ZURICH UNIVERSITY OF APPLIED SCIENCES

SCHOOL OF LIFE SCIENCES AND FACILITY MANAGEMENT

Institute of Natural Resource Sciences

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: 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, community-level ecological indicator values, and species-specific 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. Unweighted community-level ecological indicator values indicate consistent shifts toward thermophilic and drought-tolerant plant assemblages, suggesting climate warming and changes in moisture availability. At the species level, 97 taxa showed significant increases or declines in occurrence frequency, highlighting ongoing compositional turnover and potential environmental filtering processes.

Together, these results provide an integrated assessment of biodiversity change across Swiss landscapes. They emphasise the importance of elevation, land-use intensity, and regional context in shaping vegetation responses and offer valuable insights for conservation and ecological monitoring under global change.

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# 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 (Primack et al., 2018).

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 a combination of anthropogenic and climatic 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 (Pazúr et al., 2022). 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 (Begert & Frei, 2018; Steinbauer et al., 2018). These interacting forces are expected to leave discernible marks on 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.

Several studies have utilized BDM Z9 data to analyse biodiversity trends in grasslands and other habitats. For instance, Häberlin and Dengler (2025) investigated biodiversity change in Swiss grasslands from 2001 to 2023, showing shifts in community composition, thermophilisation trends, and changes in ecological indicator values (EIVs). However, their focus was limited to grasslands, and the study did not address trends at the species level beyond temperature indicator values.

Despite the potential of the BDM dataset, there is still a lack of comprehensive analyses that use the full Z9 time series to explore plant diversity trends across all major land-use types, biogeographic regions, and elevation zones. In addition, no study to date has systematically analysed individual species trends across the entire dataset, nor combined these with a broad set of community-weighted indicator values.

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. Have certain regions or land-use types experienced stronger biodiversity losses or gains? Does elevation modulate the direction or strength of temporal trends?

In addition to species richness, the study investigates how community-level ecological indicator values have shifted over time. Can changes in community-weighted means of indicator values reveal signals of eutrophication, climate warming, or altered moisture regimes? Do these patterns differ across land-use types or elevational gradients?

Finally, species-level analyses are conducted to explore whether specific species show strong increases or declines over the monitoring period. Which species emerge as clear "winners" or "losers"? Are observed compositional shifts driven by neophytes, habitat generalists, or specialists?

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.

To do so, this study combines analyses of species richness, ecological indicator values, and species-specific trends based on long-term vegetation data from the Swiss Biodiversity Monitoring programme (BDM).

# 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 approximately 1,600 terrestrial plots (Figure 1). In each grid cell, one plot is located in a dominant land-use type and surveyed every five years using a rotating scheme. This staggered design ensures consistent temporal comparisons while minimising the influence of short-term weather variability (BDM Coordination Office, 2014).

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

Field surveys follow standardised presence/absence protocols. 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. Aggregated across the national grid, these data provide robust estimates of mean alpha-diversity across major land-use types, forests, permanent grasslands, arable land, settlements, and alpine zones, further stratified into colline, montane, and subalpine belts. 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, diversity components, 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 aggregated species observed. For vascular plants, this resulted in a plot-level species richness measure per sampling year that served as the primary response variable for mixed-effects modeling. Moss species richness was calculated analogously but analyzed descriptively due to differences in temporal coverage.

In addition to species richness, community-weighted means (CWMs) of 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, which provides ordinal scores for various environmental gradients such as temperature (T), light (L), soil moisture (F), reaction (R), nutrients (N), mowing frequency tolerance (MV), and Ellenberg moisture index (EM). Additionally, Grime’s CSR strategy components (C, S, R scores) were incorporated as functional trait proxies.

