

Temporal changes in soil properties: Insights from a 37-years-old Swiss soil library

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ABSTRACT

Over time, soils undergo qualitative and structural changes under the influence of climate, geomorphic processes, parent material weathering, and vegetation, ultimately developing into unique soil types and profiles. Although these pedological drivers are conserved globally, it remains unclear to what extent different soil profiles undergo similar changes over comparable timespans in various environments. To address this gap, we employed a diachronic approach to investigate temporal changes in soil physicochemical properties across diverse Swiss landscapes. Utilizing a comprehensive soil library initiated in 1982, we analyzed 28 archived and modern soil profiles from natural and semi-natural habitats across the Swiss landscape. Several soil properties across 256 soil horizons, including pH, organic matter content, cation exchange capacity, and carbon-to-nitrogen ratio, were assessed in 2020, and findings were compared with archived data to track changes over up to 37 years. We found that distinct soil types such as Cambisols, Fluvisols, and Gleysols exhibit unique physicochemical characteristics, with notable variations observed in the carbon-to-nitrogen ratio. We also found significant variation in how much the physicochemical properties of soil profiles changed over time, with predictable patterns related to climate. Habitats with warmer temperatures, more solar radiation, and increased humidity were the most susceptible to change. By elucidating how climate influences soil properties, this research contributes to more accurate predictions of climate change impacts on soil organic carbon storage.

1. Introduction

Soils are crucial natural resources that support the health of entire ecosystems, as well as human well-being, through a variety of emergent properties, such as carbon storage, water retention or maintaining habitats for soil biodiversity (Dazzi & Lo Papa, 2022; Dror, Yaron, & Berkowitz, 2022; Eswaran, Lal, & Reich, 2019; Lal, 2015; Telo da Gama, 2023; Zwanzig, Zwanzig, & Sauer, 2021). The formation and evolution of soils, known as pedogenesis, are influenced by a complex interaction of biotic and abiotic factors, including climate, topography, parent mineral material, vegetation, and soil microorganisms, as well as time (Jenny, 1994; A. Lehmann & Rillig, 2015; J. Lehmann & Kleber, 2015). Understanding how these factors affect pedogenesis across different ecosystems is essential for preserving soils and the services they provide, especially in the face of rapid environmental changes (Drenning, 2021). Nonetheless, one of the main challenges in understanding soil

physicochemical changes is that the interactions among various pedogenesis factors vary across ecosystems. This leads to different trajectories in soil formation and significantly affects the variation in soil carbon content and distribution across ecosystems (Davidson & Janssens, 2006). For example, tropical rainforest soils exhibit high organic matter due to elevated plant productivity and decomposition. In contrast, arid region soils show low organic matter and high salinity due to minimal rainfall and vegetation (Asner, Knapp, Cooper, Bustamante, & Olander, 2005). Along these lines, topography impacts soil formation through erosion and deposition, while parent mineral material influences the soil's physical and chemical properties, affecting carbon storage (Anderson, 1988; Basile-Doelsch, Balesdent, & Pellerin, 2020; Gregorich, Greer, Anderson, & Liang, 1998; Kögel-Knabner & Amelung, 2021). Hence, understanding variation in soil changes across habitats can help better predict changes in the services provided during land use and climate change across ecosystems (Briones, 2014; Wall et al., 2012;

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Wang et al., 2021).

A diachronic approach involving the study of soil changes over time is essential for understanding the long-term dynamics of soil properties and their responses to environmental changes (Fujisaki, Perrin, Garric, Balesdent, & Brossard, 2017; Trevisani & Bogunovic, 2022). Chronosequences, which, according to Walker et al. (2010), represent “a set of sites formed from the same parent material or substrate that differs in the time since they were formed”, have been advocated for studying soil development and carbon dynamics (Galluzzi, Plaza, Priori, Giannetta, & Zaccone, 2024; Walker et al., 2010). Studies using chronosequences have examined soil development and evolution following natural disturbances such as volcanic eruptions, landslides, and glacier retreats (Rasigraf & Wagner, 2022). While multiple studies successfully utilized chronosequences to investigate soil carbon dynamics, one limitation of using chronosequences is the assumption that all sites within the sequence have experienced similar environmental conditions apart from the time factor. In reality, factors such as variations in climate, biological activity, and human influence can introduce discrepancies, making it challenging to isolate the effects of time on soil development (Lin, 2011). Additionally, chronosequences may not fully capture transient or non-linear soil changes due to episodic disturbances or feedback mechanisms within the ecosystem. These limitations suggest the need for complementary approaches, such as long-term monitoring studies or experimental manipulations, to enhance our understanding of soil evolution and carbon dynamics over time (Luo et al., 2011).

In contrast, using soil libraries—consisting of well-documented, stored soil samples collected over time—offers a valuable resource for detecting subtle shifts in soil properties and pedogenetic characteristics (Bergh et al., 2022; Rhymes et al., 2020). Accordingly, soil archives in long-term soil monitoring enable retrospective analyses that account for methodological advancements and evolving research questions. However, soil archives also have limitations, including potential sample degradation, inconsistencies in storage methods, and the need for robust metadata to ensure comparability over time. Therefore, in principle, through the standardization of storage and documentation, combined with precise site description and geolocalisation, one could analyze the properties of—almost—the same soil profile at different time points and identify trends and patterns in soil carbon content and other properties, contributing to more accurate predictions of future soil changes (Jandl et al., 2014; Li, Wu, & Ma, 2020). In this regard, the National Cooperative Soil Survey Soil Characterization Database (Reinsch & West, 2010), the GlobalSoilMap project (Hartemink et al., 2010), or the LUCAS soil database (Orgiazzi, Ballabio, Panagos, Jones, & Fernández-Ugalde, 2018), among others, have been instrumental in tracking changes in soil organic carbon content due to land use changes and other factors (Arrouays, Poggio, Salazar Guerrero, & Mulder, 2020). For instance, studies have shown that organic matter in the mineral topsoil horizons changes rapidly due to various processes such as accumulation, decomposition, and incorporation (Cotrufo & Lavelle, 2022; J. Lehmann & Kleber, 2015; Rumpel & Kögel-Knabner, 2011; Schmidt et al., 2011). Hence, soil libraries could help refine models for better predicting future soil changes across ecosystems, provided archived soil samples do not change significantly during storage (Nunes et al., 2021).

In this study, we asked whether soil profiles and their inherent physicochemical properties change similarly across ecosystems over several decades. To address this question, we utilized a soil physical library from the University of Neuchâtel, Switzerland, to investigate changes in soil types and their properties over time across different climatic conditions and environmental gradients. By accurately describing horizon-by-horizon soil profiles' changes from diverse habitats, including grasslands, forests, and riparian areas, we aimed to determine if soil libraries can reveal broad changes in soil physicochemical properties and how these changes vary according to soil types across environments. We hypothesized that soil variables related to soil organic carbon show significant variation over time, particularly in the uppermost layers, and that different climatic conditions will generate

variation in the rate of these changes. Specifically, we predicted that ecosystems with higher levels of disturbance (i.e., such as Fluvisols) or with higher biological activity in warmer and more humid habitats (i.e., Leptosols and Umbrisols) would show higher levels of change. In contrast, soil types already undergoing complex pedogenetic processes in more stable conditions, such as Podzol, would show little physicochemical change. An important assumption of our study is that, over the approximately four decades covered by our soil library, the climate in the Central European Alps has been changing rapidly (Barros et al., 2014; Gobiet et al., 2014). This likely exerts significant abiotic pressure, potentially accelerating soil evolution (Karmakar, Das, Dutta, & Rakshit, 2016).

2. Material and methods

2.1. The soil library and selection of soil profiles

We used both synchronic and diachronic approaches to investigate variations in soil properties across the landscape and through time. The synchronic approach compares soil profiles across habitats (spatial), while the diachronic approach compares the same soil profiles at different time points (temporal). This was achieved using a physical soil library initiated by one of our co-authors (J.-M. Gobat) in 1982 at the University of Neuchâtel, Switzerland. This soil library now includes more than 4000 referenced soil samples taken for each horizon described in the field, dried in an oven at 40 °C, sieved at 2 mm, and stored in a dark and temperate environment in plastic boxes.

