



Vegetation changes since the late Middle Ages around Bern, Switzerland

Philip Stevanon^{1,2,3} · Erika Gobet^{1,2} · Christoph Schwörer^{1,2} · Christian Rohr^{1,3} · Willy Tinner^{1,2}

Received: 28 April 2023 / Accepted: 21 December 2023
© The Author(s) 2024

Abstract

While the impacts of modern farming and land use practices on climate and biodiversity since 1900 are well-studied in Western and Central Europe, less is known about the preceding transitional period of the 18th and 19th century. By combining information from both natural and historical archives, this study strives to understand the impacts of 18th century agrarian modernisation on Central European ecosystems. Here we present a multi-proxy palaeoecological study from Egelsee (548 m a.s.l., within the city of Bern, Switzerland) spanning the late Middle Ages to the early 20th century. We use pollen, charcoal, dung fungal spores and spheroidal carbonaceous particles (SCPs) as proxies for vegetation and land use changes as well as radiocarbon wiggle matching for the chronology. Our pollen record suggests a shift from cereal cultivation towards grazing from the 16th century onwards, and from the 18th century towards fertilised meadows for animal husbandry. The pollen-inferred decrease of woods since 1700 quantitatively confirms the historically described timber scarcity in the lowlands of Switzerland, while the positive correlation between climate indices and our pollen-inferred cereal production suggests a certain vulnerability of societies to subsistence crises. From the 1850s, urbanisation rapidly altered the vegetation from an open agricultural landscape to a highly urbanised area, leading to a decline of biodiversity towards the present. This study shows that historically well-documented changes in agricultural practices in livestock farming and fodder production, and later urbanisation, can likewise be reconstructed with palaeoecological approaches. Our interdisciplinary approach provides new insights into how agricultural innovations affected vegetation and ecosystems during the past 500 years.

Keywords Land use change · Palaeoecology · Pollen analysis · Agrarian modernisation · Animal grazing · Urbanisation · Climate history

Introduction

Modern farming is a major contributor to man-made climate change. In 2020, agriculture, forestry and other land use forms accounted for 23% (12.0 ± 2.9 GtCO₂ eq yr⁻¹) of

total net anthropogenic greenhouse gas emissions (Henderson et al. 2021). Alongside the climatic impact, modernisation of agriculture has brought severe consequences for biodiversity and ecosystem services. Due to habitat loss and degradation, land use change constitutes the strongest driver for biodiversity losses (IPBES 2019). However, while the impacts of modern farming and land use practices on climate and biodiversity since 1900 are well-studied in Western and Central Europe (IPBES 2019; Jepsen et al. 2015), the issue remains obscured for the preceding transitional period of the 18th and 19th century. With recent efforts for more sustainable and small-scale farming (FAO 2014; Bruinsma 2017; Helfenstein et al. 2020), it is crucial to understand how pre-industrial land use and its modernisation have affected vegetation dynamics. The general process of modernisation in Western Europe is very well documented and historically investigated. During the earliest phase of

Communicated by F. Bittmann.

✉ Philip Stevanon
philip.stevanon@blw.admin.ch

¹ Oeschger Centre for Climate Change Research, University of Bern, Hochschulstraße 4, Bern 3012, Switzerland

² Institute of Plant Sciences, University of Bern, Altenbergrain 21, Bern 3013, Switzerland

³ Institute of History, University of Bern, Länggassstraße 49, Bern 3012, Switzerland

agrarian modernisation in Western Europe, agricultural reform movements took the first steps towards transformation of agriculture in the second half of the 18th century (Pfister 1995; Stuber et al. 2009). This marks the transition towards more intensive land use, higher agricultural yields and generally, less sustainable farming practices (Mathieu et al. 2016). A prominent example of such reform societies would be the *Oekonomische Gesellschaft Bern (OeGB)*, an economic society founded in 1759 in Bern, Switzerland, which promoted a series of novel farming practices such as new crop types and livestock summer stabling. This allowed for a more effective use of manure as organic fertiliser, and the transition from collective to individual and market-oriented farming (Keller 2008). Nevertheless, little is known about the impact of these new production systems on the environment (Pfister 1995).

In Europe, palaeoecological studies have mostly focused on large-scale changes over hundreds or thousands of years, such as climate-driven vegetation responses or prehistoric land use impacts (e.g. Finsinger et al. 2017; Hafner and Schwörer 2018; Roberts et al. 2018; Zanon et al. 2018; Rey et al. 2020; Lang et al. 2023). The inclusion of historical research based on written sources in palaeoecological studies remains rare. Most palaeoecological studies focus on pre-modern or even prehistoric periods, where written evidence on ecological processes is sparse. On the other hand, a ^{14}C plateau from ca. 1650–1950 (Hua 2009) hinders precise chronologies and attributions of cause and effect during modern periods.

By combining information from natural and historical archives, this study strives to understand the impacts of 18th century agrarian modernisation on Western European, pre industrial vegetation and ecosystems. Here, we present the first multi-proxy palaeoecological study of the lake sediments of Egelsee (548 m a.s.l.) within the present-day city of Bern, the modern capital of Switzerland. It spans the late Middle Ages to Modern Times. Although there are other palynological study sites close by (Rytz 1938; Welten 1982; Rey et al. 2020), the early modern, pre-industrial period has never been the focus of palaeoecological studies on the Swiss Plateau. We particularly have chosen Egelsee as a case study for similar agricultural processes in Western and Central Europe during this period, since there are abundant historical studies concerning the land use change in both the canton (Pfister 1995; Stuber 2008) and the city of Bern (Bill 1992; Bühler et al. 2003; Stuber and Baumgartner 2019).

In this study, we first assess the state of the vegetation before and after agricultural modernisation in the 18th century. In a second step, historical literature and sources are used to explain marked changes in the vegetation dynamics and contextualize them within the wider Swiss and European setting. Our interdisciplinary approach couples

methods and evidence from both palaeoecology and history within the framework of an integrated landscape history (Bürgi et al. 2005), assessing the natural and economical-cultural drivers and their impact on land use. With this, we aim to (1) identify vegetation changes around Egelsee for the period 1500 to 1900 using palaeoecological proxies, (2) explain such changes by shifts in agricultural practices, and (3) identify other possible drivers such as climate variability and urbanisation.

Study site

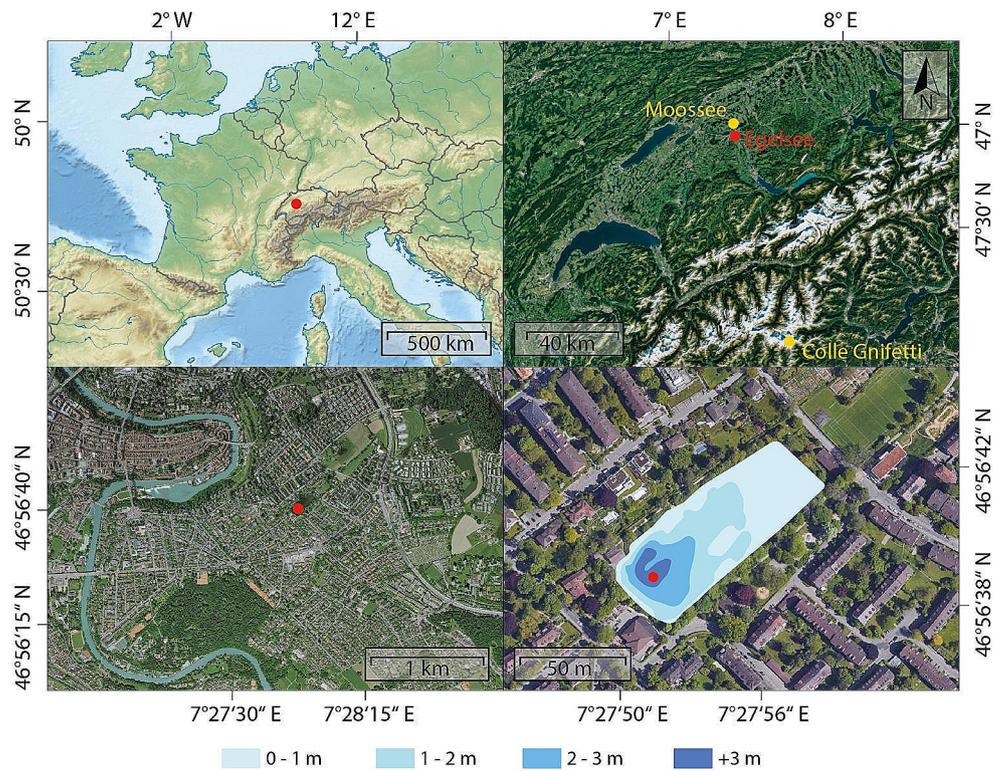
Egelsee is a small eutrophic lake located at 548 m a.s.l. on the Swiss Plateau (46°56'39.2" N, 07°27'51.0" E), within the city of Bern. Its total surface area is 1.52 ha, with a maximal depth of 3.5 m (Fig. 1), a minor inlet and no outlet. Egelsee is situated in the carbonate-rich molasse region with sandstone bedrock (Guthruf et al. 1999). It was formed between two moraine ramparts after the retreat of the Aare glacier at the end of the last glaciation. During the Holocene, the lake transitioned to a mire that intermittently had a small open water body. Historically, the area was called *Egelmoos* or *Egelmöösli* (lit. leech mire) (von Tavel 1933; Weber 1976). In 1884, the small pond was enlarged to increase its surface area to produce natural ice. The northeastern bank was removed, giving the lake its rectangular appearance (Fig. 1), and the excavated material was deposited in the deeper part. This destroyed many of the before thriving ecosystems (von Tavel 1933). In 1995, the northeastern shore became a protected area where shallow banks were created and the former inlet creek Wysslochbach, which was diverted into the sewage system in 1933 (Guthruf et al. 1999), was re-diverted into the lake (Bossert 1996). The climate at the site is temperate oceanic with a mean annual temperature of 8.8 °C and mean annual precipitation of 1,059 mm (reference period 1991–2020). January temperatures average -0.4 °C and July temperatures 18.6 °C (MeteoSwiss 2020). Today, the area around Egelsee is highly urbanised. Nevertheless, there are stands of *Alnus glutinosa*, *Fraxinus excelsior*, *Salix* and *Betula* around the lake, whereas the surrounding avenues are dominated by large *Acer* and *Fraxinus excelsior* trees. Open meadows and a vineyard cover the area beyond the northeast end of the lake.