Species names from the BDM dataset were manually matched to the corresponding taxa in the indicator value database 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 CWM calculations for the corresponding trait. Community-weighted 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). Data processing and statistical modelling were carried out using tidyverse-based workflows 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 (LMMs) 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) biogeographic region (BGR\_6), (ii) dominant land use type (HN), and (iii) elevation, modelled both as a standardised continuous variable and as categorical 400 m elevation bands (from 200 m to 3100 m). For each model, diagnostic checks of residuals were performed using the DHARMa package to assess model validity. Group-wise predictions and marginal trends were visualised using functions from the ggeffects and emmeans packages. 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, model comparisons were made using Akaike Information Criterion (AIC), and key statistics (AIC values, 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 indicativa for temperature (T), light (L), soil moisture (F), soil reaction (R), nutrients (N), Ellenberg moisture variability (EM), mean vegetative height (MV) and Grime’s C, S and R scores. Community-weighted means (CWMs) for each trait were then calculated for every plot with FD::functcomp() (unweighted by abundance, i.e. each species present contributes equally). CWMs were merged with plot metadata and enriched with a continuous time index (year\_index = year − 2001). For each trait, we fitted a Gaussian linear mixed-effects model of the form CWM ~ year\_index + (1 | plot) using glmmTMB, 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. From each model we extracted the slope (yearly change), its standard error and p-value, and used emmeans::emtrends() together with ggeffects / ggemmeans to generate marginal predictions and visualise temporal trajectories. Finally, all slope estimates were compiled into a summary table, annotated with significance levels (\*\*\* p < 0.001, \*\* p < 0.01, \* p < 0.05, . p < 0.1), 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 (year − 2000). Plot identity (aID\_STAO) was included as a random intercept to account for repeated measures across years. Species were only analysed if they occurred in at least ten plots and exhibited variation in presence across the study period.

For each species, the slope coefficient of the fixed effect (year\_index) was extracted along with the standard error and p-value. To avoid interpreting unstable estimates, models with extreme slope values (|β| > 5) were excluded. From the estimated slopes, we calculated the average annual relative change in occurrence probability (%), as well as the cumulative change from 2001 to 2023. 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 (*β* = 0.0585, *p* < 0.001). Fixed effects explained 0.1% of the variance in species richness (*R²m* = 0.001).

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

When including an interaction between year and biogeographic region, the temporal trend was no longer globally significant but varied significantly between regions as shown in Figure 3. The strongest increases were observed in the Central Plateau (*p* = 0.0014) and the Eastern Central Alps (*p* < 0.001), while other regions showed weaker or non-significant changes. Fixed effects explained 12.1% of the variance in species richness (*R²m* = 0.121).

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Figure 3: Temporal trends in vascular plant species richness from 2001 to 2023 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 |

A similar interaction model with dominant land use type revealed clear differences in temporal trends among land use categories. 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 (*R²m* = 0.177).

Table 1: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 |

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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 instead of a continuous variable, the model also revealed significant variation in temporal trends across altitude zones. 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 (*p* < 0.001). 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 (*R²m* = 0.139).

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

Table 3: Estimated temporal trends in vascular plant species richness for different elevation bands between 2001 and 2023. Values represent linear trend coefficients (change per year) with 95% confidence intervals. A trend is considered significant confidence interval does not include zero.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Elevation Band** | **Trend** | **Lower CI** | **Upper CI** | **Significant** |
| 200 – 600 m a.s.l. | 0.06510 | 0.0272 | 0.1031 | Yes |
| 600 – 1000 m a.s.l. | 0.05742 | 0.0190 | 0.0958 | Yes |
| 1000 – 1400 m a.s.l. | -0.00992 | -0.0568 | 0.0370 | No |
| 1400 – 1800 m a.s.l. | -0.00263 | -0.0549 | 0.0496 | No |
| 1800 – 2200 m a.s.l. | 0.07963 | 0.0201 | 0.1392 | Yes |
| 2200 – 2600 m a.s.l. | 0.19072 | 0.1316 | 0.2498 | Yes |
| 2600 – 3100 m a.s.l. | 0.15997 | 0.0340 | 0.2859 | Yes |

## Mean ecological indicator values

Mean ecological indicator values were calculated for ten indicators across 6,283 vegetation surveys using unweighted species presence data. Linear mixed-effects models with random intercepts for plot location were used to assess temporal trends from 2001 to 2023.