We followed a multistep selection protocol to address our aims of comparing modern and archived soils, as shown in Fig. S1. First, we only selected natural and semi-natural habitats across Switzerland, representing a wide range of continental to temperate conditions. Second, we only selected soil profiles whose data was as complete as possible and contained valid reference information, including precise GPS coordinates, vegetation cover, soil type, and habitat. This information was necessary to retrieve the original soil location precisely. Third, we selected soil profiles that originated from a variety of habitats, here including the alpine grasslands (above 2000 m above sea level), lowland grasslands, coniferous and broadleaf forests, riparian ecosystems, and low-elevation lakeshore habitats. Finally, we only selected those profiles in which all soil samples were sufficient to re-perform the necessary analyses in 2020 and referenced for the entire soil profile. Based on these selection criteria, we obtained 37 complete soil profiles spread across Switzerland's three major biogeographic zones: the Jura, the Plateau, and the Alps. Next, we removed all soil profiles containing a single horizon and soil profiles from which we could not trace back their original documentation, either in the form of a thesis, a report, or a peer-reviewed publication. Ultimately, we obtained 28 complete soil profiles that were surveyed and analyzed in 2020, including 6 Cambisols, 7 Fluvisols, 7 Gleysols, 1 Leptosol, 1 Luvisols, 5 Podzols, and 1 Umbrisol (see Fig. 2, Appendix A. Fig. S2 and Fig.S3).

To ensure that the storage of the archived soil samples did not significantly alter their physicochemical properties over time, we used—as a reference—the loss on ignition (LOI) method (Allen et al., 1974a) to compare initial archived results with those of 2020. The LOI method estimates the total organic matter in the soil (SOM), for which the basic technique did not change during the past 40 years. We randomly selected several profiles from the archived soil samples list. Then, by performing the loss of ignition analysis on all soil samples again in 2020 (i.e., weighting the sample before and after burning the sample at 450 °C for 4 hrs) and by obtaining comparable results on the stored samples, we assumed that little to no alteration happened during sample storage (see Appendix A. Table S1).

2.2. Soil sampling and analyses

During the summer of 2020, we visited all 28 initial soil profile

locations, re-dug a soil profile, and described and classified the soil profile horizons following the FAO Guidelines for soil description (Jahn, Blume, Asio, Spaargaren, & Schad, 2006). We collected soil samples for every layer (organic and mineral horizons), removing coarse elements > 2 cm and roots. Soil description included the following descriptors: horizon depth, colour (Munsell soil colour chart), coarse elements (> 2 mm), structure (single grain, massive, granular, polyedric), texture (sand 2 mm – 50 µm, silt 50–2 µm, clay < 2 µm) and geological substrate. In addition, we determined the relative abundance of carbonates in situ by the HCl 6 M test and soil pH Hellige (for details on the modern soils, see Appendix A. **Table S2 and Table S3**).

The archived and modern soil samples were subsequently analyzed in parallel with the same protocols by initially drying the modern soils at 40 °C. We retrieved seven different parameters on all soil samples: (1) pH, measured in distilled water and KCl, using a 1:5 soil-to-solution ratio with a Metrohm 827 pH meter (Metrohm AG, Herisa, Switzerland). (2) Soil organic matter, using the LOI method (Allen et al., 1974b) and corrected by the 'Howard' correction factor (Howard & Howard, 1990). (3) Soil total cationic exchange capacity (CEC), using the 'cobalt hexamine trichloride' method (Ciesielski & Sterckeman, 1997). (4) Total carbonates (CaCO₃) using a Calcimeter Bernard method and HCl 6 M. (5) Total carbon (C_{tot}) and nitrogen (N_{tot}), with an elemental analyzer (FLASH 2000, Thermo Scientific, Waltham, Massachusetts, USA), SOC was determined using CHN elemental analysis for all carbonated and non-carbonated samples. Organic carbon samples were first decarbonated (37 % fuming HCl for 6 h in a desiccator) to remove the mineral fraction. Then, organic carbon was quantified using the same method as for total carbon. By calculation, we added this information to the text. (6) carbon-to-nitrogen ratio (C: N). And (7) Soil relative humidity (Rh)

after drying the soils at 105 °C for three days. This was done for both recent and archived soil samples. (8) Soil particle size analysis was done using laser granulometry (Pansu & Gautheyrou, 2003). Particle size analysis was classified as follows: clays: < 2 µm, fine silt: 2—20 µm, coarse silt: 20—50 µm, fine sands: 50—200 µm, coarse sands: 200—2000 µm.

2.3. Extraction of climatic variables

To obtain the site-specific climatic niche, for each site, we extracted environmental data at a 20 m resolution from Swiss maps, including growing degree days, annual average potential solar radiation, and potential evapotranspiration, from associated environmental layers, since these variables have been shown to explain best the Alpine climatic conditions (C. Körner, 2007; L. Pellissier et al., 2013; Loïc Pellissier et al., 2016). Values for degree days and potential evapotranspiration were calculated from meteorological stations using a Digital Elevation Model (DEM) at 20 m resolution and interpolated based on Zimmermann & Kienast (1999).

2.4. Statistical analysis

We performed all statistical analyses with R software, version 3.5.1 (R Development Core Team 2020). We used algorithms for quantitative pedology, the *aqp* package (Beaudette, Roudier, & O'Geen, 2013) to visualize and analyze soil horizons and profiles between archived and modern soil profiles. To visualize initial soil similarities based on the measured soil parameters, we computed a summed, depth-segment-aligned dissimilarity matrix (using the *profile_compare* function in the

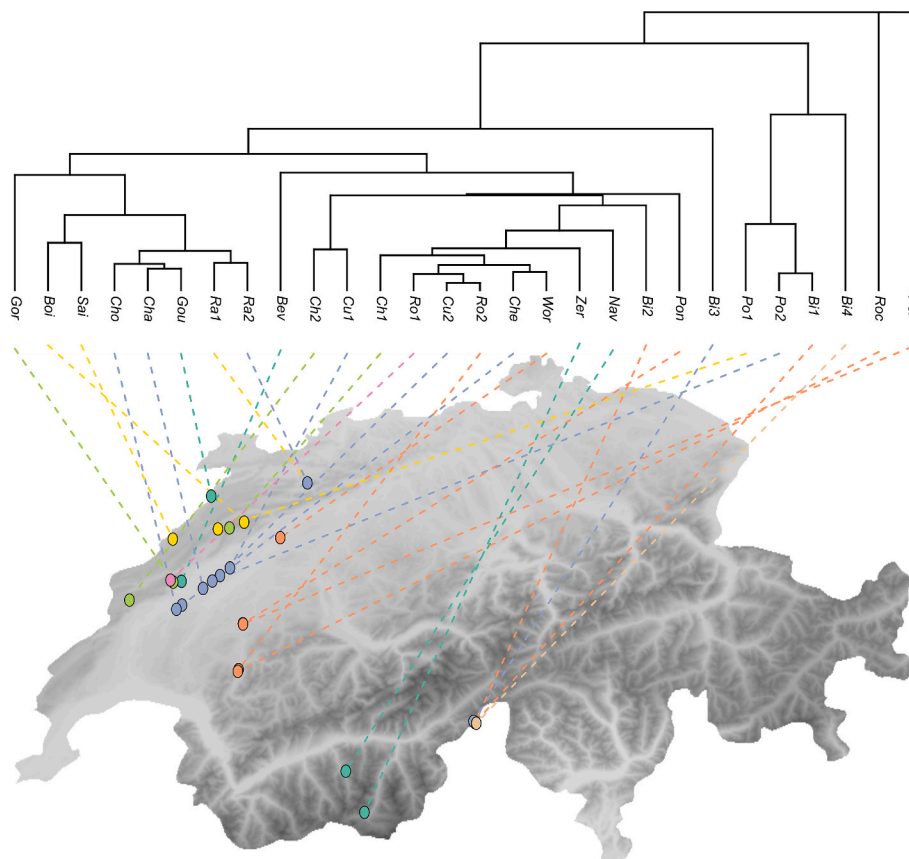


Fig. 1. Location of 28 soil profiles. Shown is the divisive hierarchical clustering of 28 soil profiles based on five soil physicochemical parameters, including soil pH, soil organic matter (SOM), organic carbon (C_{org}), total nitrogen (N_{tot}), and the carbon-to-nitrogen ratio (C: N). Soil profile locations are visualized on a map of Switzerland. Soils are colour-coded based on soil classes as determined by the World Reference Base for Soil Resources (WRB): Cambisols (turquoise), Fluvisols (orange), Gleysols (purple), Leptosols (pink), Luvisols (green), Podzols (yellow) and Umbrisols (brown).

aqp package) to a maximum depth of 40 cm. We selected soil pH, soil organic matter (SOM), organic carbon (C_{org}), total nitrogen (N_{tot}), and the carbon-to-nitrogen ratio (C:N) as the key physicochemical properties anticipating these would exhibit faster changes (Fig. 1 and Fig. 2). Based on this matrix, we computed a divisive hierarchical clustering (*diana* in the package *cluster*) and visualized it using the *hclust* function. Initial soil profiles (those from the soil libraries) and their physicochemical similarities tree were then mapped on a Swiss map using the *phylo.to.map* function in the package *phytools* (Revell, 2012) (Fig. 1).