Methods

Coring and chronology

In November 2020, three parallel sediment cores were taken 1 m apart with a modified Streif-Livingstone piston corer

Fig. 1 Geographical location of the study site. Top left: Overview map of Europe, red dot marks coring site Egelsee. Top right: Map overview of Switzerland (Wikimedia Commons 2011) with coring site (red dot) and other relevant palaeoecological sites mentioned in the text (yellow dots); Moossee (Rey et al. 2020); Colle Gnifetti (Brugger et al. 2021). Bottom left: Detail of the city of Bern with the coring site (Google Earth). Bottom right: Aerial image of Egelsee and immediate surroundings (Geodaten Stadt Bern 2020) overlaid with bathymetry (Guthruf et al. 1999) and the exact coring location (46°56'39.2" N, 7°27'51.0" E)



from a small platform at the deepest part of the lake (3.5 m). In the palaeoecological laboratory at the University of Bern, the cores were joined to one master sequence of 1,132 cm, according to matching sequences in their lithostratigraphy. For this study, a continuous section from 352 to 512 cm was analysed.

The age-depth model (Fig. 2) is based on 9 radiocarbon dates from terrestrial plant macrofossils (Table 1) and one marker layer in the sediment as a result of the historically documented enlargement of Egelsee in 1884 (von Tavel 1933). For the macrofossil analysis, we sieved sediment subsamples with a 200 μm mesh width. The ages of the terrestrial plant macrofossils were measured by radiocarbon dating using accelerator mass spectrometry (AMS) at the laboratory for the analysis of radiocarbon with AMS (LARA) at the University of Bern. When calibrating the three uppermost ^{14}C ages in R (RStudio Version 2021.09.0) using the package “clam” (Blaauw 2010) with the IntCal20 calibration curve (Reimer et al. 2020), the 95%-range (2σ) of all dates extended from 1660 to 1950. We therefore used the program OxCal 4.4 (Bronk Ramsey et al. 2001; Bronk Ramsey 2009; Bronk Ramsey and Lee 2013) with a P-Sequence model for all dates to establish a more precise radiocarbon wiggle-matching chronology. The P-sequence model assumes that ^{14}C ages from known depths are unequally spaced in time. Thus, the model allows for fluctuations in the sedimentation rate between events (Rey et al. 2019a, b). Furthermore, the disturbed sediment layer corresponding to the enlargement

of the lake in 1884 was added to the model. The age-depth curve (Fig. 2) was created in R using the package “clam” (Blaauw 2010) and is based on linear interpolation showing a 95% confidence interval of the OxCal 4.4 wiggle matching model (P-Sequence).

Pollen, spore, microcharcoal and spheroidal carbonaceous particle (SCP) analysis

For pollen and charcoal analysis, we took a total of 35 samples of 1 cm^3 sediment from the master core between 352 and 512 cm. From 430 to 450 cm (ca. 1590 to 1880 CE) we subsampled continuously. This high-resolution sequence consists of 21 contiguous samples with ca. 14 years/sample. The other samples were spaced at intervals of 16, 8, 4 or 2 cm. In the laboratory, all samples were treated with HCl, KOH, HF, and acetolysis, following standard preparation methods (Moore et al. 1991; Beug 2004). Before chemical treatment, *Lycopodium* spore tablets were added to the samples to estimate charcoal, spore, and pollen concentrations (Stockmarr 1971). We analysed the pollen under a light microscope at 400 to 1,000x magnification. For pollen and palynomorph identification, we used palynological keys and photo atlases (Moore et al. 1991). A minimum of 500 pollen grains, excluding aquatic pollen and spores, were counted per sample. Following Finsinger and Tinner (2005) and Tinner and Hu (2003), microscopic charcoal particles $> 10 \mu\text{m}$ were counted for all samples. Charcoal influx (fragments

Fig. 2 Age-depth model of the Egelsee sediment sequence based on linear interpolation (red line). The black bars and blue area show the 95% confidence interval of the OxCal wiggle matching model (P-Sequence). Black dots without confidence interval mark the 1884 to 1885 disturbance layer (gravel/sand). On the right: lithology of the entire core as well as a detail of the core section from 386 to 460 cm containing the disturbed layer (421 to 430 cm, gravel/sand), and where the majority of samples were taken from

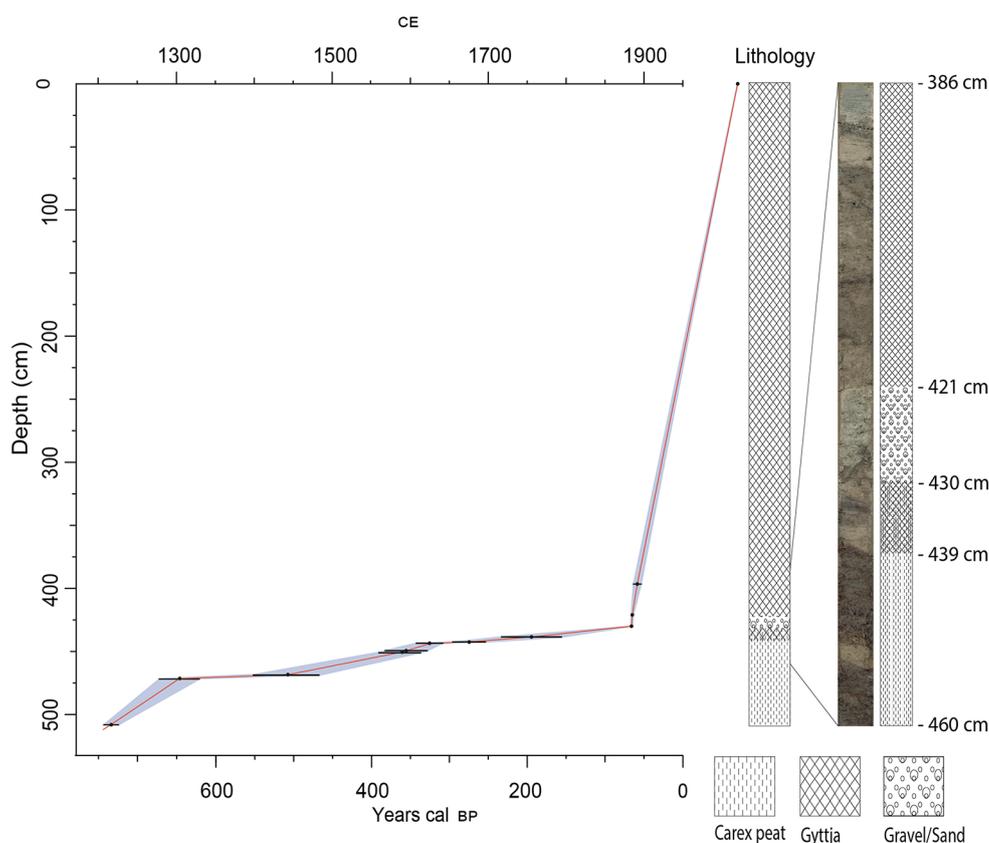


Table 1 Radiocarbon dates from the Egelsee sediment record

Depth (cm)	Lab. code	Material	^{14}C -age (yrs BP)	Calibrated age (cal CE, 2 σ -range)	Modelled age (cal BP)	Modelled age (median, CE)
396–397	BE-15801.1.1	Cyperaceae stem, Brassicaceae seed; <i>Carex</i> seed	175 ± 20	1661–1950	54–64	1889
438–439	BE-16073.1.1	<i>Carex</i> rhizome	180 ± 20	1660–1950	147–195	1756
442–443	BE-15802.1.1	<i>Salix</i> twig, twig indet	170 ± 20	1662–1950	251–295	1676
443–444	BE-16074.1.1	<i>Carex</i> rhizome	390 ± 25	1446–1624	312–345	1624
449–450	BE-16075.1.1	<i>Carex</i> rhizome	370 ± 35	1448–1635	334–386	1595
450–451	BE-16076.1.1	<i>Carex</i> rhizome	375 ± 20	1453–1627	339–392	1589
468–469	BE-16077.1.1	<i>Carex</i> fragment indet	515 ± 55	1304–1469	465–543	1443
471–472	BE-16078.1.1	<i>Carex</i> fragment indet	495 ± 50	1319–1483	623–672	1303
507–509	BE-15803.1.1	<i>Carex</i> seeds, seeds indet, leaf fragments	960 ± 25	1027–1158	728–743	1215

$\text{cm}^{-2} \text{yr}^{-1}$) was calculated by using the accumulation rates (cm yr^{-1}) inferred from the age-depth model and the charcoal concentrations (fragments cm^{-3}). We identified SCPs following Rose (2001). SCPs are produced during combustion of fossil fuels (coal and oil) and are markers for the onset of industrial activities (Swindles et al. 2015). The pollen, spores, charcoal, and SCP diagrams were drawn in Tilia (version 2.6.1.) and were separated into statistically significant local pollen assemblage zones (LPAZ), using optimal sum of squares partitioning and the broken stick method (Birks and Gordon 1985; Bennett 1996). The palynological surface sample was excluded for this zonation.

Ordination analysis

The numerical analysis was performed with the unmodified pollen percentage data using Canoco5 (ter Braak and Šmilauer 2018). We chose to use linear distribution models, because the first axis of the detrended correspondence analysis (DCA) measured 1.4σ (SD units) (Lepš and Šmilauer 2003). We calculated a principal component analysis (PCA) to determine environmental gradients in our dataset. The samples were grouped according to LPAZ. A redundancy analysis (RDA) was used to assess the response of the vegetation to fire, grazing and climate. As environmental variables, we used microscopic charcoal influx as a proxy for fire, fungal dung spores (*Cercophora*

and *Podospora*) influx as a proxy for grazing and summer Pfister indices as a proxy for temperature. Pfister indices are aggregated data from historical sources (quantitative and qualitative) ranked from -3 to $+3$ (extremely dry/cold to extremely wet/warm) when compared to a reference period. For our purposes we used the indices data from Pfister and Wanner (2021), with the reference period 1961 to 1990, and averaged all values between two samples. For both ordination analyses, Cichorioideae percentages were excluded from the pollen sum and plotted passively in the RDA, since the dominance of Cichorioideae in some samples would mask underlying vegetation trends. Additionally, the surface sample was also excluded to account for the large gap in sampling resolution.

