ZURICH UNIVERSITY OF APPLIED SCIENCES

SCHOOL OF LIFE SCIENCES AND FACILITY MANAGEMENT

INSTITUTE OF COMPUTATIONAL LIFE 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: 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, 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. Mean 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, 221 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.

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 (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 (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. 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 long-term plant diversity trends across the full range of land-use types, biogeographic regions, and elevation zones 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. Can changes in community 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 1’650 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 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 (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, settlementsforests, 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 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 modelling

In addition to species richness, 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 , reflecting increasing intensity of the respective environmental factor. 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).

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 worflows based on tidyverse (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 main biogeographic regions (UFAM, o. J.) (BGR\_6), (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 (Lüdecke, 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 indicativa(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 (year\_index = year − 2001). For each trait, we fitted a Gaussian linear mixed-effects model of the form CM ~ year\_index + (1 | 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 (Lüdecke, 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 (year − 2000). Plot identity 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.

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 (*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 interaction term was significant (*p* = 0.0006), indicating that temporal trends in species richness varied significantly between regions as shown in Figure 3. 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 (*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, the model revealed a significant interaction between year and elevation (*p*< 0.001), indicating that temporal trends in species richness varied across elevation 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 . 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.



## Mean ecological indicator values

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 competitors scores.

Table 4: 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 7: Increasing Species from 2001 to 2023) and 82 decreasing (Appendix 6: 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 (Appendix 5: Top 10 Species Winners and Losers between 2001 and 2023), 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.

# 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 Central Plateau. 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 Central Plateau and the Eastern Central Alps, 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 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. 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 iincreases 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 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 (e.g. Rumpf et al., 2018; Wipf et al., 2013). 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 (Fischer et al., 2023). hemeroby 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 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 (Hagedorn et al., 2019).

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.

## 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 modeled 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.

# 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 unweighted 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, with substantially more increasing than decreasing.

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.

Thank you for generously sharing your time, insights, and enthusiasm for biodiversity.

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# Appendix

## 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

## Appendix 4: Coding of CSR-strategies

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

Automatisch generierte Beschreibung

## Appendix 5: Top 10 Species Winners and Losers between 2001 and 2023

Ein Bild, das Text, Screenshot, Quadrat enthält.

Automatisch generierte Beschreibung

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 (±130%) and was truncated for visual clarity.