To estimate how soil properties (except total carbonates, for which field tests showed too little or no reaction) changed over time, we first computed a depth-wise summary (medians \pm 25 and 75 percentiles) of horizon-level attributes using the *slab* function in *aqp* (Fig. 3) to visualize average changes in soil properties between archived and modern profiles. Second, we computed the horizon depth-weighted mean value for each parameter and each soil horizon at a maximum of 30 cm depth. Differences between archived and modern soils for each variable were then tested using linear models with soil age class as a fixed factor and soil profile as the blocking factor (Fig. 4).

Finally, to estimate the effect of climate on soil changes, we performed a linear regression analysis between the first and second climate principal component analysis (PCA) axes (Fig. S2), separately, and the pairwise distances between each archived and its corresponding modern soil from the dissimilarity matrix (*profile_compare* function) as computed above.

3. Results

3.1. Climate effect on soil profiles' change over time

The environmental PCA (Fig. S2) indicates that the selected soil profiles from the soil library ($n = 28$) and homologous modern soil profiles are relatively well spread and grouped along the environmental gradient from cold (frost days) and humid (humidity = average evapotranspiration, precipitations = average precipitations) to warm (degree-days) and dry (solar radiations). This also indicates that archived and modern soil profiles are under the same climate conditions as homologous profiles are close to each other. In addition, we show that the coordinates placement method for archived soil samples collected before 1989 was done accurately. Moreover, observations made during the fieldwork and the physicochemical analyses on archived and modern soil samples also attest to the accuracy of the information referenced in the soil library and its corresponding archived documents.

3.2. Did soils change over decades?

The divisive hierarchical clustering of 28 soil profiles, based on five physicochemical parameters (soil pH, soil organic matter (SOM), organic carbon (C_{org}), total nitrogen (N_{tot}), and the carbon-to-nitrogen ratio (C: N), reveals distinct clusters among soil profiles across Switzerland (Fig. 1). These results highlight the diversity of soil types

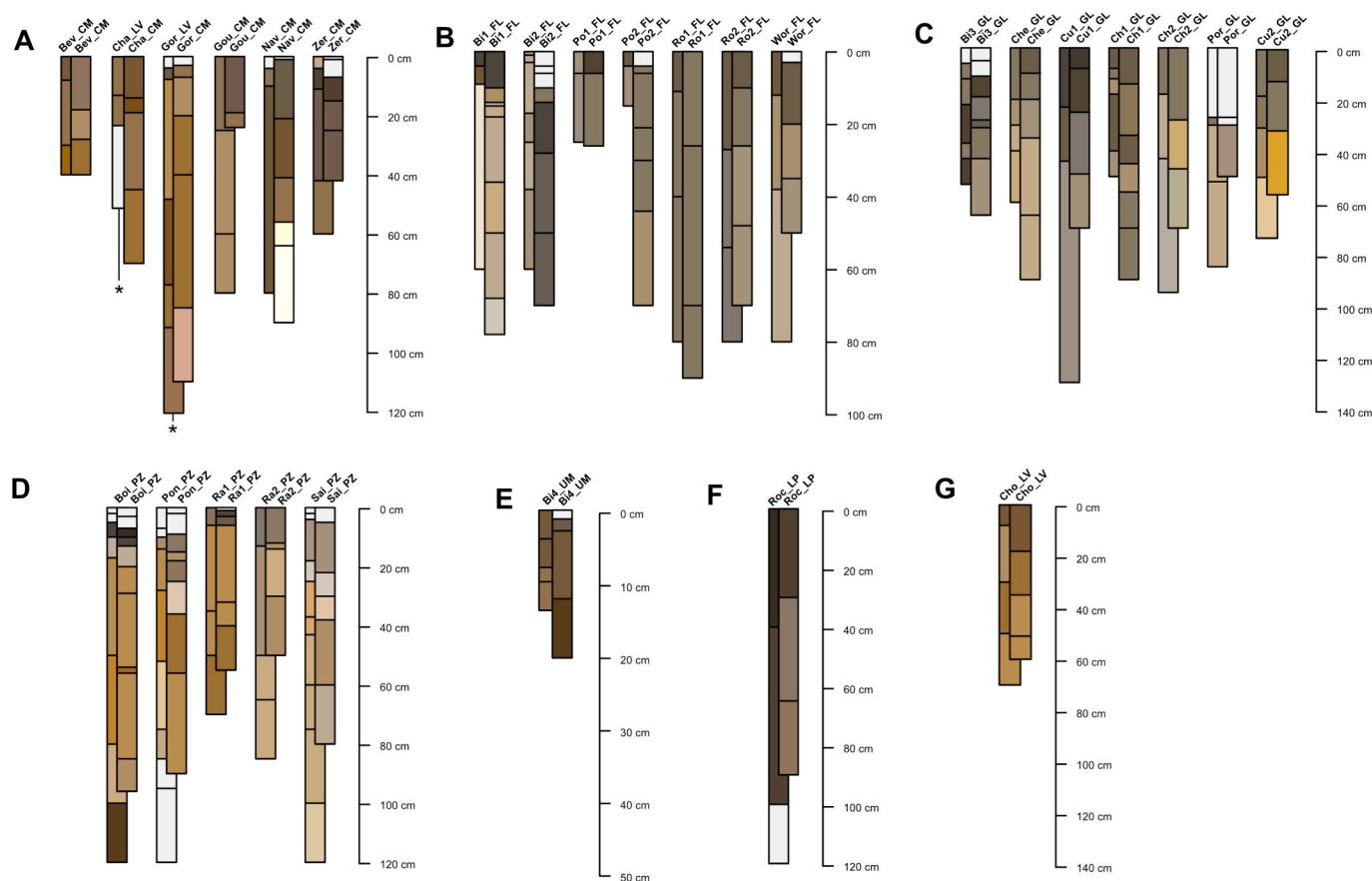


Fig. 2. Soil profile collection of archived and modern soil groups. The figure shows a numerical generation of all archived soil profiles (background) and the modern soil profiles (foreground). Panel (A) shows all Cambisols for archived and modern soil profiles. Three archived soils were not described as Cambisols but are still shown side by side. These three soils' profiles are highlighted with a star (*). Archived and modern soil profiles' numerical generation are shown for: Cambisols (A), Fluvisols (B), Gleysols (C), Podzols (D), Umbrisols (E), Leptosols (F), and Luvisols (G). The first three letters of the name represent the location as described in Table 1. The last two letters represent the soil class: Cambisols (CM), Fluvisols (FL), Gleysols (GL), Podzols (PZ), Umbrisols (UM), Leptosols (LP), and Luvisols (LV). Colours indicate the horizon Munsell colour codes for organo-mineral and mineral horizons are represented, the white colour indicates all histic organic horizons (H, Hf, Hm), the organic horizons (OL) on the surface are not shown here.