Temperature preference (T) and Ellenberg moisture (F) showed significant positive and negative trends, respectively. T increased by 0.00208 units per year (*p* < 0.001), while F decreased by 0.00076 units per year (*p* < 0.001). Light (L) declined slightly over time (–0.00077 units per year, *p* = 0.006), whereas soil aeration value (EM) increased significantly by 0.00250 units per year (*p* < 0.001).

Several other traits also showed significant trends: the mycorrhizal value (MV) declined (–0.00141 per year, *p* = 0.007), the sociological score for synanthropy (S\_score) decreased (–0.00132, p < 0.001), and the ruderal score (R\_score) increased (0.00107, p = 0.0013). No significant temporal trends were found for soil reaction (R), nitrogen preference (N), or the constancy score (C\_score).

Table 4: Temporal trends in mean ecological indicator values of vascular plants from 2001 to 2023.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Trait** | **Description** | **Yearly Change** | **Std. Error** | **z-value** | **p-value** | **Significance** |
| T | Temperature preference | +0.00208 | 0.00021 | 9.94 | <0.001 | \*\*\* |
| L | Light availability | –0.00077 | 0.00028 | –2.74 | 0.006 | \*\* |
| F | Moisture | –0.00076 | 0.00020 | –3.77 | <0.001 | \*\*\* |
| R | Soil reaction | –0.00009 | 0.00024 | –0.39 | 0.696 | n.s. |
| N | Nitrogen | +0.00001 | 0.00024 | 0.06 | 0.955 | n.s. |
| EM | Soil aeration (Ellenberg M) | +0.00250 | 0.00032 | 7.72 | <0.001 | \*\*\* |
| MV | Mycorrhizal value | –0.00141 | 0.00052 | –2.69 | 0.007 | \*\* |
| C\_score | Constancy score | +0.00026 | 0.00029 | 0.89 | 0.372 | n.s. |
| S\_score | Synanthropy score | –0.00132 | 0.00022 | –5.96 | <0.001 | \*\*\* |

## Species level

Out of 1,381 vascular plant taxa analysed with logistic generalized linear models (GLMs), 97 species showed statistically significant temporal trends in their presence across the survey years 2001–2023 (p < 0.05). Among these, 20 species exhibited the strongest significant increases in relative frequency, including Barbarea intermedia (n = 5), Capsella rubella (n = 10), Geranium pusillum (n = 15), and Euphorbia platyphyllos (n = 9). These species showed high positive model coefficients and reached significance levels of p < 0.001, p < 0.01, or p < 0.05.

The 20 species with the strongest significant declines included Gnaphalium uliginosum (n = 5), Solidago canadensis (n = 8), Symphytum officinale (n = 13), and Juncus alpinoarticulatus (n = 15). All exhibited negative coefficients with p < 0.05, and several showed highly significant declines (p < 0.001 or p < 0.01). The total number of survey years per species varied from 5 to 23.

Plots display the top 20 species with increasing and decreasing yearly changes in relative frequency, respectively, using color coding for statistical significance levels (red = p < 0.001; orange = p < 0.01; blue = p < 0.05).

# Discussion

## Species richness

The observed nation-wide rise in vascular plant richness (≈ +0.06 species yr⁻¹) aligns with earlier assessments from the Swiss Biodiversity Monitoring (BDM): based on the 2005–2015 panel, FOEN reported “a slight but statistically valid increase in the average number of vascular‐plant species… for Switzerland as a whole” and, more specifically, for the (Mittelland). 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 m² scale.