## Appendix 6: Decreasing Species from 2001-2023

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **species** | **yearly\_change\_%** | **p\_value** | **trend** | **n\_obs** |
| Mentha aquatica | -99.98363295 | 0.026045673 | decreasing | 11 |
| Ranunculus flammula | -97.11475761 | 0.020346814 | decreasing | 12 |
| Asperula taurina | -96.62226477 | 0.003897824 | decreasing | 18 |
| Alnus incana | -38.56981419 | 0.000458305 | decreasing | 41 |
| Rumex scutatus | -35.05184274 | 2.20917E-05 | decreasing | 63 |
| Crepis vesicaria | -33.65834139 | 0.006885346 | decreasing | 11 |
| Thesium pyrenaicum | -32.60672602 | 0.002259711 | decreasing | 11 |
| Aruncus dioicus | -27.90576917 | 0.001235618 | decreasing | 29 |
| Chenopodium bonus-henricus | -23.94652307 | 0.017492343 | decreasing | 22 |
| Juncus alpinoarticulatus | -21.04454498 | 0.00030552 | decreasing | 26 |
| Sempervivum tectorum | -20.55346413 | 0.00064424 | decreasing | 39 |
| Vinca minor | -20.4784057 | 0.027627839 | decreasing | 35 |
| Galium palustre | -20.1011401 | 0.017924744 | decreasing | 22 |
| Solidago canadensis | -19.09976391 | 0.013894539 | decreasing | 10 |
| Daphne laureola | -18.5614038 | 0.029962746 | decreasing | 11 |
| Onobrychis viciifolia | -17.67929328 | 0.012445267 | decreasing | 22 |
| Allium oleraceum | -17.2473244 | 0.00983476 | decreasing | 18 |
| Sedum rupestre aggr. | -17.13648833 | 0.004514848 | decreasing | 24 |
| Viola rupestris | -16.99737709 | 0.003959145 | decreasing | 23 |
| Lathyrus vernus | -16.56917902 | 0.002826813 | decreasing | 91 |
| Astrantia minor | -16.54788582 | 0.000213406 | decreasing | 72 |
| Potentilla pusilla | -14.3097907 | 0.008661406 | decreasing | 21 |
| Crepis conyzifolia | -14.0223667 | 0.014404871 | decreasing | 26 |
| Stellaria alsine | -13.93658668 | 0.042490351 | decreasing | 18 |
| Galium verum | -13.57776496 | 0.005989414 | decreasing | 53 |
| Calamagrostis epigejos | -13.36002756 | 0.043294927 | decreasing | 10 |
| Salvia pratensis | -13.323634 | 0.015784984 | decreasing | 58 |
| Eriophorum latifolium | -12.69522833 | 0.040266737 | decreasing | 12 |
| Hypericum hirsutum | -12.59491995 | 0.025259649 | decreasing | 25 |
| Juncus bufonius | -12.47004453 | 0.0413283 | decreasing | 11 |
| Lamium maculatum | -12.15994298 | 0.004010307 | decreasing | 37 |
| Polygonum mite | -11.91083187 | 0.028716368 | decreasing | 15 |
| Saxifraga stellaris | -11.41989566 | 0.00112281 | decreasing | 109 |
| Heracleum sphondylium | -11.34458039 | 3.30573E-12 | decreasing | 443 |
| Anthriscus sylvestris | -11.06338684 | 5.58427E-06 | decreasing | 150 |
| Gentiana lutea | -10.10619333 | 0.021367185 | decreasing | 81 |
| Colchicum autumnale | -10.06688157 | 0.007708444 | decreasing | 95 |
| Gymnocarpium dryopteris | -9.752331109 | 0.01702931 | decreasing | 136 |
| Pimpinella major | -9.732659872 | 0.000679665 | decreasing | 169 |
| Melampyrum pratense | -9.352913432 | 0.012449863 | decreasing | 53 |
| Sambucus racemosa | -9.349960213 | 0.002685555 | decreasing | 57 |
| Campanula trachelium | -9.216188176 | 0.006972406 | decreasing | 67 |
| Phleum hirsutum | -9.154165772 | 0.017385097 | decreasing | 90 |
| Arenaria biflora | -8.735387681 | 0.023068161 | decreasing | 62 |
| Origanum vulgare | -8.687136526 | 0.022186477 | decreasing | 51 |
| Adenostyles alpina | -8.620043051 | 0.00062998 | decreasing | 139 |
| Viola tricolor aggr. | -8.456684587 | 4.66239E-05 | decreasing | 174 |
| Rubus saxatilis | -8.402192357 | 0.009079365 | decreasing | 117 |
| Veronica fruticans | -7.736919345 | 0.032996151 | decreasing | 90 |
| Alchemilla vulgaris bdm-agg. | -7.72025114 | 7.47098E-09 | decreasing | 1285 |
| Anemone nemorosa | -7.503430121 | 0.00026337 | decreasing | 460 |
| Brachypodium pinnatum | -7.479796342 | 0.000446852 | decreasing | 158 |
| Saxifraga exarata | -7.443681951 | 0.029026362 | decreasing | 85 |
| Hieracium villosum | -7.392589687 | 0.03360756 | decreasing | 61 |
| Lysimachia nummularia | -7.204747445 | 0.002604851 | decreasing | 136 |
| Huperzia selago | -7.076132149 | 0.010337356 | decreasing | 139 |
| Rhinanthus minor | -7.011525074 | 0.020847948 | decreasing | 47 |
| Maianthemum bifolium | -6.785336696 | 0.026388796 | decreasing | 218 |
| Gentiana purpurea | -6.378812504 | 0.032127551 | decreasing | 102 |
| Rumex obtusifolius | -6.134135961 | 1.10527E-06 | decreasing | 511 |
| Quercus robur | -6.097831329 | 0.00266187 | decreasing | 110 |
| Viola biflora | -6.019271339 | 0.00254272 | decreasing | 502 |
| Prenanthes purpurea | -5.635607489 | 0.018620574 | decreasing | 288 |
| Euphorbia cyparissias | -5.626012486 | 0.04204908 | decreasing | 196 |
| Silene dioica | -5.265242114 | 0.032271557 | decreasing | 165 |
| Geum montanum | -5.193908575 | 0.047063783 | decreasing | 366 |
| Soldanella alpina | -5.11283732 | 0.001627138 | decreasing | 507 |
| Carum carvi | -4.985320282 | 0.02663396 | decreasing | 265 |
| Pimpinella saxifraga aggr. | -4.81154343 | 0.048077411 | decreasing | 143 |
| Silene vulgaris | -4.294254802 | 0.029680576 | decreasing | 323 |
| Polygonum viviparum | -4.28374225 | 0.042958339 | decreasing | 543 |
| Campanula rotundifolia | -4.278260352 | 0.001926196 | decreasing | 294 |
| Leontodon hispidus | -3.938565484 | 0.000617611 | decreasing | 740 |
| Potentilla erecta | -3.706113166 | 0.048618363 | decreasing | 608 |
| Thymus serpyllum aggr. | -3.547815181 | 0.039511181 | decreasing | 621 |
| Cardamine pratensis aggr. | -3.304210078 | 0.011446009 | decreasing | 605 |
| Achillea millefolium aggr. | -3.293488219 | 0.025826818 | decreasing | 632 |
| Ranunculus acris | -3.143768023 | 0.002587656 | decreasing | 1436 |
| Leucanthemum vulgare aggr. | -3.10224354 | 0.024203625 | decreasing | 639 |
| Phyteuma spicatum | -3.079933058 | 0.042061518 | decreasing | 366 |
| Ranunculus repens | -2.970708295 | 0.009666539 | decreasing | 847 |
| Poa annua | -1.704222705 | 0.04495846 | decreasing | 975 |