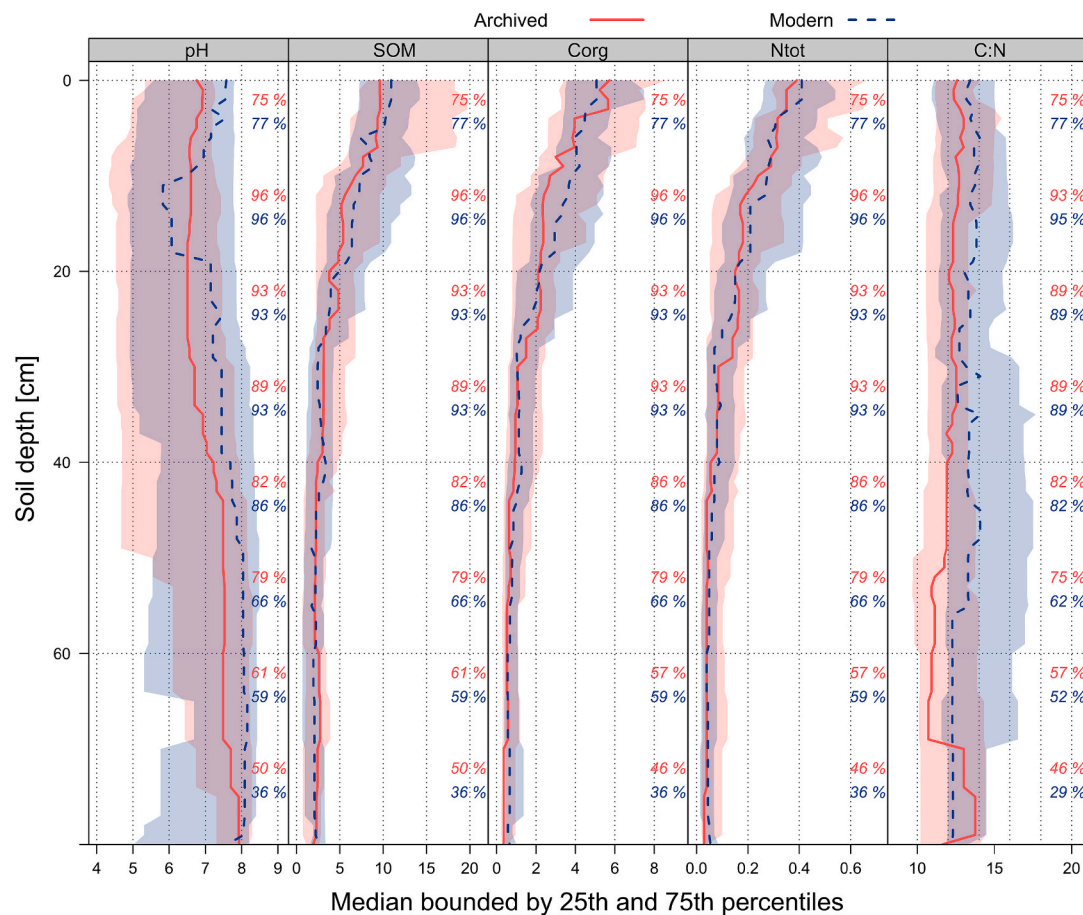


Fig. 3. Depth-wise aggregation of archived and modern soil profiles, for pH, soil organic matter (SOM), organic carbon (C_{org}), total nitrogen (N_{tot}), and carbon-to-nitrogen ratio (C: N). Lines represent median values, and shaded areas represent the 25th (left) and 75th (right) percentiles around the median values (lines) calculated for each variable across all 28 soil profiles. Blue colours represent the archived soil profiles, and red colours represent the modern soil profiles.

within regions, showcasing unique characteristics and variations across different landscapes. In total, we identified seven Cambisols, including one previously classified as a Luvisol in the soil library but renamed as a Cambisol in 2020, as well as seven Fluvisols, seven Gleysols, and five Podzols. Additionally, we found one Umbrisol, one Leptosol, and one Luvisol (Fig. 2). The varied nature of these soils emphasizes the diversity of soil types across the Swiss landscape.

Cambisols (Fig. 2A; $n = 6$) feature subsurface horizons with varied degrees of pedogenetic alteration, from weak to relatively strong. These soils were observed across diverse landscapes in pastures, grasslands, and forests. All Cambisols exhibited cambic horizons with varying degrees of brownification processes (Appendix B. Table S1-3 and Fig. S1-S3). Notably, in the Swiss Alps (Nav and Zer), two Cambisols were found on screes and steep slopes (Appendix B. Table S46-S48 and Table S80-S82, and Fig. S24 and Fig. S37). Additionally, two soil profiles (Cha and Gou) displayed altered subsurface horizons in the Jura Mountains under grasslands (Appendix B. Table S25-S27 and Table S43-S45, and Fig. S17 and Fig. S23). Comparison of archived and modern soil profiles revealed that except for two Cambisols (Cha_CM and Gor_CM), which were previously classified as Luvisols in the soil library (Appendix B. Table S40-S42 and Fig. S22), the reference soil group remained consistent.

Fluvisols (Fig. 2B; $n = 7$) were predominantly located in ecosystems with frequent alluvial deposits characterized by heterogeneous sandy textures. These soils primarily developed in carbonated sedimentary rock environments. Riparian Fluvisols near the Sarine River (Po1, Po2, Ro1, Ro2) and Aar River (Wor) originated from calcareous parent material (Appendix B. Table S48-S52, Table S65-S70, Table S77-79 and

Fig. S25-S26, Fig. S32-S33, and Fig. S36). In alpine settings such as the Swiss Alps (Bi1 and Bi2), Fluvisols formed from alluvial deposits derived from the North Pennine Trias dolomite (Appendix B. Table S4-S9, and Fig. S4-S8). Comparing old and modern profiles, Fluvisols retained their classification over nearly four decades, showing minimal differentiation between those from recent riparian deposits and older flood-prone alluvial valleys (Ro1). However, older Fluvisols displayed higher organic matter content, exhibited deeper profiles with thicker layers, and sustained finer surface sands than the recent soil profiles.

Gleysols (Fig. 2C; $n = 7$), characterized by gleyic properties and reducing conditions, were predominantly found in low-elevation lake-shore environments along the southern shore of Lake Neuchâtel and alpine swamps like the Binntal Valley (Bi3, Table S10-S12 Table, and Gower's dissimilarity metric. These soils exhibit hydromorphic features, varying in water saturation levels with principal and supplementary qualifiers (Appendix B. Table S28-S30 and Fig. S18, Table S34-S36 and Fig. S20, Table S19-S21 and Fig. S15, Table S22-S24 and Fig. S16, Table S56-S58 and Fig. S29). Due to intermittent groundwater saturation, one profile initially identified as a Stagnosol (Cu2) was alternatively described as a Gleysol to emphasize its varying saturation characteristics (Appendix B. Table S37-S39, and Fig. S21).

Podzols (Fig. 2D; $n = 5$) with spodic horizons were observed in pine forests in the Jura mountains. These soils demonstrated diverse characteristics reflected in principal and supplementary qualifiers. Across archived and modern profiles, the reference soil group remained consistent (Appendix B. Table S16-S18 and Fig. S14, Table S53-S55 and Fig. S27-S28, Table S59-S64 and Fig. S30-S31, Table S74-S76 and Fig. S35).