We determined cross-correlations (Bahrenberg et al. 2020) of pollen percentages with charcoal influx or fungal dung spore concentrations to assess impacts of fire or grazing on selected taxa, including leads and lags. To reach stationarity of the time series, the pollen, charcoal and fungal dung spore data were linearly de-trended before the cross-correlation analysis. Each time lag corresponds to 14 ± 8.6 years. For this analysis, as well as for the synthesis diagram we created a pollen sum from selected pasture or meadow indicator types (*Rumex acetosa*-type, *Plantago major*-type, *P. lanceolata*-type, excluding Cichorioideae and Poaceae) and fungal dung spores (*Cercophora* and *Podospora*).

Biodiversity analysis

For the analysis of past biodiversity trends, we determined the palynological richness index (PRI, Birks and Line 1992) and the probability of interspecific encounter (PIE, Birks and Line 1992). For PRI, a proxy for both species richness and evenness at local to landscape scales, a rarefaction analysis (Birks and Line 1992) was performed with a minimum pollen sum of 394. PIE is primarily a proxy for evenness that measures how equally distributed taxa abundances are in a pollen sample (Colombaroli and Tinner 2013). Additionally, we also estimated evenness-detrended palynological richness (DE-PRI), accounting for the possible bias of evenness on PRI (Colombaroli and Tinner 2013). All biodiversity analyses were run in R (RStudio Version 2021.09.0) using the Vegan package (Oksanen et al. 2020).

Results and interpretation

Lithology and chronology

The analysed section of the master core in this study starts at 512 cm or 1205 CE (Fig. 2). Until 439.5 cm, the sediment consists of organic *Carex* peat, with silty sediment layers at irregular intervals. Above this, the sediment shifts to gyttja at

around 439.5 cm or 1735 CE with a major change in the sedimentation rate. This shift suggests the transition from mire to an open water body, presumably due to damming of a former outflowing stream. From 430 cm to 421 cm, we found a highly disturbed sandy layer with a lot of coarse gravel and even construction rubble (e.g. sandstone, red bricks). This disruption was most likely caused by the enlargement of the lake and re-deposition of the excavated material as well as rubble during the year 1884 (von Tavel 1933), so that this layer can be used as a chronological marker. Above this disturbed layer we observe organic gyttja until present. The drastically increased sedimentation rate (420 cm in 135 years) in the 20th century is explained by high productivity in response to fertilization or pollution due to agricultural activities and high urbanisation in the catchment area (Guthruf et al. 1999). Together with the marker layer, the wiggle matching of the ^{14}C dates led to the construction of a highly precise age-depth model (Fig. 2).

Pollen, charcoal, fungal dung spores and SCP analysis

Four statistically significant local assemblage zones (LPAZ) were identified (see Figs. 3a, b and 4 and ESM Fig. S1).

LPAZ EGL-1 (1200–1400 CE) consists of only two samples at 512 cm (1205 CE) and at 480 cm (1282 CE) respectively. In this zone arboreal pollen percentages (AP) remain at 50%, dominated by *Quercus robur*-type, *F. sylvatica*, *A. glutinosa*-type and *Corylus*. Many cultural indicator species are quite prominent such as Cerealia-type (10–15%), Poaceae, *Rumex acetosa*-type, and *Plantago lanceolata*-type. A peak of *Cannabis*-type occurs as is often the case for medieval times due to the hemp retting in ponds (Ranalli and Venturi 2004; Rey et al. 2020). Charcoal influx values are among the highest in the whole reconstruction. This assemblage of taxa and the charcoal evidence suggest an open cultural landscape with agricultural fields for cereal and hemp production, moderate pastoral activities, small mixed deciduous forest stands and regular burning activities during the Middle Ages.

In LPAZ EGL-2 (1400–1725 CE) pollen percentages of conifer trees such as *Picea abies*, *Pinus sylvestris* and *Abies alba* increase, whereas pollen percentages of some deciduous trees such as *Fagus sylvatica*, *Alnus glutinosa*-type and *Betula* gradually decline after the 15th century. Pollen of *Quercus* and fruit trees such as *Juglans regia* and *Castanea sativa* on the other hand becomes more frequent around Egelsee in the 16th and 17th centuries before percentages start to decrease thereafter. Charcoal influx remains at its lowest. A peak of herbaceous pollen of Apiaceae, Asteroideae and Brassicaceae occurs at the beginning of the 16th century, however, tree pollen reaches its maximum of ca. 70% between 1550 and 1700. Grazing proxies, such as the dung fungal spore taxa *Cercophora* and *Podospora* (Baker

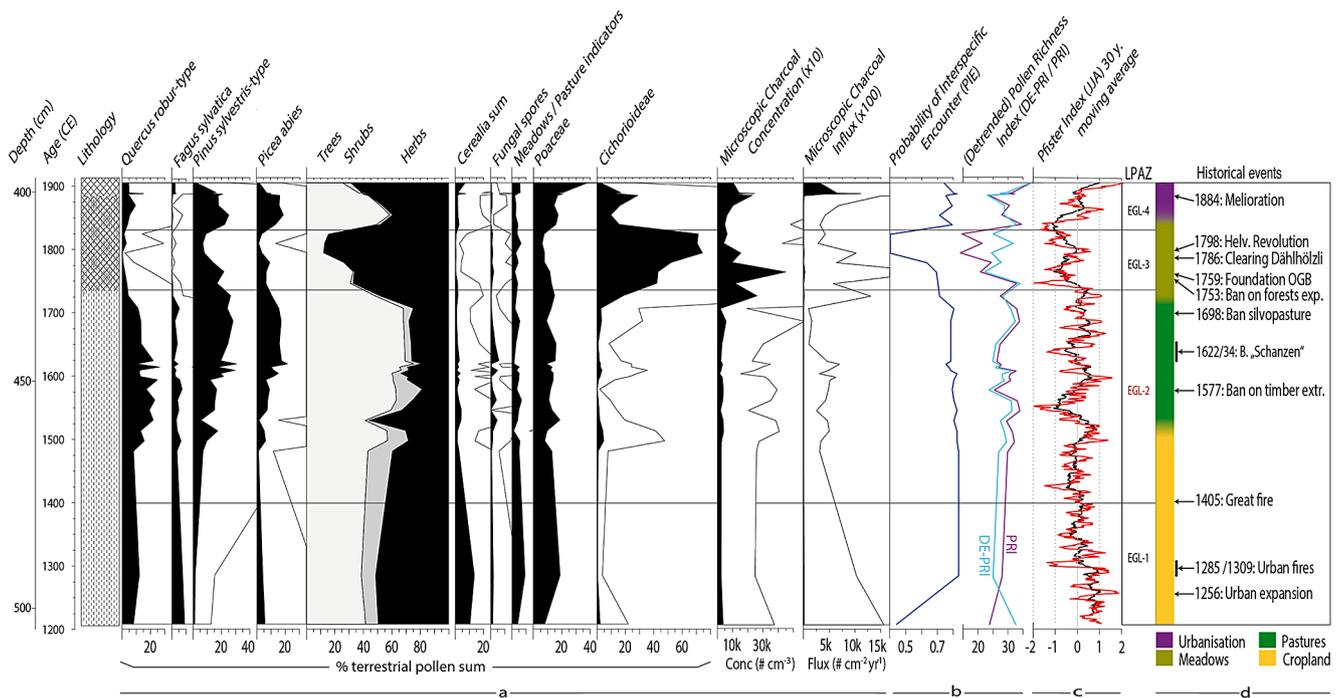


Fig. 4 Synthesis diagram with (a) selected pollen percentages and sums; microscopic charcoal concentration and influx values (hollow curves show 10x exaggerations with exception of microscopic charcoal influx). (b) Probability of interspecific encounter (PIE) and (detrended) pollen richness index (DE-PRI/PRI). (c) Mean summer (JJA) Pfister indices (red) and 30 year moving average (black), negative values indicating cold and dry, positive values indicating warm and wet years (Pfister and Wanner 2021). (d) Historical events relevant for forestry and agriculture as well as predominant forms of land use around Egelsee

increase in herb pollen percentages indicates a drastic opening of the landscape around the lake.

LPAZ EGL-3 (1725–1830 CE) is characterized by a large peak in Cichorioideae (> 70%). The simultaneous decrease of arboreal pollen percentages suggests a very pronounced opening of the landscape at that time. The decreasing arboreal pollen influx (ESM Fig. S1) shows that this is not a mere percentage effect. Pollen of shrubs is now only sparsely present. Fungal dung spore concentrations are low, which together with the pollen evidence might suggest a shift in grassland management, from grazing to mowing fertilised meadows. Both charcoal influx and concentrations (Fig. 4) have substantial peaks in this zone, suggesting a higher fire activity. SCPs, up until this point only found intermittently, reach their empirical limit (i.e. a continuous curve) around 1745 (439 cm), suggesting the initial use of fossil fuels (coal) for industrial activities in Europe (Brugger et al. 2021).

In LPAZ EGL-4 (1830–1905 CE), AP increases again (> 50%) but does not reach its previous high levels (1500–1700) and declines towards 1900. The sharp peaks observed with all taxa around 1900 are most likely due to artificial enlargement of the water body in 1884 that left a highly disturbed layer in the sediment record. The pollen data suggest that during the period 1850–1900 grazing became less important in the area, while trees, particularly conifers,

recovered. SCPs increased in the second half of the 19th century and mark the onset of substantial industrialisation of the economy.

The surface sample (ca. 2020) shows the highest values of AP (> 90%) in the whole reconstruction. *Alnus glutinosa*-type, *Picea abies*, *Pinus sylvestris*, *Corylus* and *Fagus sylvatica* are the most prominent taxa. Herbs on the other hand are at their lowest. The highly urbanised landscape with many ornamental and wetland tree stands around the lake, interrupted by only small patches of open meadows in the vicinity of the lake, explains the high share of arboreal pollen.

