</i>	-5.6	0.019	decreasing	288
<i>Euphorbia cyparissias</i>	-5.6	0.042	decreasing	196
<i>Silene dioica</i>	-5.3	0.032	decreasing	165
<i>Geum montanum</i>	-5.2	0.047	decreasing	366
<i>Soldanella alpina</i>	-5.1	0.002	decreasing	507
<i>Carum carvi</i>	-5.0	0.027	decreasing	265
<i>Pimpinella saxifraga</i> aggr.	-4.8	0.048	decreasing	143
<i>Silene vulgaris</i>	-4.3	0.030	decreasing	323
<i>Polygonum viviparum</i>	-4.3	0.043	decreasing	543
<i>Campanula rotundifolia</i>	-4.3	0.002	decreasing	294
<i>Leontodon hispidus</i>	-3.9	0.001	decreasing	740
<i>Potentilla erecta</i>	-3.7	0.049	decreasing	608
<i>Thymus serpyllum</i> aggr.	-3.5	0.040	decreasing	621
<i>Cardamine pratensis</i> aggr.	-3.3	0.011	decreasing	605
<i>Achillea millefolium</i> aggr.	-3.3	0.026	decreasing	632
<i>Ranunculus acris</i>	-3.1	0.003	decreasing	1436
<i>Leucanthemum vulgare</i> aggr.	-3.1	0.024	decreasing	639
<i>Phyteuma spicatum</i>	-3.1	0.042	decreasing	366
<i>Ranunculus repens</i>	-3.0	0.010	decreasing	847
<i>Poa annua</i>	-1.7	0.045	decreasing	975

Appendix 6: Increasing Species from 2001 to 2023

species	yearly_change_%	p_value	trend	n_obs
Asplenium adiantum-nigrum	3553.4	0.008	increasing	16
Bupleurum stellatum	2724.6	0.007	increasing	27
Salix hastata	51.8	0.026	increasing	11
Geum reptans	33.4	0.005	increasing	31
Globularia cordifolia	32.1	0.025	increasing	34
Valerianella carinata	30.4	0.002	increasing	18
Gentiana orbicularis	28.0	0.002	increasing	24
Euphorbia platyphyllos	27.5	0.010	increasing	11
Leontodon montanus	27.1	0.004	increasing	33
Capsella rubella	25.9	0.000	increasing	22
Geranium pusillum	25.7	0.000	increasing	26
Salix helvetica	25.1	0.007	increasing	22
Diphasiastrum alpinum	24.0	0.009	increasing	27
Pulmonaria australis	23.1	0.009	increasing	40
Ilex aquifolium	22.9	0.000	increasing	47
Eragrostis minor	22.3	0.004	increasing	27
Carex pendula	22.0	0.004	increasing	43
Artemisia genipi	22.0	0.004	increasing	20
Echium vulgare	20.4	0.003	increasing	26
Arabis bellidifolia	20.4	0.011	increasing	26
Hypochaeris radicata	20.1	0.000	increasing	289
Trifolium pallescens	17.3	0.032	increasing	19
Brachypodium rupestre	16.8	0.000	increasing	44
Polystichum lonchitis	16.8	0.006	increasing	59
Prunus laurocerasus	16.8	0.050	increasing	19
Salvia glutinosa	16.4	0.013	increasing	32
Minuartia sedoides	15.8	0.000	increasing	121
Digitaria sanguinalis aggr.	15.7	0.000	increasing	143
Impatiens glandulifera	15.5	0.020	increasing	16
Geranium dissectum	15.5	0.000	increasing	86
Malva neglecta	15.4	0.036	increasing	14
Pedicularis kernerii	14.3	0.011	increasing	47
Arenaria serpyllifolia aggr.	14.2	0.000	increasing	113
Arum maculatum	13.8	0.005	increasing	100
Setaria pumila	13.6	0.000	increasing	47
Rosa arvensis	13.2	0.001	increasing	59
Portulaca oleracea	13.1	0.001	increasing	52
Carex brizoides	13.0	0.027	increasing	30
Prunus spinosa	12.9	0.004	increasing	56
Cryptogramma crispa	12.6	0.038	increasing	50
Erigeron annuus	12.6	0.000	increasing	73
Poa minor	12.5	0.002	increasing	66
Euphrasia hirtella	12.5	0.044	increasing	15