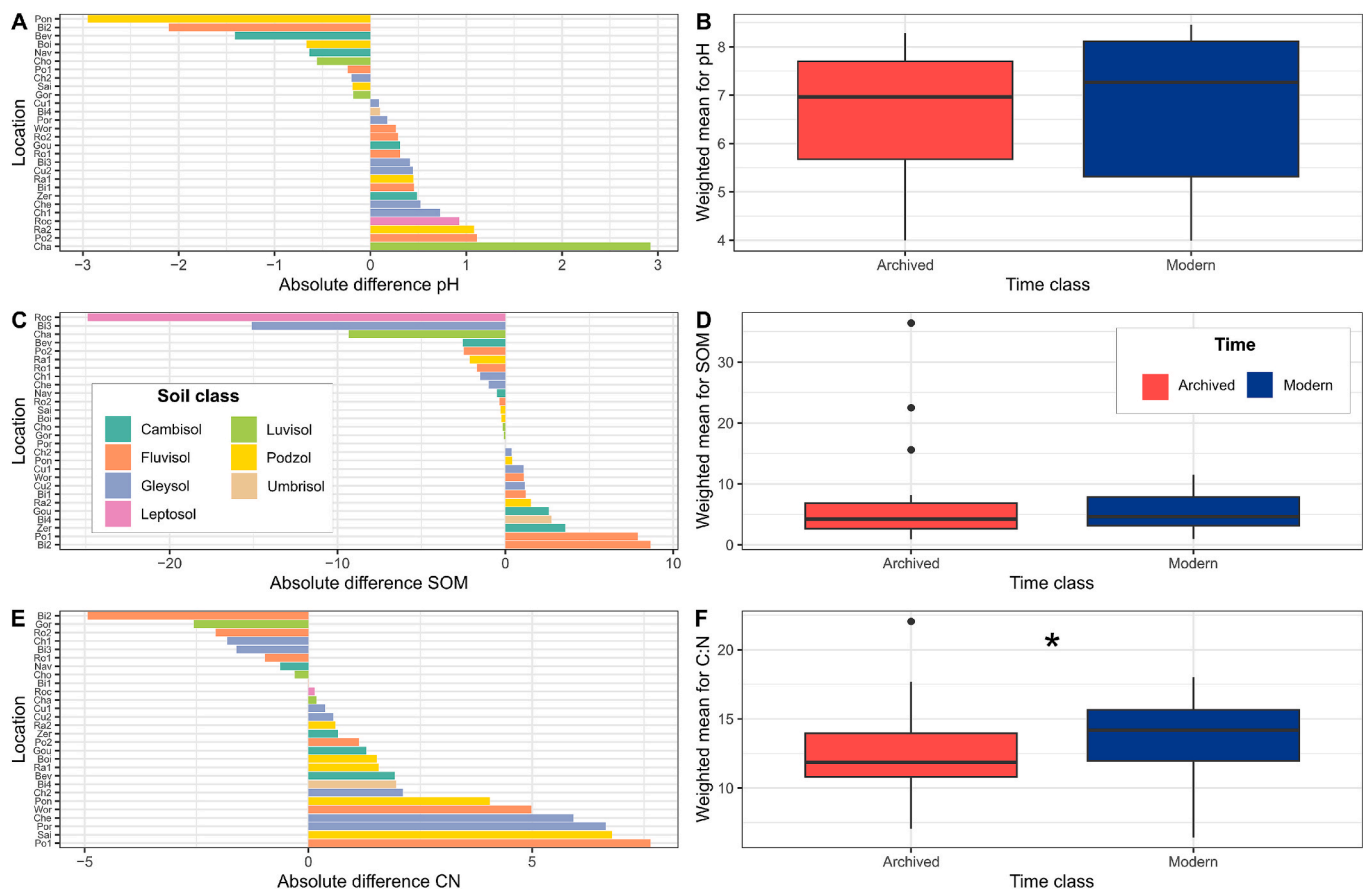


Fig. 4. Soil physicochemical parameters change over time. Shown are the absolute differences between modern and archived soil parameters based on the horizon depth weighted means for the first 30 cm, including pH, soil organic matter (SOM), and carbon-to-nitrogen ratio (C: N) with the left bar plots representing the absolute differences (modern minus archived value) for each soil profile. Positive values indicate an increase, while negative values indicate a decrease in the soil parameter. Colours indicate soil classes: Cambisols (turquoise), Fluvisols (orange), Gleysols (purple), Leptosols (pink), Luvisols (green), Podzols (yellow), and Umbrisols (brown). Panels on the right represent average differences between archived and modern soils. Colours indicate the time class: archived (red) and modern (blue). Asterisks indicate significant differences between time classes ($p < 0.05$).

One unique **Umbrisol** profile (Fig. 2E; $n = 1$) featured a surface horizon with significant organic matter content and low base saturation, situated southwest of Ofenhorn peak in the Binntal Valley (Bi4, Appendix B. Table S13-S15, and Fig. S11-S13).

One unique Hyperskeletal **Leptosol** (Fig. 2F; $n = 1$) was identified in 2020 (Roc). It is composed of hard rock material and less than 20 % fine earth and is located in a limestone scree-filled cirque at Roche-Devant. This soil profile corresponded closely with its description in the soil library, which was previously also classified as a Leptosol (Appendix B. Table S71-S73 and Fig. S34).

Lastly, in 2020, only one soil profile remained in the **Luvisol** class (Fig. 2G; $n = 1$) (Appendix B. Table S31-S33 and Fig. S19). Luvisols are indeed characterized by an argic horizon starting before 100 cm depth (WRB, 2022a; WRB, 2022b). Following this definition, we reclassified two archived Luvisols (Gor_LV, Cha_LV) as modern Cambisols (Fig. 2A; Gor_CM, Cha_CM).

To summarize, the comparative analyses of soil profiles across Swiss landscapes reveal persistent classifications for most soil classes over nearly four decades, with a notable evolution for specific soil characteristics. Fluvisols, for instance, maintained a consistent classification across archived and modern profiles, showing minor variations in granulometry and clay content across different environments. Conversely, soils exhibiting gleyic properties demonstrated subtle changes, exemplified by the Cu2 profile reclassified as a Gleysol due to intermittent groundwater saturation and variable clay content.

3.3. Changes in soil physicochemical parameters

The soil segmentation analyses highlighted changes in physicochemical parameters between archived and modern across soil depth (Fig. 3). Overall, independently of the archived versus modern comparison, soil pH tended to become more alkaline from top to bottom, moving from an average of 7 to 8 below 60 cm of depth (Fig. 3, pH). The total organic matter decreased from an average of 9.6 % to 1.1 % at the bottom (Fig. 3, SOM), total nitrogen decreased from 0.39 to 0.02 % (Fig. 3, N_{tot}), and total carbon from 7.8 to 0 (Fig. 3, C_{tot}). On the other hand, the carbon-to-nitrogen ratio remained constant throughout the soil profiles, from 12.6 to 15.8 on average (Fig. 3, C: N). Noteworthy, the trends observed for total organic carbon (Corg), total nitrogen (Ntot), and the carbon-to-nitrogen (C: N) ratio show distinct patterns across the soil profiles. Both Corg and Ntot decreased over time or depth, with Corg declining from 7.8 % to 0 % and Ntot from 0.39 % to 0.02 % (Fig. 3). In contrast, the C: N ratio remained relatively stable or increased slightly, ranging from 12.6 to 15.8 on average. The vertical percentages in Fig. 3 indicate relative parameter variations across different depths or time points. Despite the overall decline in carbon and nitrogen content, the C: N ratio did not show a corresponding decrease, suggesting a differential rate of change between these two components.

Weighted means' comparisons between archived and modern soils show that all soil parameters measured to a total depth of 40 cm did not change across time (Fig. 4, and Fig. S4), except for the C: N ratio, which significantly increased from an average of 12.5 to an average of 13.7 across all soil profiles (Fig. 4, and Table S5, Time effect: $p = 0.036$).

Table 1

Sites of soil profiles. Shown are the names of the study locations, with their corresponding coordinates (WGS84), the environment in which the soil profile was found, the soil class based on the World Reference Base for Soil Resources (WRB, 2022) nomenclature, and the year in which the soil was archived in the soil library. Location ID corresponds to what is shown in Fig. 1. Environments considered were alpine grassland, beech forest, lakeshore forest, mesic grassland, pine forest, riparian forest, and subalpine grassland.