Ordination and biodiversity analysis

The first axis of the PCA (ESM Fig. S2) explains 41.1% of the variance in the pollen percentage data. It displays a gradient from rather closed vegetation dominated by deciduous trees (e.g. *Alnus glutinosa*-type, *Fagus sylvatica*, *Quercus*) to an open vegetation characterised by grasses and herbs (Poaceae, Cichorioideae). Axis 2, accounting for 12.4% of the variation, potentially shows an economic production shift from timber and tree fruit production (*Juglans*, *Quercus*, *Picea abies*, *Pinus sylvestris*-type) to open land grazing (*Plantago lanceolata*-type) and arable fields (Cerealia-type, *Cannabis*-type). Overall, we observe a trend from older

cropland (e.g. *Cerealia*- and *Cannabis*-type) and forests (*Alnus glutinosa*-type, *Fagus sylvatica*, *Quercus*) in EGL-1 and 2 towards younger pastures and meadows (Poaceae, Cichorioideae) in EGL-3 and 4.

In the RDA (Fig. 5), charcoal and dung spores account for 11.1% of the variation (simple term effects). The climatic variables account for less than 5% each, with summer Pfister indices having the highest influence (4.1%). We observe a strong correlation of cereal pollen and warm and wet summers, suggesting a high dependence of the pre-industrial agrarian system to warm and sufficiently moist climate. Passively plotted Cichorioideae sums seem to be opposed to fungal dung spore sums, suggesting a negative correlation between grazing and Cichorioideae growth, which is in agreement with the interpretation of a shift in cattle farming from grazing to fertilised, mowed meadows.

PIE, PRI and DE-PRI (Fig. 4) remain relatively stable throughout the record, except for EGL-3 (1725–1830), where the high Cichorioideae percentages are reflected in a low evenness (PIE) that in turn also affected richness (PRI). Accordingly, DE-PRI is not affected by the uneven samples (Senn et al. 2022) and shows a positive trend towards 1900. Modern vegetation around the year 2020 shows a lower PRI

(24) and DE-PRI (22) than during the whole reconstruction period, while PIE remains constant (data not shown). Cross correlation analyses show a positive, significant correlation between charcoal influx values and selected pasture and meadow indicator species (*Rumex acetosa*-type, *Plantago major*-type, *P. lanceolata*-type, excluding Cichorioideae and Poaceae; ESM Fig. S3a and b). However, the analysis does not suggest an influence of fire on woody plants. The results thus point to the use of fire to keep the arable and pastoral areas open. However, pasture or meadow indicator plants (e.g. Poaceae) and fungal dung spores are significantly negatively correlated (Fig. 5). This finding suggests pressure of grazing on these plants.

Agro-historical context

Pre-industrial agricultural system around the city of Bern

Until the mid-19th century, Egelsee was surrounded by sparsely populated land mainly used for agriculture and forestry managed by private manors and estates, as well as the city's commons (Bauinventar Stadt Bern 2022). While the sources for the private estates are rare, Messmer (1830) and Baumgartner (2013) give a relatively detailed account on land use of the commons. Even though there were many different types of collective agricultural management systems (Stuber and Wunderli 2021), in most areas of Central Europe locally adapted forms of the three-field system were used (Fig. 6a): Fertile land was divided into three large plots, which were planted in a fixed rotation of winter and summer cereals and, in every third year, left fallow, to allow the soils to replenish nutrients (Pfister 1995). In the proximity of Egelsee, a regulated form of the field-grass economy (in German *Feldgraswirtschaft*; Ineichen 2005; Stuber and Baumgartner 2019) was practised (Fig. 6b), where one of several city fields was planted with summer crops and, after fertilisation, winter cereals, before it was left fallow and used as pasture. Fertilising was not only intended to secure the following cereal yield, but also to prevent soil depletion so that pasture usage would not be limited. Fallow land, therefore, not only served to regenerate the soil but also had its primary purpose in cattle grazing (Messmer 1830; Stuber and Baumgartner 2019). The comparatively high crop yields indicate an abundant supply of fertiliser. This was due to a higher ratio of grassland to arable land around the city of Bern (between 1:1 and 4:1) than what is usually assumed for the lowlands (Pfister 1995), allowing for a large livestock population (Baumgartner 2013). Most regulations of the commons therefore concerned the overuse of pastures (Stuber and Baumgartner 2019). According to livestock

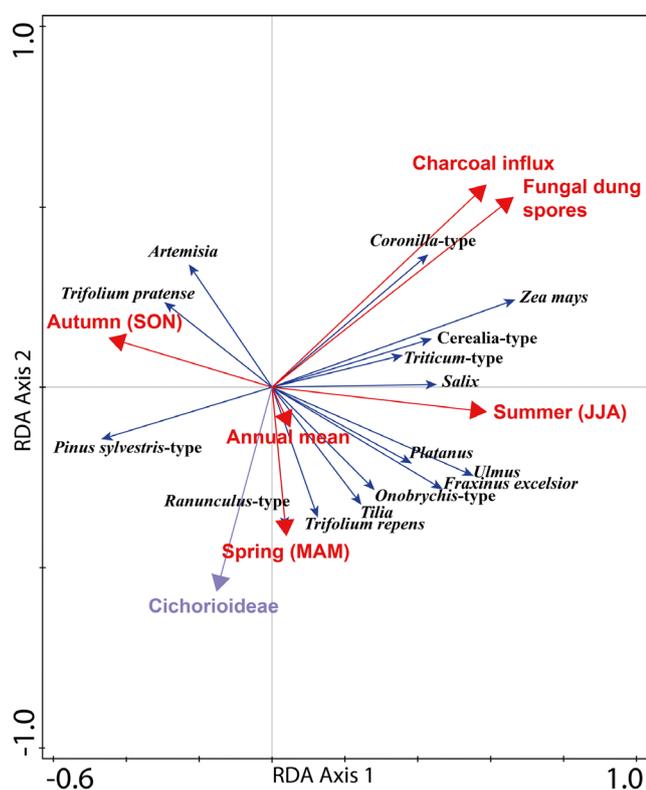


Fig. 5 Redundancy analysis (RDA) biplot showing both species and explanatory environmental variables including seasonal and annual mean Pfister indices (Winter DJF not plotted), microscopic charcoal and fungal dung spore influx. Explanatory variables account for 26.1% of the variance. Cichorioideae was plotted passively

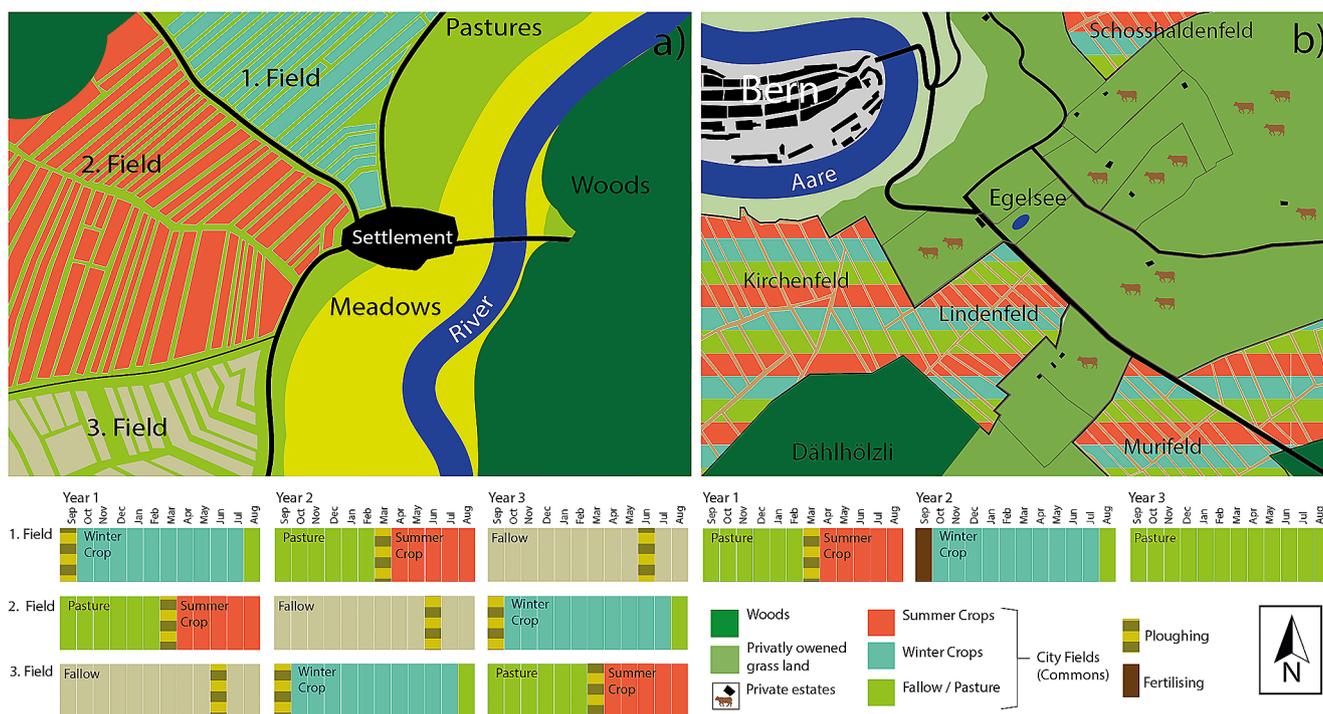


Fig. 6 a) Ideal type of the three-field system (after Pfister 1995) with typical crop rotation before the revolution of 1798. Large fields (Flur) are subdivided into smaller, collectively managed fields. On these, collective management is mandated (Flurzwang). Meadows are mostly found on soils too steep or wet for agriculture. Woods are used for a variety of purposes e.g. timber, fuel, silvopastures, mowing, litter.

b) Scheme of the regulated field-grass system (after Baumgartner 2013) in the lower district of Bern ca. 1750. Every year a cultivation cycle starts on one of several city fields. The others are mostly used for grazing. Private estates are not under Flurzwang and mostly used for grazing

censuses from the end of the 18th century, about 30% of the approximately 1,000 cows kept around the city of Bern would be driven onto the commons in summer. Cowherds were also brought to the city by herdsmen from surrounding areas for overwintering. This provided the city with an ample supply of protein products, such as milk or cheese, but also a considerable amount of fertiliser (Pfister 1995).