## Appendix 7: Increasing Species from 2001 to 2023

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **species** | **yearly\_change\_%** | **p\_value** | **trend** | **n\_obs** |
| Asplenium adiantum-nigrum | 3553.392803 | 0.007735669 | increasing | 16 |
| Bupleurum stellatum | 2724.563167 | 0.006751951 | increasing | 27 |
| Salix hastata | 51.82126592 | 0.025999298 | increasing | 11 |
| Geum reptans | 33.44802574 | 0.004986867 | increasing | 31 |
| Globularia cordifolia | 32.07883258 | 0.024880744 | increasing | 34 |
| Valerianella carinata | 30.40028795 | 0.001569724 | increasing | 18 |
| Gentiana orbicularis | 28.01620298 | 0.001543833 | increasing | 24 |
| Euphorbia platyphyllos | 27.54637363 | 0.01021326 | increasing | 11 |
| Leontodon montanus | 27.10982078 | 0.003633873 | increasing | 33 |
| Capsella rubella | 25.87491383 | 8.26865E-05 | increasing | 22 |
| Geranium pusillum | 25.65089796 | 4.66033E-05 | increasing | 26 |
| Salix helvetica | 25.08424507 | 0.006786327 | increasing | 22 |
| Diphasiastrum alpinum | 23.96705395 | 0.008737195 | increasing | 27 |
| Pulmonaria australis | 23.1156462 | 0.009162509 | increasing | 40 |
| Ilex aquifolium | 22.89336784 | 2.86005E-05 | increasing | 47 |
| Eragrostis minor | 22.27151884 | 0.004186046 | increasing | 27 |
| Carex pendula | 22.00989342 | 0.003857593 | increasing | 43 |
| Artemisia genipi | 21.98847955 | 0.003713447 | increasing | 20 |
| Echium vulgare | 20.38787781 | 0.003109381 | increasing | 26 |
| Arabis bellidifolia | 20.38440292 | 0.011424611 | increasing | 26 |
| Hypochaeris radicata | 20.06552199 | 2.83521E-21 | increasing | 289 |
| Trifolium pallescens | 17.25465058 | 0.032014726 | increasing | 19 |
| Brachypodium rupestre | 16.83749897 | 5.83599E-05 | increasing | 44 |
| Polystichum lonchitis | 16.79173661 | 0.006077061 | increasing | 59 |
| Prunus laurocerasus | 16.7845182 | 0.049783489 | increasing | 19 |
| Salvia glutinosa | 16.44987404 | 0.012637372 | increasing | 32 |
| Minuartia sedoides | 15.84359241 | 0.000113714 | increasing | 121 |
| Digitaria sanguinalis aggr. | 15.72549744 | 2.26098E-11 | increasing | 143 |
| Impatiens glandulifera | 15.52081973 | 0.019501248 | increasing | 16 |
| Geranium dissectum | 15.47923123 | 1.9201E-07 | increasing | 86 |
| Malva neglecta | 15.41398337 | 0.036410135 | increasing | 14 |
| Pedicularis kerneri | 14.3373611 | 0.010917387 | increasing | 47 |
| Arenaria serpyllifolia aggr. | 14.15197644 | 7.69772E-07 | increasing | 113 |
| Arum maculatum | 13.80557463 | 0.004835942 | increasing | 100 |
| Setaria pumila | 13.58091035 | 0.000271882 | increasing | 47 |
| Rosa arvensis | 13.16536073 | 0.001342977 | increasing | 59 |
| Portulaca oleracea | 13.10817548 | 0.001317535 | increasing | 52 |
| Carex brizoides | 12.97688778 | 0.026914061 | increasing | 30 |
| Prunus spinosa | 12.86256009 | 0.004481076 | increasing | 56 |
| Cryptogramma crispa | 12.64016661 | 0.038118729 | increasing | 50 |
| Erigeron annuus | 12.61382577 | 2.74342E-05 | increasing | 73 |
| Poa minor | 12.52100694 | 0.00215841 | increasing | 66 |
| Euphrasia hirtella | 12.5042957 | 0.043871135 | increasing | 15 |
| Verbena officinalis | 12.29953717 | 0.030538925 | increasing | 27 |
| Geranium molle | 11.93444627 | 0.0166652 | increasing | 20 |