Location	Location_ID	Environment	Latitude	Longitude	Archived profile soil calss1	Year archived
Bevaix	Bev	Beech forest	46.9239342	6.80642195	Cambisol (Calcaric)	1992
BinntalBlatt1	Bi1	Alpine grassland	46.3764917	8.28762418	Arenic Dolomitic Fluvisol	1989
BinntalBlatt2	Bi2	Alpine grassland	46.3753131	8.28643598	Stagnic Histic Dolomitic Fluvisol	1989
BinntalBlatt3	Bi3	Alpine grassland	46.3812222	8.27815689	Epihistic Reductic Gleysol	1989
BinntalBlatt4	Bi4	Alpine grassland	46.373596	8.29227089	Cambic Umbrisol	1989
BoisRaiguel	Boi	Beech forest	47.1534827	7.12183631	Podzol	1985
Chasseral	Cha	Subalpine grassland	47.1311101	7.04797414	Luvisol (Calcaric)	1985
Chasseron	Cho	Subalpine grassland	46.8512509	6.54375673	Luvisol (Calcaric)	1985
Chevroux	Che	Lakeshore forest	46.8966314	6.91487742	Reductic Gleysol	1983
Cheyres1	Ch1	Lakeshore forest	46.8318322	6.80877451	Reductic Gleysol (Humic)	1983
Cheyres2	Ch2	Lakeshore forest	46.8155713	6.78060872	Reductic Gleysol	1983
Cudrefin1	Cu1	Lakeshore forest	46.976042	7.05033719	Reductic Gleysol	1983
Cudrefin2	Cu2	Lakeshore forest	46.9462845	7.00016603	Stagnic Gleysol	1983
Gorgier	Gor	Beech forest	46.9210838	6.76406129	Luvisol	1984
Goumois	Gou	Mesic grassland	47.2544947	6.95595703	Cambisol	1986
Nava	Nav	Alpine grassland	46.1876782	7.63431763	Cambisol	1988
Pontins	Pon	Pine forest	46.9251253	6.96136889	Podzol (Calcaric)	1983
Portablan	Por	Beech forest	47.1269848	6.98977767	Epihistic Reductic Gleysol	1984
Posieux1	Po1	Riparian forest	46.7598333	7.11558789	Fluvisol (Calcaric)	1987
Posieux2	Po2	Riparian forest	46.7583958	7.11625097	Fluvisol (Brunic, Calcaric)	1987
Raimeux1	Ra1	Beech forest	47.3055776	7.44067361	Podzol	1988
Raimeux2	Ra2	Beech forest	47.3055506	7.44067361	Stagnic Gleysol on Podzol	1988
RocheDevant	Roc	Alpine grassland	46.9287591	6.75078134	Hyperskeletal Leptosol	1984
Rossens1	Ro1	Riparian forest	46.5817282	7.09371542	Fluvisol (Oxyaquic, Calcaric)	1989
Rossens2	Ro2	Riparian forest	46.574808	7.08993738	Fluvisol	1989
Saignolis	Sai	Pine forest	47.0876771	6.76213602	Podzol	1995
Worben	Wor	Riparian forest	47.0932328	7.30426767	Fluvisol (Brunic, Calcaric)	1989
Zermatt	Zer	Alpine grassland	46.0281193	7.7286543	Cambisol	1989

^aFor additional nomenclature and name change across modern and archived sampling see Tables S1 and S2.

Fig. 4 illustrates the absolute differences in key soil parameters between archived and modern soil profiles across various soil classes: Cambisols, Fluvisols, Gleysols, Leptosols, Luvisols, Podzols, and Umbrisols. All soil types were heterogeneously distributed across the axis for pH, showing no particular grouping. However, Cambisols (Bev, Nav, Gor), Fluvisols (Bi2, Po1), Podzols (Pon, Sai, Boi), Luvisol (Cho), and Gleysol (Ch2) all exhibited a decrease in pH over 37 years. In contrast, the remaining 18 soil profiles showed increased soil pH. In terms of soil organic matter (SOM), a similar trend of heterogeneous distribution is observed, with decreases in SOM for Cambisols (Nav, Cha, Gor, Bev), Fluvisols (Ro1, Ro2), Podzols (Ra1, Sai, Boi), Gleysols (Bi3, Che, Ch1, Por), Luvisol (Cha), and Leptosol (Roc). The other 13 profiles displayed an increase in SOM content. Lastly, the carbon-to-nitrogen ratio (C:N) was lower for Cambisols (Gor, Nav), Fluvisols (Bi1, Bi2, Ro1, Ro2), Gleysols (Bi3, Ch1), and Luvisol (Cho), while the remaining 10 profiles exhibited a higher C: N ratio.

3.4. Soil physicochemical properties change across climatic gradients

When correlating the first two axes of the PCA with the average physicochemical distance between modern and archived soil profiles (Fig. 5A), our analysis revealed significant negative correlations with both the first (Fig. 5B, PCA1, $n = 28$, $r = -0.61$, $p = 0.03$) and the second (Fig. 5C, PCA2, $r = -0.56$, $p = 0.001$) axis of climate-based principal component analysis (PCA). These findings suggest that soils exhibiting the most remarkable changes in their physicochemical properties are in regions characterized by lower elevations, warmer and drier conditions (correlated with PCA1), and areas with lower solar radiation levels (correlated with PCA2). This result indicates that environmental factors such as temperature, moisture, and solar exposure play crucial roles in modifying soil physicochemical properties over time.

4. Discussion

4.1. Soil evolution over time: Profile-level observations

We investigated various ecosystems to determine whether soils have remained stable or undergone significant transformations over 37 years. Although our selection of soil profiles is not exhaustive relative to the highly heterogeneous landscape of the Central European Alps (Gobat & Guenat, 2019) and is constrained by the availability of our soil library, it still captures a wide array of pedogenetic processes. Our research demonstrates significant soil diversity within the relatively small biogeographical area investigated (Fig. 1). By characterizing the presence or absence of specific diagnostic horizons, we were able to precisely assign names to the different modern soil types and compare topological changes over time. From each reference soil group, according to the World Reference Base for Soil Resources (Schad, 2023) we discriminated seven major soil types (Cambisol, Fluvisol, Gleysol, Leptosol, Luvisol, Podzol, Umbrisol). With few exceptions, most of the names assigned to the soils, remained unchanged, indicating minimal changes at the soil profile level. This is not entirely surprising, as pedogenetic processes that significantly alter soil types typically extend over periods longer than four decades (Jenny, 1994). However, slight variations were observed in situ, which are discussed below.

Cambisols, as one of the most widespread soil groups in our study, demonstrated a range of pedogenetic responses depending on their environmental context. While Cambisols are often considered transitional soils that can evolve into more developed soil types given sufficient time and stable conditions, our findings suggest that over 37 years, these soils exhibit limited horizon differentiation and overall structural stability. In high-altitude or steeply sloped environments, Cambisols can be subjected to active geomorphic processes, including colluviation and episodic mass wasting, which may counteract more profound horizon development. In contrast, the minimal change displayed Cambisols in lowland or forested areas might be explained by the balance between

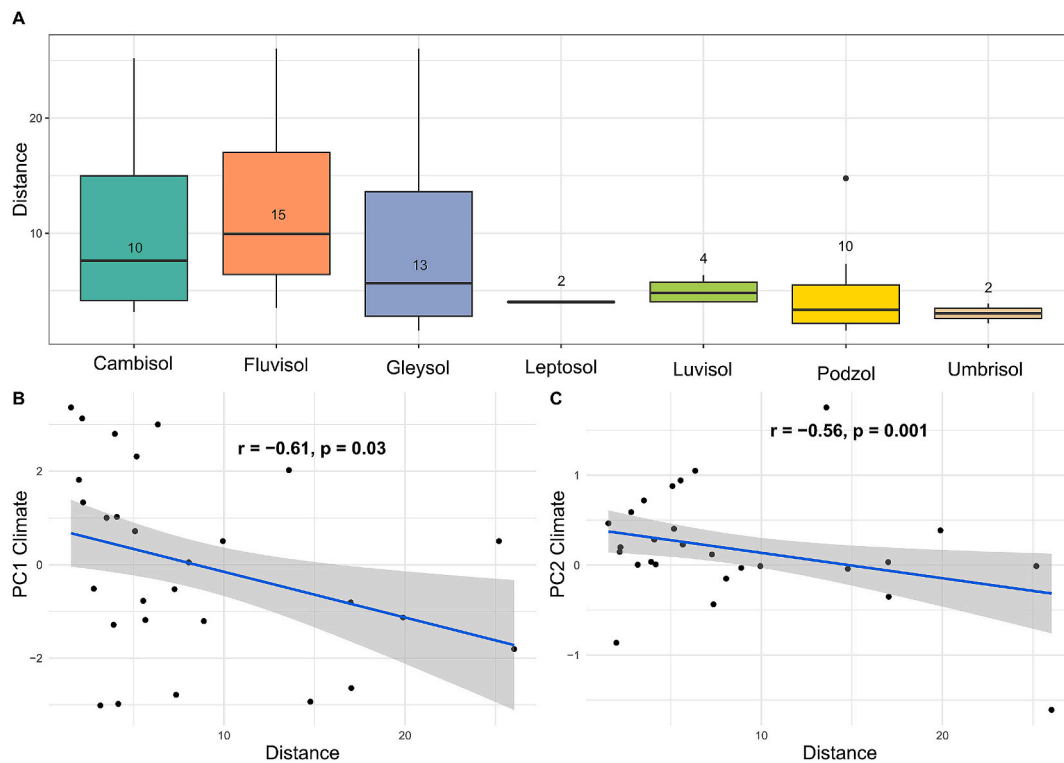


Fig. 5. Physicochemical distance between archived and modern soil profiles. Shown are (A) Boxplots averaging the physicochemical distance between time classes (archived and modern) and soil classes based on soil pH, cation-exchange-capacity (CEC), soil organic matter content (SOM), organic carbon (C_{org}), total nitrogen (N_{tot}) and the carbon-to-nitrogen ratio (C: N). Colours indicate the different soil classes: Cambisols (turquoise), Fluvisols (orange), Gleysols (purple), Leptosol (pink), Luvisols (green), and Podzols (yellow), and Umbrisols (brown). Boxplots represent, from bottom to top, minimum, first quartile, median, third quartile, and maximum, and dots represent the outliers. Scatterplots (B, C) show the linear regression between the physicochemical distance and the principal component (PCA) 1 and 2 of the climate for each site, respectively. The blue line and shaded grey area represent the linear fit and the 95% confidence intervals, respectively.