Forest usage

Forests provided many important resources in the pre-industrial economy, such as construction material, tools and energy (Stuber 2008; Stuber and Bürgi 2011). Woods also had an agrarian purpose: silvopastures for cattle, sheep and pigs were widespread up until the early 20th century. Especially oak, but also beech forests were used for pig feeding (*Acherum*). This practice, as well as a variety of other forest usages, thinned out the forests and promoted the growth of grasses, mown for hay or litter, or even allowed the cultivation of crops (Stuber and Bürgi 2011).

Written sources hardly document forest use around Egelsee before the 15th century (Fankhauser 1893; Bill 1992). In 1577, extraction of wood was banned but illegal logging remained common (Bodmer 1973; Bill 1992). At the

beginning of the 17th century, the Bernese Council issued a regulation concerning the previously unregulated silvopastures and *Acherum*. Grass cutting or grazing in the woods was prohibited and some forests were fenced off for cattle (Bill 1992). However, the implementation of these bans remained inconsequential, as they were apparently frequently violated (Baumgartner 2013).

In the beginning of the 18th century, it became increasingly difficult to cover the wood demand from the city's own forests alone (Bill 1992). Most of them were in a precarious state, thinned out and depleted of quality timber. A detailed report states that the mixed forests with e.g. *Picea abies*, *Pinus sylvestris*, *Fagus* and *Quercus* around Bern consisted mainly of young and small trees (Stuber 2008). In 1753, the authorities decided on an expansion and tightening of the ban on individual clearings (Bodmer 1973). These scarcity claims might thus be viewed within the context of the so-called wood scarcity discourse (in German *Holznotdebatte*; Radkau 1983; Marek 1994; Schenk 2006), which reasons that presumed scarcities and following tightening of bans may rather reflect the expansion of rights of authorities than actual scarcities. Nevertheless, the high building activity in the 17th and 18th centuries and the import of timber to the

city since the 1730s (Bill 1992) clearly point to a high wood demand.

Agrarian modernisation

The early phase of agricultural modernisation in Bern started in the second half of the 18th century with the foundation of a local enlightenment reform society for agricultural practices (*Oekonomische Gesellschaft Bern*, *OeGB*; Wyss 2015). They promoted and slowly introduced new crops (e.g. potatoes) and nitrogen-fixing meadow fodder crops (e.g. *Trifolium pratense*, *Onobrychis viciifolia*, *Medicago sativa*) into Bernese agriculture to increase yields. In 1771, as a result of the subsistence crisis of 1770 to 1773 (Pfister and Brázdil 2006), it was permitted to plant potatoes and legumes on fallow lands. Clover (e.g. *Trifolium* species) cultivation for fodder became common on the city fields around 1795 (Stuber and Baumgartner 2019). Shortly after, the city banned grazing on the city fields, because of fear of a cattle epidemic (Stuber and Wyss 2008) that was raging in the area. The fields were auctioned off for haymaking instead, promoting a transition from arable to dairy farming. This was accompanied by an increase in fodder production, especially clover (Stuber and Baumgartner 2019). Towards the end of the 18th century, cattle was increasingly kept indoors in summer and was fed with fodder crops. This meant that manure and slurry could be collected effectively and then distributed on the fields, further increasing yields.

Undisputedly, these agricultural reform programs marked the transition towards modernisation and industrialisation of agriculture with the goal to increase productivity and tithe income. Nevertheless, only with the liberalisations of the Helvetic era after 1798–1803, when farmers were relieved of feudal tithes and cultivation regulations (Pfister 1995), came more market orientation and margin for self-initiative. Already in the 1810s, clover and potato cultivation would dominate the lower city fields. Grazing on the commons was never allowed again, but violations were reported often (Baumgartner 2013).

Climate

Most of our reconstruction falls into the so-called Little Ice Age (LIA) period, with yearly average temperatures 0.6 °C lower compared to the reference period of 1961–1990. It also stands out because of the higher frequency of cool and wet seasons from 1570 onwards (Pfister and Wanner 2021). The pre-modern agrarian system was to a certain degree resilient to single extreme events. For example, the cultivation of winter cereals offered protection against a total crop failure because most of its growing phase is from September to April. In spring, the extent of the damage by

unfavourable weather could be estimated, and if necessary, the winter plots could be planted again. Plots were deliberately distributed over different soils and elevations, and the cultivation of different cereals, even within individual plots, reduced the likelihood of a simultaneous bad harvest on all fields. However, these strategies may have failed during prolonged phases with cold and wet weather. The worst type of such a catastrophic phase was a wet winter, followed by a cold snowy spring, a wet, cold summer with severe flooding, and a wet, cold autumn with early onset of the winter (Pfister 1985). Among others, such extreme weather patterns occurred in the so-called “hunger crisis of 1770/71” (Pfister and Brázdil 2006; Collet 2019) or the “year without summer” 1816 after the Tambora volcanic eruption of 1815 (Krämer 2015; Brönnimann and Krämer 2016), releasing marked subsistence crises (Pfister 1985). Prolonged precipitation was mostly the trigger for the harvest failures. Damp soils made fieldwork challenging and lowered the quantity and quality of yields. Additionally, higher humidity in the air and in the harvested grains diminished their storability leading to sprouting or the development of mould in the storehouse (Collet 2019).

Urbanisation around Egelsee

Other than the building activities in the 17th and 18th centuries that had an impact on wood consumption, the spatial aspect of urbanisation heavily influenced land cover in the second half of the 19th century. The Egelsee area was largely rural until 1850 and most of the buildings belonged to private estates (Fig. 7). It was primarily after the election of Bern as the capital of Switzerland in 1848 and the connection of Bern to the railway network (Bühler et al. 2003; Dubler et al. 2016), when constructions on the former city fields set in (Stuber and Baumgartner 2019). Until the outbreak of the First World War, and then in a second wave after the end of the Second World War, the city expanded considerably. Within less than 100 years, the area outside the medieval city centre on the eastern side of the Aare was transformed from an agricultural landscape to an urban residential area (Bühler et al. 2003, pp 18–29).

Discussion

Agricultural production shift

The decline in cereal cultivation and the increase in meadow taxa in our pollen record suggests a shift from arable towards cattle farming from the 16th century onwards. This overall trend to more pastures and meadows is consistent with spatially aggregated low-resolution records of land cover



Fig. 7 Urbanisation of Bern from 1850 to 1941. The development was mapped on the Mülleratlas (1797–1798) to demonstrate the change of land use (Geodaten Stadt Bern 2020). The red dot indicates the study site Egelsee

change inferred by pollen data for temperate Europe (Fyfe et al. 2015). While the marked increase in Cichorioideae in the early 18th century in our record could indicate both an expansion of pastures (grazing) and meadows (mowing) (Hjelle 1997; Mercuri et al. 2006), we propose that in the Egelsee area it reflects an intensification of meadow forage production. An overrepresentation due to selective corrosion of other pollen (Mercuri et al. 2006) is unlikely since the preservation of other pollen types in the samples is good. While Cichorioideae is considered an important indicator of pastures and meadows (Florenzano et al. 2012), the differentiation between mowed (meadows) or grazed (pastures) landscape based on pollen assemblages can be ambiguous (Hjelle 1997). The calibration study of Court-Picon et al. (2005) showed that Cichorioideae are generally more abundant in mown meadows. In agreement, the low concentration of fungal dung spores at the beginning of the Cichorioideae peak (ca. 1700) points towards cutting as the driver for this expansion rather than grazing. Furthermore,

our cross-correlation (ESM Fig. S3a and b) and RDA (Fig. 5) do not show a correlation between Cichorioideae and fungal dung spores. Targeted fertilisation with nitrogen and potassium likely led to the expansion of *Taraxacum officinale*, a prominent representative of the Cichorioideae family, on grasslands (Ellenberg 1986, p 726; Tilman et al. 1999; Martinkova and Honek 2014; Supek et al. 2017). Bi-annual cutting of meadows, as is often the practice for hay production (Ellenberg 1986, p 726), may have further increased the presence of *T. officinale*, as it decreases the competition for light by tall grasses (Mølgaard 1977; Martinkova and Honek 2014; Supek et al. 2017). The regenerative capacity of the long taproot may also help its establishment (Stewart-Wade et al. 2002). Indeed, historical records indicate that fodder production for summer stable feeding had replaced traditional grazing on the city fields by the end of the 18th century (Messmer 1830, p 40). The shift from grazed pastures to fertilised meadows in the 18th century occurred in other Swiss regions e.g. Zürich (Baumgartner 2017) and in

other European countries with similar movements such as England (Lane 1980; Overton 1985; Campbell and Overton 1993). Indeed, the OGB was heavily influenced by the actions of English reform societies (Stuber et al. 2009). The historically documented increase of nitrogen fixing plants (*Trifolium pratense*, *Onobrychis viciifolia*) is not prominent in the pollen-based reconstruction, but the RDA suggests a relation with Cichorioideae. The introduction of *Solanum tuberosum* to the Bernese agriculture is not reflected in the pollen record, presumably due to low pollen productivity.