| Festuca arundinacea | 11.7397256 | 4.49918E-08 | increasing | 200 |
| Festuca pulchella | 11.54206129 | 0.016588501 | increasing | 36 |
| Papaver rhoeas | 11.45859105 | 0.014459608 | increasing | 30 |
| Hieracium piliferum aggr. | 11.32865293 | 0.003978419 | increasing | 58 |
| Veronica aphylla | 11.31494364 | 0.006825972 | increasing | 73 |
| Festuca violacea aggr. | 11.21340384 | 1.31294E-07 | increasing | 171 |
| Dryopteris carthusiana | 11.01391286 | 1.18652E-09 | increasing | 186 |
| Gentiana nivalis | 10.64403449 | 0.003331919 | increasing | 89 |
| Carex hirta | 10.16022864 | 0.001934148 | increasing | 138 |
| Luzula alpinopilosa | 9.610709876 | 0.000267611 | increasing | 305 |
| Epilobium anagallidifolium | 9.544721963 | 0.020367095 | increasing | 36 |
| Brassica napus | 9.489553469 | 0.000346484 | increasing | 84 |
| Carex echinata | 9.431247092 | 0.03716093 | increasing | 56 |
| Potentilla reptans | 9.295600259 | 9.74059E-05 | increasing | 265 |
| Agrostis alpina | 9.243301999 | 0.000196406 | increasing | 128 |
| Bromus sterilis | 9.038694196 | 0.01593248 | increasing | 45 |
| Galium mollugo aggr. | 9.022071247 | 1.60817E-09 | increasing | 516 |
| Viola hirta | 8.769109062 | 0.003446075 | increasing | 81 |
| Lactuca serriola | 8.727275879 | 0.018914137 | increasing | 34 |
| Senecio ovatus | 8.54466698 | 0.005310132 | increasing | 96 |
| Amaranthus hybridus aggr. | 8.463414142 | 0.040947457 | increasing | 26 |
| Tilia platyphyllos | 8.46012264 | 0.020513302 | increasing | 58 |
| Ligusticum mutellina | 8.449886231 | 4.14881E-05 | increasing | 448 |
| Pulsatilla alpina | 8.184777968 | 0.034496245 | increasing | 135 |
| Sonchus oleraceus | 8.157492142 | 0.000181065 | increasing | 100 |
| Crepis biennis | 8.152552389 | 1.44056E-05 | increasing | 249 |
| Cerastium glomeratum | 8.060564531 | 2.76932E-05 | increasing | 166 |
| Trifolium dubium | 8.010390324 | 0.000796981 | increasing | 119 |
| Trifolium alpinum | 7.992529583 | 0.032410107 | increasing | 204 |
| Ulmus glabra | 7.677931449 | 0.016951064 | increasing | 106 |
| Rubus fruticosus s. l. bdm-agg. | 7.617102499 | 6.47064E-07 | increasing | 673 |
| Agrostis schraderiana | 7.589445735 | 1.97231E-05 | increasing | 321 |
| Cirsium arvense | 7.513597423 | 0.004986629 | increasing | 88 |
| Brachypodium sylvaticum | 7.437797023 | 2.10067E-05 | increasing | 311 |
| Alopecurus pratensis | 7.11881419 | 1.23633E-05 | increasing | 369 |
| Carpinus betulus | 7.118249812 | 0.049734361 | increasing | 79 |
| Medicago sativa | 7.090256859 | 0.0016484 | increasing | 112 |
| Veronica montana | 7.067259491 | 0.033698212 | increasing | 62 |
| Agrostis capillaris | 7.003207369 | 1.33836E-12 | increasing | 916 |
| Senecio vulgaris | 6.936275808 | 0.009232722 | increasing | 86 |
| Erophila verna aggr. | 6.919432429 | 0.040542302 | increasing | 43 |
| Hedera helix | 6.770998735 | 8.23081E-05 | increasing | 668 |
| Epilobium parviflorum | 6.750960603 | 0.02273572 | increasing | 48 |
| Soldanella pusilla | 6.539241137 | 0.002579402 | increasing | 222 |
| Vicia sativa | 6.526745951 | 0.015238218 | increasing | 77 |
| Corylus avellana | 6.502037652 | 0.000108289 | increasing | 385 |
| Crepis aurea | 6.410616702 | 0.000643071 | increasing | 244 |