pedogenic processes and stabilizing factors such as vegetation cover and soil organic matter accumulation (Catoni, D'Amico, Zanini, & Bonifacio, 2016; Kögel-Knabner & Amelung, 2021). Moreover, one of our study's most notable aspects of Cambisols is their sensitivity to localized environmental conditions. In some profiles, we observed slight changes in organic matter content and soil structure, likely influenced by variations in vegetation dynamics and microclimatic factors (de Godoy Fernandes, de Souza, Tanaka, & Sebastiani, 2021; von Oppen et al., 2024). The role of biological activity, particularly root penetration and bioturbation by soil fauna, appears to also play a role in maintaining soil structure and mixing surface horizons (Lavelle & Spain, 2024; Le Bayon et al., 2021). However, despite these minor changes, the fundamental characteristics of Cambisols remained essentially unchanged over the study period, reinforcing the notion that significant pedogenetic shifts require longer timescales or more pronounced environmental disturbances.

Fluvisols, primarily found in alluvial zones (Bi1, Po1), exhibited notable textural variations linked to alluvial dynamics, with periodic rejuvenation due to erosion and sediment deposition (Ro1, Bi2). The reanalysis of Fluvisols revealed minimal shifts in soil structure or horizon development, confirming that their formation is largely dictated by active fluvial processes (Le Bayon et al., 2017; Rowley, Grand, & Verrecchia, 2018; Schomburg et al., 2018). In some cases, subtle organic matter accumulation was observed, indicating slow pedogenetic evolution when stable conditions persisted (H. P. Blume, Kuhn, & Bölker, 2002; Le Bayon, Bullinger, Gobat, & Guenat, 2013; Petts & Gurnell, 2005; Schilling et al., 2018). **Cambisols**, located on steep slopes in the Swiss Alps, displayed some evidence of colluviation, where material from upslope contributed to slight horizon thickening. In contrast, Cambisols in more stable environments showed little change in soil structure or composition, supporting the notion that these soils remain

relatively stable unless subjected to external disturbances such as erosion or human activity (Šarapatka et al., 2024; Tang, Hua, Cao, Jiang, & Cai, 2024).

Gleysols, found in waterlogged environments along lake shores and alpine swamps, exhibit distinct horizon sequences shaped by leaching and translocation processes (H.-P. Blume et al., 2016; Hewitt, Balks, & Lowe, 2021). Their evolution is closely tied to hydrological stability on the Swiss Plateau, influenced by the corrections of Jura waters that occurred in the 19th and 20th centuries (Bresson, 1978; Duchaufour, 1977; Weil & Brady, 2017; WRB, 2022b; Zech, Schád, & Hintermaier-Erhard, 2022). The Cu2 Gleysol exemplifies the challenges in soil classification based on water conditions dynamics and seasonal variations. Seasonally impeded water percolation plays a crucial role in forming Gleysols, affecting redox dynamics, especially in the presence of clays and fine silts. While our study shows low clay content across all profiles, variations in Gleysols specific horizons are linked to water saturation and redox processes. Silt content exhibits high variability, particularly in reductive and rust-stained horizons, indicating its role in influencing redox conditions and suggesting significant impacts of hydrological factors on soil development over time. Understanding these dynamics is crucial for accurate soil mapping and ecological understanding in global waterlogged environments (IUSS, 2022; Schad, 2023; WRB, 2022a).

In contrast to the soil types described above, due to their shallow development in rocky and erosive settings, Leptosols represent weakly developed soils, typical of the initial phases of soil formation (Zech et al., 2022). These soils were located in a glacier retreats circus filled with limestone scree, where the potential for pedogenetic evolution is very low. The weathering of the region's hard limestone and the fresh scree's setting create highly unfavourable conditions for the rapid development of thick soil horizons. This explains why this soil has remained virtually

unchanged for 36 years. Still, this hypothesis needs to be confirmed with a much broader set of similar case studies, including the also likely effect of soil rejuvenation due to ongoing mass wasting processes, such as landslides, rockfalls, and debris flows, which can reset soil formation by exposing fresh parent material, influencing soil properties and nutrient availability (van Beek, Cammeraat, Andreu, Mickovski, & Dorren, 2008).

Luvissols, distinguished by clay translocation processes that form clay-enriched horizons (illuviation), were prominent in the Jura region. Luvissols are generally fertile soils mainly found in the humid mid-latitudes (Zech et al., 2022) and often found in the Swiss Jura Mountains submitted to loess deposits (Martignier, Nussbaumer, Adatte, Gobat, & Verrecchia, 2015; Martignier & Verrecchia, 2013; Zárate, 2017). Moderate slopes, clay-rich parent materials, and high precipitation facilitate their development (Weil & Brady, 2017). These soils exhibited variable horizon development, influenced by local climate and erosion dynamics (Gómez-Guerrero & Doane, 2018). Yet, in our study, two Luvissols were reclassified as Cambisols. However, as migration of clays up the profile is, of course, impossible, and in an evolving pedological sequence, a Luvisol never becomes a Cambisol again, it is therefore very likely that the identification of these two soils in 1984 and 1985 was erroneous, and that the Cambic horizon was not correctly identified in situ.

Podzols, characterized by their distinctive eluvial (E) and illuvial (B) horizons, demonstrated remarkable stability over the study period. These soils are typically found in acidic environments under coniferous forests, where organic acids drive leaching processes that result in the translocation of iron, aluminium, and organic matter into deeper horizons (Brock, Kalbitz, Absalah, & Jansen, 2020; Buurman & Jongmans, 2005). In our study, Podzols displayed consistent horizon structures with minimal organic matter distribution or spodic horizon development changes. The stability of Podzols suggests that the podzolization process operates over much longer timescales than the four decades covered by our study. However, subtle variations were observed in surface organic layer thickness and organic matter content in some profiles, potentially linked to shifts in vegetation cover or decomposition rates. The Rai1 profile, observed in 1988 and 2020 within a subalpine forest with substantial deadwood, was shown to maintain a pH = 4 all the way down to 32 cm of depth, with slight increases in surface organic matter and decreases in clay content since 1988, despite sandy soil and earthworm activity (Appendix B. Table S60). The Rai2 profile, also found within a subalpine forest, exhibited redox phenomena throughout, indicating water influence, with a persistent organomineral Ag horizon and fluctuations in organic matter. The Pon profile, established in 1984 in a *Sphagno-Piceetum* pine forest, shows typical Podzol characteristics with increased organic horizon thickness and redox features extending beyond 30 cm by 2020, maintaining acidic surface pH and declining clay content. Lastly, the Boi Podzol, from 1985 under a beech forest, while in 2020 under spruce, likely indicating land use change, showed evolving horizons and stable acidic conditions promoting podzolization, with increased clay and organic matter contents over decades. These variabilities highlight the dynamic interactions between biological activity and soil formation processes in Podzols. Additionally, the resilience of Podzols in our dataset aligns with previous findings that suggest their long-term persistence in stable environments despite potential shifts in climate or land use (Zwanzig et al., 2021). Future research incorporating detailed land cover history and vegetation dynamics would be valuable in understanding the finer-scale changes occurring in Podzol environments over time.