Forest dynamics driven by silvopastures and timber extraction

Generally, the open landscape with small, forested areas and large share of croplands used for cereal cultivation in the Middle Ages is in accordance with historical (Pfister 1990) and palaeoecological evidence (Lotter 1999; Fyfe et al. 2015; Rey et al. 2017, 2020; Brugger et al. 2021). The warmer and more stable climate during the Medieval Climate Anomaly allowed increased production and expansion of farmland all over Europe (Rohr et al. 2018; Pfister and Wanner 2021). The forest dynamics until the early 17th century in our record corresponds with historically documented forest use within 1–2 km of Egelsee (Bill 1992). For instance, the marked expansion of oak during the 16th century points to the selective promotion of oak forests for pannage (it had started during the Celtic Iron Age and was intensified in the subsequent Roman period, Ammann 1989; Rey et al. 2020). In general, the tree taxa composition in the early 18th century in our pollen record matches the historical description of the forests around Bern, with a high proportion of coniferous species (Bill 1992). Contemporary commentators noted the precarious state of the city's forest and since the early 18th century, the city started to import wood from its alpine state territories (Bill 1992). Indeed, the pollen data show a decline in forest abundance since 1700, quantitatively confirming the presumed wood scarcity. Therefore, this study contributes scientific evidence within the historical dispute, the so-called wood scarcity debate (dt. *Holznotdebatte*; Radkau 1983; Marek 1994; Schenk 2006). Specifically, pollen influx values show that the decline of tree pollen is not only a percentage effect produced by the high Cichorioideae abundances (ESM Fig. S1). This vegetation pattern is in line with a general trend towards deforestation in Western and Central Europe at that time (Hejcman et al. 2013). Apart from the increased demand for construction, the local proto-industry (e.g. metalworking) was most likely also a factor for wood scarcity. From the 18th century onwards, attempts were made to settle such large-scale consumers to rural areas in order not to place an even greater burden on the city's wood supply

(Stuber 2008). The marked decline in forests at the end of the 18th century could be explained by the clearing of a part (5.741 ha) of the Dählhölzli forest close to the city of Bern in 1786–1787 (Bill 1992).

SCP concentrations start to rise in the second half of the 18th century (Fig. 3b), matching the SCP record from Colle Gnifetti at 4,450 m a.s.l. Since SCPs are not produced during wood or charcoal combustion, they are unambiguous indicators for the use of fossil fuels like coal, peat or later oil (Rose 2001). Swiss industrial production only switched to coal when it could be imported by railway in the second half of the 19th century, which is reflected in a large increase in SCP concentrations towards the top of our record. Swiss deposits of peat and coal did not allow for a large-scale, independent industrial production (Marek 1994), due to their physical properties and low density. The early onset of our SCP curve may thus suggest long-distance transport from other areas of Europe. Indeed modelling studies and pollen evidence suggest that subcontinental to continental catchments for air-borne microscopic particles contributed to the early appearance of SCPs around 1750 at the high-elevation site Colle Gnifetti (Gilgen et al. 2018; Osmont et al. 2020; Brugger et al. 2021).

The high charcoal influx and concentration values in the 18th century (Fig. 4, EGL-3) coincide with an increased sedimentation rate. Since ash was an alternative to organic fertilisers for meadows and pasturelands (Pfister 1985), this may therefore reflect local in-wash of charcoal particles. Indeed, we found no references to vegetation fires in the historical literature on Bern's city forests (Fankhauser 1893; Bill 1992; Stuber 2008). In agreement, Rey et al. (2020) do not record any microscopic charcoal peaks after the Middle Ages at Moossee, which is 8.7 km from our site, further suggesting the local origin of the particles.

Climate impact on agricultural production

While climate oscillated over the past 500 years, reaching coldest and wettest LIA conditions ca. 1576–1864, short term extreme weather events were common (Wanner et al. 2022). Historical records document the influence of extreme events on the agricultural system, especially the negative impact of a series of cold and wet vegetation periods during the LIA (Pfister and Wanner 2021). Our record corroborates this quantitatively by showing a positive correlation of cereals with summer Pfister indices (i.e. warm-dry conditions) in the RDA (Fig. 5). This remarkable result is in line with a recent, continental-scale palynological study from the Colle Gnifetti glacier, which demonstrated the vulnerability of early modern, pre-industrial agricultural production to extreme events (Brugger et al. 2021). Indeed, climate variables together account for 13%, and summer temperature

for 4.1% of the variance in our pollen data. However, vulnerability of societies to subsistence crises can be determined by other factors as well (e.g. cereal grain storage and market integration), and was relatively low for the Bernese territories from the 17th century onwards when compared to the rest of Europe (Pfister and Brázdil 2006).

Urbanisation as a dominant factor after 1850

While our palaeoecological record documents a very open landscape until 1905, the surface sample shows a markedly different vegetation composition, with little to no taxa indicating agricultural activities and arboreal species at higher abundances than in the preceding 800 years (Fig. 3 and ESM S2). The high proportion of *Alnus glutinosa* in the surface sample reflects shore protection measures that caused the expansion of alder around the lake. The expansion of the city in the 19th and 20th century (Fig. 7), which is emblematic for western and central Europe, was the major factor for shaping the local vegetation. Interestingly, PRI and DE-PRI indicate the highest species richness towards the top of our record (Fig. 4), likely because urban and low-intensive agricultural areas, such as non-mechanically ploughed fields and fertilised meadows can often be biodiversity hot spots (Fischer et al. 2012). Considering that the intensification of agriculture, namely mechanisation and the use of mineral fertilisers only started in the late 19th century (Schüpbach 2012), we can assume, that its effects would not yet have been reflected in the vegetation assemblage. Indeed, the surface samples indicates that by 2020, diversity had been lower than during the whole reconstruction period. However, further analysis is needed to better understand the underlying processes in these last 100 years.

Conclusions

Changing agricultural practices, namely in livestock farming and fodder production, and later urbanisation were the strongest drivers of vegetation change in the city of Bern during the past 500 years, which is likely emblematic for other cities and regions in western and central Europe. Before the increasing urbanisation of the late 19th century, the study area was a rather intensive, non-industrialized agricultural landscape. Changes in agriculture and forest management left a considerable mark in the vegetation, which was fundamentally different from natural conditions, as e.g. observed at the onset of agricultural activities during the mid Holocene with a prevalence of closed mixed oak and beech forests (Rey et al. 2019a, b). Our results show that non-industrialized urban cultural landscapes resulted in high biodiversity, which supports recent efforts to promote

more sustainable and small-scale farming (FAO 2014; Bruinsma 2017; Helfenstein et al. 2020). Comparing palynological reconstructions with historical literature and documents can be an effective tool to test and evaluate the standard methods of both fields and encourage further studies using this combined approach. The prerequisite for such interdisciplinary comparisons between natural and societal archives is an excellent chronology of the sedimentary records, which we here reached with radiocarbon wiggle matching. This procedure allowed us to bridge the radiocarbon plateau spanning from about 1650 to 1950 (Hua 2009). Since our reconstruction only covers the first stages of agricultural modernisation, the effects of later modernisation such as mechanisation and mineral fertilisers are not discussed in detail in this study. Additional dating methods for the uppermost part of the sediment record (^{210}Pb or ^{137}Cs dating), as well as the availability of suitable historical sources concerning agriculture and ecology, yield a lot of potential for further research.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s00334-024-00985-x>.

Acknowledgements We thank Sevil Coşgun, Kathrin Ganz, Luc Hächler, Maria Leunda, César Morales del Molino, and Lieveke van Vugt for their help during fieldwork, Sevil Coşgun and Stefan Hersberger for help with lab work, Jacqueline van Leeuwen and Lieveke van Vugt for assisting with pollen determination and Sönke Szidat for radiocarbon dating. We also extend our gratitude to the team of Stadtgrün Bern for granting us permission to core at Egelsee and providing documentation on the site, as well as Sarah Baumgartner for her expertise in the Bernese' agricultural system. Funding was provided by the Oeschger Centre for Climate Change Research (OCCR) as part of the Graduate School of Climate Sciences at the University of Bern.

Funding Open access funding provided by University of Bern

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Ammann B (1989) Late-Quaternary palynology at Lobsigensee: Regional vegetation history and local lake development. Diss Bot, Vol 137. Schweizerbart, Stuttgart