| Veronica officinalis | 6.297048976 | 0.000183142 | increasing | 367 |
| Potentilla sterilis | 6.122654591 | 0.016947825 | increasing | 165 |
| Prunus avium | 6.08741361 | 0.000654697 | increasing | 198 |
| Veronica persica | 6.062813827 | 5.93336E-07 | increasing | 545 |
| Calamagrostis varia | 6.062233228 | 0.002461999 | increasing | 259 |
| Leontodon autumnalis | 6.022843201 | 0.002840062 | increasing | 220 |
| Sorbus aucuparia | 5.98956535 | 4.39332E-05 | increasing | 794 |
| Ranunculus bulbosus | 5.964124783 | 0.016679091 | increasing | 179 |
| Avenella flexuosa | 5.838567827 | 0.000340126 | increasing | 637 |
| Euphrasia rostkoviana | 5.708989714 | 0.027022331 | increasing | 102 |
| Parnassia palustris | 5.383230862 | 0.043149392 | increasing | 190 |
| Sorbus aria | 5.37074454 | 0.010820041 | increasing | 234 |
| Crepis capillaris | 5.368183799 | 0.002908172 | increasing | 173 |
| Daucus carota | 5.353417513 | 0.020214754 | increasing | 157 |
| Juncus effusus | 5.13741021 | 0.037486849 | increasing | 178 |
| Carex pilulifera | 5.10498004 | 0.048098862 | increasing | 107 |
| Plantago lanceolata | 5.065531564 | 1.94048E-06 | increasing | 1249 |
| Calamagrostis villosa | 4.992704244 | 0.007931816 | increasing | 320 |
| Phyteuma orbiculare | 4.980940925 | 0.027695641 | increasing | 191 |
| Galium aparine | 4.815391545 | 0.00255005 | increasing | 249 |
| Circaea lutetiana | 4.802307879 | 0.040808052 | increasing | 170 |
| Rhinanthus alectorolophus | 4.763559923 | 0.032962001 | increasing | 154 |
| Sonchus asper | 4.740370658 | 0.005329497 | increasing | 157 |
| Festuca rubra aggr. | 4.700372642 | 1.93063E-08 | increasing | 1819 |
| Carex flacca | 4.632207748 | 0.003365458 | increasing | 509 |
| Viola reichenbachiana bdm-agg. | 4.624023827 | 0.000346867 | increasing | 752 |
| Euphrasia minima | 4.480161923 | 0.006730169 | increasing | 502 |
| Festuca halleri bdm-agg. | 4.380103663 | 0.013254014 | increasing | 297 |
| Carex caryophyllea | 4.36550279 | 0.049300838 | increasing | 141 |
| Echinochloa crus-galli | 4.245776023 | 0.016389359 | increasing | 163 |
| Nardus stricta | 4.215631402 | 0.033037644 | increasing | 634 |
| Cardamine resedifolia | 4.173372219 | 0.043844722 | increasing | 264 |
| Geum urbanum | 4.128296274 | 0.014762396 | increasing | 307 |
| Luzula sylvatica aggr. | 4.094418531 | 0.014053959 | increasing | 551 |
| Helictotrichon versicolor | 4.069657871 | 0.037523819 | increasing | 359 |
| Holcus lanatus | 3.799931263 | 0.003726887 | increasing | 767 |
| Ranunculus montanus aggr. | 3.510599259 | 0.006556408 | increasing | 709 |
| Fragaria vesca | 3.50117332 | 0.019359973 | increasing | 732 |
| Carex sylvatica | 3.337309111 | 0.008654842 | increasing | 658 |
| Medicago lupulina | 3.130612906 | 0.037183556 | increasing | 357 |
| Campanula scheuchzeri | 3.084187583 | 0.012210338 | increasing | 813 |
| Prunella vulgaris | 2.767203283 | 0.0145086 | increasing | 892 |
| Ranunculus tuberosus aggr. | 2.742083406 | 0.046724542 | increasing | 408 |
| Abies alba | 2.740643116 | 0.038839691 | increasing | 878 |
| Lolium perenne | 2.277960989 | 0.024098173 | increasing | 1549 |
| Phleum pratense aggr. | 2.196777582 | 0.029352225 | increasing | 627 |
| Anthoxanthum odoratum aggr. | 2.045954464 | 0.0320552 | increasing | 1788 |