Yet the biogeographic interaction highlights pronounced spatial heterogeneity. The strongest gains occurred in the Mittelland and the Östlichen Zentralalpen, mirroring the BDM report 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 (Wohlgemuth et al. 2020). 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 (Wipf et al. 2013), consistent with the positive slope observed for the Eastern Central Alps in our dataset.

The land-use model underscores 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. 2015). By contrast, forests and settlements showed no detectable trend, matching FOEN’s conclusion 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.

Finally, the elevation analyses reveal a dual pattern: a continuous model points to stronger year-to-year gains at higher altitudes, while the banded model confines significant 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 (Fischer 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 (Körner & Paulsen 2020).

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-weighted means (CWMs) reveals consistent shifts in plant community composition across Switzerland over the past two decades. A significant upward trend in the temperature indicator (T) suggests ongoing thermophilisation, in line with earlier findings from alpine summit resurvey studies (e.g. Rumpf et al., 2018; Wipf et al., 2013). Simultaneously, the decrease in moisture indicator values (F) 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 (L) may reflect increased canopy closure or encroachment by competitive species in certain habitats, a phenomenon also observed in abandoned meadows and forest edge plots (Fischer et al., 2023). Soil aeration (EM) values increased, potentially due to a shift toward species adapted to drier or better-aerated soils. Meanwhile, changes in functional scores such as a decline in synanthropy (S\_score) and an increase in ruderality (R\_score) 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 (Hagedorn et al., 2019).

No significant trends were observed for soil reaction (R), nitrogen (N), or species constancy (C\_score), implying that these conditions have remained relatively stable at the 10 m² scale. Overall, the CWM analysis supports the notion that Swiss plant communities are responding to climate-related drivers and management changes through gradual but directionally consistent trait shifts.

## Species level

The species-level analysis revealed a total of 97 vascular plant taxa with significant changes in presence across Switzerland between 2001 and 2023. While the statistical models do not explain the causes of these trends, the observed species-specific dynamics are consistent with findings from other long-term vegetation monitoring efforts in Switzerland and Central Europe.

Previous studies based on the Swiss Biodiversity Monitoring Programme (BDM) have reported similar patterns of directional change, with some taxa increasing markedly while others declined (Roth et al., 2015). For instance, Bühler and Roth (2011) documented compositional shifts in dry grasslands, where disturbance-adapted and generalist species increased, while habitat specialists and moisture-demanding species declined. Likewise, alpine vegetation surveys have highlighted a gradual turnover, with thermophilic species expanding and cold-adapted taxa showing retreat or reduced frequencies (Wipf et al., 2013; Rumpf et al., 2018).

The current analysis detected some of the strongest increases among taxa with relatively few observations (e.g., Barbarea intermedia, Capsella rubella), while widespread declines were noted for species associated with wetlands (Gnaphalium uliginosum, Juncus alpinoarticulatus) or nutrient-poor soils (Viola rupestris, Potentilla pusilla). Although causal inference is beyond the scope of this study, such trends may reflect environmental filtering processes such as habitat degradation, altered land-use practices, or climate-driven shifts, as suggested in previous literature (Hagedorn et al., 2019; Verheyen et al., 2018).

# 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 high-altitude zones, 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 community-weighted means of 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, underlining ongoing compositional turnover that may reflect environmental filtering processes.

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.

# References

Am Ende Zotero-Bibliographie einfügen.

# Appendix

Additional tables, figures, model outputs, or code documentation.

## Appendix 1: Description of 2000\_Z9\_Kopfdaten.xlsx

Ein Bild, das Text, Screenshot, Schrift, Algebra enthält.

Automatisch generierte Beschreibung

## Appendix 2: Description of 2000\_Z9\_Pflanzen.xlsx

Ein Bild, das Text, Schrift, Screenshot, weiß enthält.

Automatisch generierte Beschreibung

## Appendix 3: Variable Definitions in BDM Z9 Files

Ein Bild, das Text, Screenshot, Schrift, Zahl enthält.

Automatisch generierte Beschreibung