- Bahrenberg G, Giese E, Mevenkamp N, Nipper J (2020) Statistische Methoden in der Geographie. Schweizerbart, Stuttgart
- Baker AG, Bhagwat SA, Willis KJ (2013) Do dung fungal spores make a good proxy for past distribution of large herbivores? *Quat Sci Rev* 62:21–31. <https://doi.org/10.1016/j.quascirev.2012.11.018>
- Bauinventar Stadt Bern (2022) <https://bauinventar.bern.ch>. Accessed 1 February 2022
- Baumgartner S (2013) Die burgerlichen Stadtfelder von Bern 1700–1852. Master thesis, Universität Bern, Bern
- Baumgartner S (2017) Nützliche Gras-Arten und Kräuter: Die Zürcher *Ökonomische Kommission* und das Wissen vom Klee- und Wiesenbau. In: Boscani Leoni S, Stuber M (eds) Wer das Gras wachsen hört: Wissensgeschichte(n) der pflanzlichen Ressourcen vom Mittelalter bis ins 20. Jahrhundert. Studienverlag, Innsbruck, p 133–150
- Bennett KD (1996) Determination of the number of zones in a biostratigraphical sequence. *New Phytol* 132:155–170. <https://doi.org/10.1111/j.1469-8137.1996.tb04521.x>
- Beug H-J (2004) Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Gebiete. Pfeil, München
- Bill R (1992) Die Entwicklung der Wald- und Holznutzung in den Waldungen der Burgergemeinde Bern vom Mittelalter bis 1798. Doctoral thesis, ETH Zürich, Zürich
- Birks HJB, Gordon AD (1985) Numerical methods in quaternary pollen analysis. Academic Press, London
- Birks HJB, Line JM (1992) The use of rarefaction analysis for estimating palynological richness from Quaternary pollen-analytical data. *Holocene* 2:1–10. <https://doi.org/10.1177/095968369200200101>
- Blaauw M (2010) Methods and code for ‘classical’ age-modelling of radiocarbon sequences. *Quat Geochronol* 5:512–518. <https://doi.org/10.1016/j.quageo.2010.01.002>
- Bodmer W (1973) Die Wirtschaftspolitik Berns und Freiburgs im 17. und 18. Jahrhundert. Archiv des Historischen Vereins des Kantons Bern 57, Bern
- Bossert A (1996) Sanierung des Egelsees in Bern. Mitteilungsblatt/Berner Heimatschutz, Regionalgruppe Bern, Bern
- Bronk Ramsey C (2009) Bayesian analysis of radiocarbon dates. *Radiocarbon* 51:337–360. <https://doi.org/10.1017/S0033822200033865>
- Bronk Ramsey C, Lee S (2013) Recent and planned developments of the program OxCal. *Radiocarbon* 55:720–730. <https://doi.org/10.1017/S0033822200057878>
- Bronk Ramsey C, van der Plicht J, Weninger B (2001) ‘Wiggle Matching’ Radiocarbon Dates. *Radiocarbon* 43:381–389. <https://doi.org/10.1017/S0033822200038248>
- Brönnimann S, Krämer D (2016) Tabora und das «Jahr ohne Sommer» 1816: Klima, Mensch und Gesellschaft. *Geographica Bernensia* G90. Oeschger Centre for Climate Change Research (OCCR), Bern. <https://doi.org/10.4480/GB2016.G90.02>
- Brugger SO, Schwikowski M, Gobet E et al (2021) Alpine glacier reveals ecosystem impacts of Europe’s prosperity and peril over the last millennium. *Geophys Res Lett* 48. <https://doi.org/10.1029/2021GL095039>. e2021GL095039
- Bruinsma J (2017) World Agriculture: towards 2015/2030. An FAO Perspective. Routledge, London. <https://doi.org/10.4324/9781315083858>
- Bühler S, Erne E, Lüthi C, Bähler A, Barth R (2003) Bern - die Geschichte der Stadt im 19. und 20. Jahrhundert. Stadtentwicklung, Gesellschaft, Wirtschaft, Politik, Kultur. Stämpfli, Bern
- Bürgi M, Hersperger AM, Schneeberger N (2005) Driving forces of landscape change - current and new directions. *Landsc Ecol* 19:857–868. <https://doi.org/10.1007/s10980-005-0245-3>
- Campbell BMS, Overton M (1993) A new perspective on medieval and early modern agriculture: six centuries of Norfolk farming c. 1250–c. 1850. *Past & Present* 141:38–105. <https://doi.org/10.1093/past/141.1.38>
- Collet D (2019) Die doppelte Katastrophe: Klima und Kultur in der europäischen Hungerkrise 1770–1772. Umwelt und Gesellschaft 18. Vandenhoeck & Ruprecht, Göttingen
- Colombaroli D, Tinner W (2013) Determining the long-term changes in biodiversity and provisioning services along a transect from Central Europe to the Mediterranean. *Holocene* 23:1625–1634
- Court-Picon M, Buttler A, de Beaulieu J-L (2005) Modern pollen–vegetation relationships in the Champsaur valley (French Alps) and their potential in the interpretation of fossil pollen records of past cultural landscapes. *Rev Palaeobot Palynol* 135:13–39. <https://doi.org/10.1016/j.revpalbo.2005.02.003>
- Dubler AM, Grütter H, Zahnd UM, Junker B, Fritzsche B, Kuert A, Bern (Gemeinde) (2016) Historisches Lexikon der Schweiz (HLS). <https://hls-dhs-dss.ch/de/articles/000209/2016-11-10/>
- Ellenberg H (1986) Vegetation Mitteleuropas mit den Alpen in ökologischer Sicht, 4th edn. Ulmer, Stuttgart
- Fankhauser F (1893) Geschichte des Bernischen Forstwesens von seinen Anfängen bis in die neuere Zeit. Stämpfli, Bern
- FAO (2014) Building a common vision for sustainable food and agriculture: principles and approaches. Food and Agriculture Organization of the United Nations, Rome
- Finsinger W, Tinner W (2005) Minimum count sums for charcoal concentration estimates in pollen slides: accuracy and potential errors. *Holocene* 15:293–297. <https://doi.org/10.1191/0959683605hl808rr>
- Finsinger W, Giesecke T, Brewer S, Leydet M (2017) Emergence patterns of novelty in European vegetation assemblages over the past 15 000 years. *Ecol Lett* 20:336–346. <https://doi.org/10.1111/ele.12731>
- Fischer J, Hartel T, Kuemmerle T (2012) Conservation policy in traditional farming landscapes. *Conserv Lett* 5:167–175. <https://doi.org/10.1111/j.1755-263X.2012.00227.x>
- Florenzano A, Torri P, Rattighieri E, Massamba N’Siala I, Mercuri AM (2012) Cichorioideae-Cichorieae as pastureland indicator in pollen spectra from southern Italy. In: Vezzalini G, Zannini P (eds) Atti Del VII Convegno Nazionale Di Archeometria (AIAR). Pàtron Editore, Modena, pp 342–353
- Fyfe RM, Woodbridge J, Roberts N (2015) From forest to farmland: pollen-inferred land cover change across Europe using the pseudobiomization approach. *Glob Chang Biol* 21:1197–1212. <https://doi.org/10.1111/gcb.12776>
- Geodaten Stadt Bern (2020) https://map.bern.ch/stadtplan/?grundplan=stadtplan_farbig&koor=2602084,1199154&zoom=4&hl=0&layer=Muellerratlas&subtheme=CatHistorisch,CatBauen,CatPlanen. Accessed 2 February 2022
- Gilgen A, Adolf C, Brugger SO, Ickes L et al (2018) Implementing microscopic charcoal particles into a global aerosol–climate model. *Atmos Chem Phys* 18:11813–11829. <https://doi.org/10.5194/acp-18-11813-2018>
- Guthruf J, Zeh M, Guthruf-Seiler K (1999) Kleinseen im Kanton Bern (Petits plans d’eau du Canton de Berne). Gewässer- und Bodenschutzlabor des Kantons Bern, Bern
- Hafner A, Schwörer C (2018) Vertical mobility around the high-alpine Schnidejoch Pass. Indications of Neolithic and Bronze Age pastoralism in the Swiss Alps from paleoecological and archaeological sources. *Quat Int* 484:3–18
- Hejman M, Hejmanová P, Pavlů V, Beneš J (2013) Origin and history of grasslands in Central Europe – a review. *Grass Forage Sci* 68:345–363. <https://doi.org/10.1111/gfs.12066>
- Helfenstein J, Diogo V, Bürgi M et al (2020) Conceptualizing pathways to sustainable agricultural intensification. In: Bohan DA, Vanbergen AJ (eds) The future of agriculture landscapes, Part 1. Advances in ecological research 63. Academic Press, London, pp 161–192. <https://doi.org/10.1016/bs.aecr.2020.08.005>
- Henderson B, Frank S, Havlik P, Valin H (2021) Policy strategies and challenges for climate change mitigation in the agriculture,