<i>Verbena officinalis</i>	12.3	0.031	increasing	27
<i>Geranium molle</i>	11.9	0.017	increasing	20
<i>Festuca arundinacea</i>	11.7	0.000	increasing	200
<i>Festuca pulchella</i>	11.5	0.017	increasing	36
<i>Papaver rhoeas</i>	11.5	0.014	increasing	30
<i>Hieracium piliferum</i> aggr.	11.3	0.004	increasing	58
<i>Veronica aphylla</i>	11.3	0.007	increasing	73
<i>Festuca violacea</i> aggr.	11.2	0.000	increasing	171
<i>Dryopteris carthusiana</i>	11.0	0.000	increasing	186
<i>Gentiana nivalis</i>	10.6	0.003	increasing	89
<i>Carex hirta</i>	10.2	0.002	increasing	138
<i>Luzula alpinopilosa</i>	9.6	0.000	increasing	305
<i>Epilobium anagallidifolium</i>	9.5	0.020	increasing	36
<i>Brassica napus</i>	9.5	0.000	increasing	84
<i>Carex echinata</i>	9.4	0.037	increasing	56
<i>Potentilla reptans</i>	9.3	0.000	increasing	265
<i>Agrostis alpina</i>	9.2	0.000	increasing	128
<i>Bromus sterilis</i>	9.0	0.016	increasing	45
<i>Galium mollugo</i> aggr.	9.0	0.000	increasing	516
<i>Viola hirta</i>	8.8	0.003	increasing	81
<i>Lactuca serriola</i>	8.7	0.019	increasing	34
<i>Senecio ovatus</i>	8.5	0.005	increasing	96
<i>Amaranthus hybridus</i> aggr.	8.5	0.041	increasing	26
<i>Tilia platyphyllos</i>	8.5	0.021	increasing	58
<i>Ligusticum mutellina</i>	8.4	0.000	increasing	448
<i>Pulsatilla alpina</i>	8.2	0.034	increasing	135
<i>Sonchus oleraceus</i>	8.2	0.000	increasing	100
<i>Crepis biennis</i>	8.2	0.000	increasing	249
<i>Cerastium glomeratum</i>	8.1	0.000	increasing	166
<i>Trifolium dubium</i>	8.0	0.001	increasing	119
<i>Trifolium alpinum</i>	8.0	0.032	increasing	204
<i>Ulmus glabra</i>	7.7	0.017	increasing	106
<i>Rubus fruticosus</i> s. l. bdm-aggr.	7.6	0.000	increasing	673
<i>Agrostis schraderiana</i>	7.6	0.000	increasing	321
<i>Cirsium arvense</i>	7.5	0.005	increasing	88
<i>Brachypodium sylvaticum</i>	7.4	0.000	increasing	311
<i>Alopecurus pratensis</i>	7.1	0.000	increasing	369
<i>Carpinus betulus</i>	7.1	0.050	increasing	79
<i>Medicago sativa</i>	7.1	0.002	increasing	112
<i>Veronica montana</i>	7.1	0.034	increasing	62
<i>Agrostis capillaris</i>	7.0	0.000	increasing	916
<i>Senecio vulgaris</i>	6.9	0.009	increasing	86
<i>Erophila verna</i> aggr.	6.9	0.041	increasing	43
<i>Hedera helix</i>	6.8	0.000	increasing	668
<i>Epilobium parviflorum</i>	6.8	0.023	increasing	48
<i>Soldanella pusilla</i>	6.5	0.003	increasing	222
<i>Vicia sativa</i>	6.5	0.015	increasing	77