Finally, **Umbrisols**, enriched in organic matter with low base saturation, were prevalent in acidic environments such as high-altitude coniferous forests (Zech et al., 2022), although they can also be found in non-forested mountainous zones (Jenco et al., 2018). In our database, the Cambic Umbrisol identified in 1989 was also identified as a Cambic Umbrisol in 2020. The “Cambic” qualifier indicates that the soil has maintained its structuring characteristics over time (Musielok, Buczek,

& Karcz, 2022). This structure is twofold: small aggregates embedded in larger ones. When the larger aggregates are crushed, the smaller ones appear (commonly known as a “fluffy structure” due to aluminium ions). The persistence of this fluffy structure over 31 years reflects a remarkable degree of soil stabilization. Yet, the consistent classification as Cambic Umbrisol, when comparing archived and modern soils, suggests that despite potential environmental pressures and land use changes (in terms of pastoral or forestry activities), the soil has preserved its essential characteristics (organic matter content and structural stability). However, this hypothesis awaits to be tested with a much larger dataset of similar soil types.

4.1.1. Climate influence on soil properties

The negative correlations between soil physicochemical properties and the two axes of a climate-based principal component analysis (PCA) illustrated in Fig. 5 provide significant insights into the influence of climatic factors on soil dynamics. Positive loadings along the first principal component (PCA1) correspond to increased warmth and aridity, while along the second loading (PCA2), reduced solar radiation (PCA 2), both correlating with diminished physicochemical distances. It has been postulated and observed that soils in warmer habitats change more rapidly than those in colder habitats, such as along elevation and latitudinal gradients (Chersich, 2018). Whether drier environments also facilitate soil physicochemical changes is less intuitive. Theory predicts that moderate humidity levels favour the biological activity of plants and soil biota, ultimately leading to more rapid modifications in soil attributes (Butenschoen, Scheu, & Eisenhauer, 2011; Valencia et al., 2018). However, our findings are closely linked to our experimental design. In our study region in the Swiss Alps, the warmer lowlands are typically associated with drier climates, whereas the colder, high-elevation habitats tend to be more humid (Christian Körner, 2021; Scherrer & Körner, 2011). Therefore, we speculate that the most significant changes observed in low-elevation soils, specifically in areas with warmer, drier, and sunnier conditions, are due to these climatic differences. Thus, our study confirms that climate influences the rate of soil evolution, although these observations cannot yet be disentangled from other factors such as elevation, geological bedrock, or vegetation composition.

4.2. Variability in soil properties over time: Horizon-level analysis

In addition to profile-level assessments, we conducted detailed analyses of soil properties, focusing on the surface horizons most sensitive to environmental changes (Sulman et al., 2020). By combining field observations with analytical measurements of physico-chemical properties from 28 profiles resampled 25 to 37 years apart, we evaluated changes in soil properties likely to vary over time. First, we observed that all soil types were heterogeneously distributed across the axis for pH, showing no particular grouping. However, Cambisols (Bev, Nav, Gor), Fluvisols (Bi2, Po1), Podzols (Pon, Sai, Boi), Luvisol (Cho), and Gleysol (Ch2) all exhibited a decrease in pH over 37 years. In contrast, the remaining 18 soil profiles showed increased soil pH. A potential explanation is that the declining pH in these soils reflects greater leaching, organic acid input, or historical land use pressures, while the rising pH in others may be due to reduced acid deposition or liming practices over time (Falkengren-Grerup et al., 2006; Xu et al., 2024).

Furthermore, weighted mean comparisons between archived and modern soils revealed consistent temporal patterns in SOM and C_{org} values between archived and modern profiles aligned with existing literature, confirming the reliability of our soil library and reinforcing the study’s findings (Arthur & Okae-Anti, 2022; Gaudinski, Trumbore, Davidson, & Zheng, 2000). Unique variations were noted in specific profiles, such as the Leptosol profile (Roc), which exhibited pronounced fluctuations in SOM content attributed to its steep slope location within a cirque. The observed variability in soil organic carbon (SOC) content across profiles highlights the influence of climatic variability and land

use practices on soil carbon dynamics. Fluvisols and Cambisols exhibited significant fluctuations in SOC content, and Gleysols showed consistent SOC accumulation patterns, while Leptosols had stable SOC levels despite their shallow profiles and erosive environments. The observed heterogeneous trends in SOM content likely reflect varying site histories, land use practices, and environmental conditions. Decreases in SOM, particularly in Cambisols, Fluvisols, Podzols, Gleysols, Luvisol, and Leptosol, may indicate intensified land use, reduced organic inputs, or enhanced decomposition rates—possibly linked to soil drainage, cultivation, or climatic changes (Leul, Assen, Damene, & Legass, 2023; Muñoz-Rojas et al., 2015; Paltineanu et al., 2024). In contrast, the increase in SOM across 13 other profiles suggests improved vegetation cover (Jarmain et al., 2023), reduced disturbance, or organic matter accumulation under more stable or rewilded conditions (Beillouin et al., 2023).

The most notable response observed was the change in the soil carbon-to-nitrogen (C:N) ratio, which increased significantly overall (Fig. 3), though this effect varied considerably by soil type (Fig. 4). Lower C:N ratios in several Cambisols, Fluvisols, Gleysols, and the Luvisol (Cho) suggest increased nitrogen availability or preferential carbon loss, potentially due to microbial activity or mineralization under altered soil moisture or temperature regimes. These patterns may be driven by increased microbial activity and organic matter mineralization, potentially accelerated by shifts in soil moisture and temperature regimes associated with land-use change or climate variability (Choreño-Parra & Treseder, 2024). Conversely, higher C:N ratios in the remaining soil profiles may reflect reduced nitrogen turnover or increased inputs of more carbon-rich organic matter, often linked to slower decomposition dynamics or vegetative litter composition (Zhang et al., 2023). Fluvisols in particular showed substantial temporal variability in C:N ratios, likely due to the episodic deposition of allochthonous organic material and fluctuating hydrological conditions, which enhance microbial turnover and nutrient cycling. Such variation is characteristic of floodplain soils with dynamic biogeochemical regimes. In contrast, soils with more stable organic matter pools, such as those in less disturbed or rewilded contexts, exhibited relatively consistent C:N ratios. This consistency implies long-term equilibrium between organic matter inputs and decomposition processes, governed by both vegetation structure and microbial community composition (Brunel, Gros, Lerch, & Da Silva, 2020; Kuśmierz, Skowrońska, Tkaczyk, Lipiński, & Mielniczuk, 2023; Wan et al., 2019).

These findings align with current literature indicating that changes in vegetation cover, land management, and climatic conditions significantly influence the quality and turnover of soil organic matter. Such influences directly impact C:N ratios, which serve as sensitive indicators of soil nutrient dynamics, microbial processing efficiency, and broader biogeochemical function (Zhou et al., 2020).

4.3. Conclusions

While soil development is a continuous process influenced by various environmental and climatic factors, our study found no significant temporal changes in soil physicochemical properties over a 37-year period across the 28 profiles and 256 soil horizons examined. This suggests that over the time span of our study, soil transformation remained minimal in most cases, reinforcing the understanding that pedogenetic changes generally occur over longer timescales, except under strong anthropogenic influence or in highly dynamic environments such as Fluvisols. Our findings underscore the need for more paired observations per Reference Soil Group (RSG) to detect meaningful shifts in soil properties and pedogenetic processes. This is particularly relevant when attributing changes to environmental or climatic drivers, which may become more apparent with a larger dataset or more extended observation periods. Future studies should integrate a more extensive set of paired observations and employ a broader temporal scope to increase the statistical power of detecting gradual changes

in soil properties. Additionally, while our study did not explicitly analyze land use and land cover changes (LU/LC) for all profiles, the literature suggests that such factors can be pivotal in driving soil transformations within human generational timescales. A thorough LU/LC consistency assessment across the observation period would be valuable in discerning whether variations in soil properties, such as C:N ratios or changes in organic carbon and pH, could be linked to shifts in vegetation cover or management practices. Our results also highlight that if pedogenetic or physicochemical modifications occur, they are most pronounced in the topsoil horizons, where biological activity, organic matter accumulation, and climatic influences are most substantial. Therefore, future research should emphasise horizon-level analyses better to capture subtle yet ecologically relevant changes in soil properties.

CRedit authorship contribution statement

Sarah Semeraro: Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Roxane Tuchschnid:** Writing – original draft, Project administration, Investigation, Formal analysis, Data curation. **Jean-Michel Gobat:** Resources. **Sergio Rasmann:** Writing – review & editing, Writing – original draft, Funding acquisition, Formal analysis, Data curation. **Renée-Claire Le Bayon:** Writing – review & editing, Writing – original draft, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.geoderma.2025.117363>.

Data availability

Data will be made available on request.

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