- forestry and other land use (AFOLU) sector. OECD Food, Agriculture and fisheries Papers 149. OECD Publishing, Paris. <https://doi.org/10.1787/47b3493b-en>
- Hjelle KL (1997) Relationships between pollen and plants in human-influenced vegetation types using presence-absence data in western Norway. *Rev Palaeobot Palynol* 99:1–16. [https://doi.org/10.1016/S0034-6667\(97\)00041-9](https://doi.org/10.1016/S0034-6667(97)00041-9)
- Hua Q (2009) Radiocarbon: a chronological tool for the recent past. *Quat Geochronol* 4:378–390. <https://doi.org/10.1016/j.quageo.2009.03.006>
- Ineichen A (2005) Feldgraswirtschaft. In: *Historisches Lexikon der Schweiz (HLS)*. <https://hls-dhs-dss.ch/de/articles/027645/2005-10-25/>. Accessed 2 February 2022
- IPBES (2019) Global assessment report on biodiversity and ecosystem services of the intergovernmental science-policy platform on biodiversity and ecosystem services. IPBES, Bonn. Chapter 2.2
- Jepsen MR, Kuemmerle T, Müller D et al (2015) Transitions in European land-management regimes between 1800 and 2010. *Land Use Policy* 49:53–64. <https://doi.org/10.1016/j.landusepol.2015.07.003>
- Keller K (2008) Die Preisfragen der Oekonomischen Gesellschaft Bern. In: Holenstein A, Schläppli D, Schnell D, Steinke H, Stuber M, Würzler A (eds) *Berns goldene Zeit. Das 18. Jahrhundert Neu Entdeckt*. Stämpfli, Bern, p 37–41
- Krämer D (2015) Menschen grasten nun mit dem Vieh. Die letzte grosse Hungerkrise der Schweiz 1816/17: mit einer theoretischen und methodischen Einführung in die historische Hungerforschung. *Wirtschafts-, Sozial- und Umweltgeschichte* 4. Schwabe, Basel
- Lane C (1980) The development of pastures and meadows during the sixteenth and seventeenth centuries. *Agric Hist Rev* 28:18–30
- Lang G, Ammann B, Behre K-E, Tinner W (2023) Quaternary Vegetation Dynamics of Europe. Haupt, Bern
- Lepš J, Šmilauer P (2003) *Multivariate analysis of ecological data using CANOCO*. Cambridge University Press, New York
- Lotter AF (1999) Late-glacial and Holocene vegetation history and dynamics as shown by pollen and plant macrofossil analyses in annually laminated sediments from Soppensee, central Switzerland. *Veget Hist Archaeobot* 8:165–184
- Marek D (1994) Der Weg zum fossilen Energiesystem: Ressourcengeschichte der Kohle am Beispiel der Schweiz 1850–1910. *Geschichte und Gesellschaft, Sonderheft* 15:57–75
- Martinkova Z, Honek A (2014) The establishment of *Taraxacum officinale* plants in grassland. *Weed Res* 54:501–510. <https://doi.org/10.1111/wre.12096>
- Mathieu J, Backhaus N, Hürlimann K, Bürgi M (2016) *Geschichte der Landschaft in der Schweiz: Von der Eiszeit bis zur Gegenwart*. Orell Füssli, Zürich
- Mercuri AM, Accorsi CA, Bandini Mazzanti M et al (2006) Economy and environment of Bronze Age settlements – Terramaras – on the Po Plain (Northern Italy): first results from the archaeobotanical research at the Terramara Di Montale. *Veget Hist Archaeobot* 16:43–60. <https://doi.org/10.1007/s00334-006-0034-1>
- Messmer BL (1830) *Die burgerlichen Stadtfelder von Bern*. Stämpfli, Bern
- MeteoSwiss (2020) Station Zollikofen. Meteo Schweiz. <https://www.meteoschweiz.admin.ch/home/klima/schweizer-klima-im-detail/klima-normwerte/klimadiagramme-und-normwerte-pro-station.html?station=ber>. Accessed 26 January 2022
- Mølgaard P (1977) Competitive effect of grass on establishment and performance of *Taraxacum officinale*. *Oikos* 29:376–382. <https://doi.org/10.2307/3543629>
- Moore PD, Webb JA, Collinson ME (1991) *Pollen analysis*. Blackwell, Oxford
- Oksanen J, Simpson GL, Blanchet FG et al (2020) *Vegan: Community ecology package*. <http://CRAN.Rproject.org/package=vegan>. Accessed 19 Nov 2023
- Osmont D, Brugger S, Gilgen A et al (2020) Tracing devastating fires in Portugal to a snow archive in the Swiss Alps: A case study. *Cryosphere* 14:3,731–3745. <https://doi.org/10.5194/tc-14-3731-2020>
- Overton M (1985) The diffusion of agricultural innovations in early modern England: Turnips and clover in Norfolk and Suffolk. *Trans Inst Br Geogr* 10:1580–1740. <https://doi.org/10.2307/621824>
- Pfister C (1985) *Bevölkerung, Klima und Agrarmodernisierung 1525–1860*. Haupt, Bern
- Pfister C (1990) The early loss of ecological stability in an Agrarian Region. In: Brimblecombe P, Pfister C (eds) *The silent countdown: essays in european environmental history*. Springer, Berlin, Heidelberg, p 37–55. https://doi.org/10.1007/978-3-642-75159-2_4
- Pfister C (1995) *Geschichte Des Kantons Bern seit 1798, Band 4: Im Strom der Modernisierung. Bevölkerung, Wirtschaft und Umwelt 1700–1914*. Archiv des Historischen Vereins des Kantons Bern 78. Haupt, Bern
- Pfister C, Brázdil R (2006) Social vulnerability to climate in the Little Ice Age: an example from Central Europe in the early 1770s. *Clim Past* 2:115–129. <https://doi.org/10.5194/cp-2-115-2006>
- Pfister C, Wanner H (2021) *Climate and society in Europe. The last thousand years*. Haupt, Bern
- Radkau J (1983) Holzverknappung und Krisenbewusstsein im 18. Jahrhundert. *Geschichte Und Gesellschaft* 9:513–543
- Ranalli P, Venturi G (2004) Hemp as a raw material for industrial applications. *Euphytica* 140:1–6. <https://doi.org/10.1007/s10681-004-4749-8>
- Reimer PJ, Austin WEN, Bard E et al (2020) The IntCal20 northern hemisphere radiocarbon age calibration curve (0–55 cal kBP). *Radiocarbon* 62:725–757. <https://doi.org/10.1017/RDC.2020.41>
- Rey F, Gobet E, van Leeuwen JFN et al (2017) Vegetational and agricultural dynamics at Burgäschisee (Swiss plateau) recorded for 18,700 years by multi-proxy evidence from partly varved sediments. *Veget Hist Archaeobot* 26:571–586
- Rey F, Gobet E, Szidat S, Lotter AF, Gilli A, Hafner A, Tinner W (2019a) Radiocarbon wiggle matching on laminated sediments delivers high-precision chronologies. *Radiocarbon* 61:265–285. <https://doi.org/10.1017/RDC.2018.47>
- Rey F, Gobet E, Schwörer C, Wey O, Hafner A, Tinner W (2019b) Causes and mechanisms of synchronous succession trajectories in primeval central European mixed *Fagus sylvatica* forests. *J Ecol* 107(1):392–1408. <https://doi.org/10.1111/1365-2745.13121>
- Rey F, Gobet E, Schwörer C, Hafner A, Szidat S, Tinner W (2020) Climate impacts on vegetation and fire dynamics since the last deglaciation at Moossee (Switzerland). *Clim Past* 16:1347–1367. <https://doi.org/10.5194/cp-16-1347-2020>
- Roberts N, Fyfe RM, Woodbridge J et al (2018) Europe’s lost forests: a pollen-based synthesis for the last 11,000 years. *Sci Rep* 8:716. <https://doi.org/10.1038/s41598-017-18646-7>
- Rohr C, Camenisch C, Pribyl K (2018) European Middle ages. In: White S, Pfister C, Mauelshagen F (eds) *The Palgrave Handbook of Climate History*. Palgrave Macmillan, London, pp 247–263
- Rose N (2001) Fly-Ash Particles. In: Last WM, Smol JP (eds) *Tracking environmental change using lake sediments, Vol 2: Physical and geochemical methods. developments in paleoenvironmental research* 2. Springer, Dordrecht, pp 319–349. https://doi.org/10.1007/0-306-47670-3_12
- Rytz W (1938) Pollenanalyse eines Torfmooses in der Schosshalde bei Bern. *Mitt Natf Ges Bern* 137:41–43
- Schenk W (2006) *Holznotze Im 18. Jahrhundert? Ein Forschungsbericht zur „Holznotdebatte der 1990er Jahre*. *Schweiz Zeitschr Forstwesen* 157:377–383

- Schüpbach A (2012) Ökonomie in der Herrschaft Worb (1645–1850). Berner Forschungen Zur Regionalgeschichte 15. Traugott Bautz, Nordhausen
- Senn C, Tinner W, Felde VA, Gobet E, van Leeuwen JFN, Morales-Molino C (2022) Modern pollen – vegetation – plant diversity relationships across large environmental gradients in northern Greece. *Holocene* 32:159–173. <https://doi.org/10.1177/09596836211060494>
- Stewart-Wade SM, Neumann S, Collins LL, Boland GJ (2002) The biology of Canadian weeds. 117. *Taraxacum officinale* G. H. Weber ex Wiggers. *Can J Plant Sci* 82:825–853. <https://doi.org/10.4141/P01-010>
- Stockmarr J (1971) Tablets with spores used in absolute pollen analysis. *Pollen Spores* 13:615–621
- Stuber M (2008) Wälder für Generationen. Konzeptionen der Nachhaltigkeit im Kanton Bern (1750–1880). Böhlau, Köln
- Stuber M, Baumgartner S (2019) From natural supply to financial yields – the common fields of the civic corporation of Bern since the seventeenth century. In: Haller T, Breu T, de Moor T, Rohr C, Znoj H-P (eds) *The commons in a global world. Global connections and local responses*. Abingdon, Oxon, New York, pp 173–190
- Stuber M, Bürgi M (2011) Hüeterbueb und Heitisträhl: Traditionelle Formen der Waldnutzung in der Schweiz 1800 bis 2000. Haupt, Bern
- Stuber M, Wunderli R (2021) Transformations of common pastures and woodlands in Switzerland: a historical perspective. In: Haller T, Liechti K, Stuber M, Viallon F-X, Wunderli R (eds) *Balancing the commons in Switzerland: institutional transformations and sustainable innovations*. Earthscan studies in natural resource management. Routledge, London, pp 17–34
- Stuber M, Wyss R (2008) Die Bekämpfung Der Viehseuche 1772/73. In: Holenstein A, Schläppi D, Schnell D, Steinke H, Stuber M, Würigler A (eds) *Berns Goldene Zeit. Das 18. Jahrhundert Neu Entdeckt*. Stämpfli, Bern, pp 71–73
- Stuber M, Moser P, Gerber-Visser G, Pfister C (2009) Kartoffeln, Klee Und Kluge Köpfe. Die Oekonomische Und Gemeinnützige Gesellschaft Des Kantons Bern OGG. Haupt, Bern, pp 1759–2009
- Supek Š, Pavlů V, Pavlů L, Gaisler J, Hejzman M, Ludvíková V, Mikulka J (2017) Effects of long-term grazing management on dandelion (*Taraxacum officinale*) in *Agrostis capillaris* grassland. *Grass Forage Sci* 72:516–523. <https://doi.org/10.1111/gfs.12260>
- Swindles GT, Watson E, Turner TE, Galloway JM, Hadlari T, Wheeler J, Bacon KL (2015) Spheroidal carbonaceous particles are a defining stratigraphic marker for the Anthropocene. *Sci Rep* 5:10264. <https://doi.org/10.1038/srep10264>
- Ter Braak CJF, Šmilauer P (2018) *Canoco reference manual and user's guide*. Software for ordination (version 5.10). University & Research, Wageningen
- Tilman EA, Tilman D, Crawley MJ, Johnston AE (1999) Biological weed control via nutrient competition: potassium limitation of dandelions. *Ecol Appl* 9:103–111. <https://doi.org/10.2307/2641171>
- Tinner W, Hu FS (2003) Size parameters, size-class distribution and area-number relationship of microscopic charcoal: relevance for fire reconstruction. *Holocene* 13:499–505. <https://doi.org/10.1191/0959683603hl615rp>
- TUBS (2011) BLANK in Europe (relief). CC BY-SA 3.0. https://commons.wikimedia.org/wiki/File:BLANK_in_Europe_%28relief%29.svg. Accessed 16 January 2024
- Von Tavel F (1933) Das Egelmoos bei Bern. *Mitt Natf Ges Bern* 1933:7–20
- Wanner H, Pfister C, Neukom R (2022) The variable European little ice age. *Quat Sci Rev* 287:107531. <https://doi.org/10.1016/j.quascirev.2022.107531>
- Weber B (1976) *Historisch-topographisches Lexikon der Stadt Bern in Ihren Grenzen vor der Eingemeindung von Bümpliz am 1. Januar 1919*. Schriften Der Berner Burgerbibliothek 11. Stämpfli, Bern
- Welten M (1982) *Vegetationsgeschichtliche Untersuchungen in den Westlichen Schweizer Alpen: Bern-Wallis*. Birkhäuser, Basel
- Wyss R (2015) Reformprogramm und Politik. Möglichkeiten und Grenzen der Umsetzung von Reformideen der Oekonomischen Gesellschaft Bern in der Zweiten Hälfte des 18. Jahrhunderts. Bibliotheca Academica Verlag, Epfendorf
- Zanon M, Davis BAS, Marquer L, Brewer S, Kaplan JO (2018) European forest cover during the past 12,000 years: a palynological reconstruction based on modern analogs and remote sensing. *Front Plant Sci* 9. <https://doi.org/10.3389/fpls.2018.00253>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.