<i>Corylus avellana</i>	6.5	0.000	increasing	385
<i>Crepis aurea</i>	6.4	0.001	increasing	244
<i>Veronica officinalis</i>	6.3	0.000	increasing	367
<i>Potentilla sterilis</i>	6.1	0.017	increasing	165
<i>Prunus avium</i>	6.1	0.001	increasing	198
<i>Veronica persica</i>	6.1	0.000	increasing	545
<i>Calamagrostis varia</i>	6.1	0.002	increasing	259
<i>Leontodon autumnalis</i>	6.0	0.003	increasing	220
<i>Sorbus aucuparia</i>	6.0	0.000	increasing	794
<i>Ranunculus bulbosus</i>	6.0	0.017	increasing	179
<i>Avenella flexuosa</i>	5.8	0.000	increasing	637
<i>Euphrasia rostkoviana</i>	5.7	0.027	increasing	102
<i>Parnassia palustris</i>	5.4	0.043	increasing	190
<i>Sorbus aria</i>	5.4	0.011	increasing	234
<i>Crepis capillaris</i>	5.4	0.003	increasing	173
<i>Daucus carota</i>	5.4	0.020	increasing	157
<i>Juncus effusus</i>	5.1	0.037	increasing	178
<i>Carex pilulifera</i>	5.1	0.048	increasing	107
<i>Plantago lanceolata</i>	5.1	0.000	increasing	1249
<i>Calamagrostis villosa</i>	5.0	0.008	increasing	320
<i>Phyteuma orbiculare</i>	5.0	0.028	increasing	191
<i>Galium aparine</i>	4.8	0.003	increasing	249
<i>Circaea lutetiana</i>	4.8	0.041	increasing	170
<i>Rhinanthus alectorolophus</i>	4.8	0.033	increasing	154
<i>Sonchus asper</i>	4.7	0.005	increasing	157
<i>Festuca rubra</i> aggr.	4.7	0.000	increasing	1819
<i>Carex flacca</i>	4.6	0.003	increasing	509
<i>Viola reichenbachiana</i> bdm-aggr.	4.6	0.000	increasing	752
<i>Euphrasia minima</i>	4.5	0.007	increasing	502
<i>Festuca halleri</i> bdm-aggr.	4.4	0.013	increasing	297
<i>Carex caryophyllea</i>	4.4	0.049	increasing	141
<i>Echinochloa crus-galli</i>	4.2	0.016	increasing	163
<i>Nardus stricta</i>	4.2	0.033	increasing	634
<i>Cardamine resedifolia</i>	4.2	0.044	increasing	264
<i>Geum urbanum</i>	4.1	0.015	increasing	307
<i>Luzula sylvatica</i> aggr.	4.1	0.014	increasing	551
<i>Helictotrichon versicolor</i>	4.1	0.038	increasing	359
<i>Holcus lanatus</i>	3.8	0.004	increasing	767
<i>Ranunculus montanus</i> aggr.	3.5	0.007	increasing	709
<i>Fragaria vesca</i>	3.5	0.019	increasing	732
<i>Carex sylvatica</i>	3.3	0.009	increasing	658
<i>Medicago lupulina</i>	3.1	0.037	increasing	357
<i>Campanula scheuchzeri</i>	3.1	0.012	increasing	813
<i>Prunella vulgaris</i>	2.8	0.015	increasing	892
<i>Ranunculus tuberosus</i> aggr.	2.7	0.047	increasing	408
<i>Abies alba</i>	2.7	0.039	increasing	878
<i>Lolium perenne</i>	2.3	0.024	increasing	1549

Phleum pratense aggr.	2.2	0.029	increasing	627
Anthoxanthum odoratum aggr.	2.0	0.032	increasing	1788