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Climatic change and contemporaneous land-use phases north and south of the Alps 2300 BC to 800 AD

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Abstract

Fluctuations in the Δ^{14}C curve and subsequent gaps of archaeological findings at 800–650 and 400–100 BC in western and central Europe may indicate major climate-driven land-abandonment phases. To address this hypothesis radiocarbon-dated sediments from four lakes in Switzerland were studied palynologically. Pollen analysis indicates contemporaneous phases of forest clearances and of intensified land-use at 1450–1250 BC, 650–450 BC, 50 BC–100 AD and around 700 AD. These land-use expansions coincided with periods of warm climate as recorded by the Alpine dendroclimatic and Greenland oxygen isotope records. Our results suggest that harvest yields would have increased synchronously over wide areas of central and southern Europe during periods of warm and dry climate. Combined interpretation of palaeoecological and archaeological findings suggests that higher food production led to increased human populations. Positive long-term trends in pollen values of Cerealia and *Plantago lanceolata* indicate that technical innovations during the Bronze and Iron Age (e.g. metal ploughs, scythes, hay production, fertilising methods) gradually increased agricultural productivity. The successful adoption of yield-increasing advances cannot be explained by climatic determinism alone. Combined with archaeological evidence, our results suggest that despite considerable cycles of spatial and demographic reorganisation (repeated land abandonments and expansions, as well as large-scale migrations and population decreases), human societies were able to shift to lower subsistence levels without dramatic ruptures in material culture. However, our data imply that human societies were not able to compensate rapidly for harvest failures when climate deteriorated. Agriculture in marginal areas was abandoned, and spontaneous reforestations took place on abandoned land south and north of the Alps. Only when the climate changed again to drier and warmer conditions did a new wide-spread phase of forest clearances and field extensions occur, allowing the reoccupation of previously abandoned areas. Spatial distribution of cereal cultivation and growth requirements of Cerealia species suggest that increases in precipitation were far more decisive in driving crop failures over central and southern Europe than temperature decreases.

1. Introduction

In rural societies population and social stability mainly depend on harvest success and thus on favourable climatic conditions. Prehistoric and medieval agriculture in Europe relied mainly on drought-adapted cereals from the Near East that are sensitive to parasite attacks under humid conditions. Hence warm and dry summers were essential for successful cereal production, whereas humid growing seasons could severely endanger or destroy crop yields (Maise, 1998). Humid and cold weather conditions, especially during spring-time, also diminished cattle-related yields. The consequences of a series of cold-humid years were famines and increased death rates, as extensively documented for the past 500 years (e.g. in the 1690s in central and northern Europe or in the 1810s in Switzerland; see Pfister, 1988; Maise, 1998). Human-population changes strongly affected the spatial extent of cultivation. Warm-dry years normally led to expansions of fields and meadows to more marginal areas (e.g. higher elevations or less fertile soils). Based on these historical observations and on

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climatic proxies such as residual $\Delta^{14}C$, glacier oscillations and palynology, Maise (1998) interpreted as climatically driven the conspicuous decreases of archaeological findings in France, Germany and Switzerland (e.g. numbers of tombs, settlements and pottery remains) at around 800 and 400 BC. Van Geel et al. (1996) came to similar conclusions for The Netherlands. The boundary from Subatlantic to Subboreal at 2500–2800 radiocarbon years BP (see Lang, 1994) has globally been identified as a time of marked climatic change (e.g. van Geel et al., 1996). Stratigraphical, palaeobotanical and archaeological evidence point to a change from a dry and warm to a more humid and cool climate in central and north-western Europe. Whether this change in atmospheric circulation patterns was primarily triggered by changes in the solar activity (e.g. van Geel et al., 1999) or by changes in the thermohaline circulation (e.g. Bond et al., 1997) is still debatable. Magny (1993a) and Gross-Klee and Maise (1997) found strong correlations between dendrochronologically dated phases of lake-dwellings and negative residual $\Delta^{14}C$ indicative of higher solar activity throughout the Neolithic and the Bronze Age (5500–800 BC). Magny (1993a), van Geel et al. (1996), Gross-Klee and Maise (1997) and Maise (1998) argue that Holocene climatic changes affected settlement and land-use activities of prehistoric European societies considerably.

In contrast to proponents of ideas of climatic determinism, some prehistorians and archaeologists attribute breaks in development of material culture solely to human factors, such as local differences in artefact production or technological retardation. For example, gaps in archaeological findings of Hallstatt C (800–650 BC) remains in marginal areas of Germany have been attributed to a persistence of Hallstatt B cultures (1050–800 BC) until the beginning of Hallstatt D (650 BC) (Maise, 1998). It has also been suggested that anthropogenic factors such as changes in religion, manageability difficulties, wars, deforestations and various ecological crises caused collapses of past European cultures (see Brown, 1998). Similar controversies are known for other continents and cultures (e.g. the collapses of the Akkadian, Peruvian-Bolivian or Maya civilizations; see deMenocal, 2001).

Since the 1980s high-resolution Holocene climatic proxies (e.g. tree-rings and stable isotopes) have provided new possibilities of interpretation of cultural shifts, and it seems that some of the most spectacular societal collapses were coincident with decade to century-scaled climatic changes (Brown, 1998; deMenocal, 2001; Polyak and Asmerom, 2001).

In this study, we compare palaeobotanical anthropogenic indicators with independent palaeoclimatic proxies (GRIP oxygen isotopes and dendroclimatological records) in order to address the response of prehistoric and historic European cultures to climatic change. Thus, the main aims are: (1) to assess whether archaeological hypotheses postulating climatically controlled changes in settlement activities in western and central Europe are supported by pollen analytical data and (2) to test whether climatic changes affected areas north and south of the Alps in a similar way. We discuss the relevance of climate to prehistoric agricultural communities, and we suggest that environmental conditions could also determine the path of history in times of famine, depopulation and migration.

2. The study areas

For palaeoecological investigations we analysed the sediments of two lakes north and two lakes south of the Alps. Soppensee (8°05′E, 47°05′30″N, 596 m a.s.l., 24 ha surface area) and Lobsigensee (7°17′55″E, 47°01′55″N, 514 m a.s.l., 8 ha) are two small lakes on the Swiss Plateau north of the Alps, separated by about 60 km. Lago di Origlio (8°56′40″E, 46°03′20″N, 416 m a.s.l., 8 ha) and Lago di Muzzano (8°55′40″E, 45°59′40″N, 337 m a.s.l., 22 ha) are small lakes situated near the town of Lugano in southern Switzerland, on the southern slope of the Alps (Figs. 1–3). The two lakes south of the Alps are 6 km away from each other, and the distance to Soppensee and Lobsigensee is ca. 135 and 170 km,

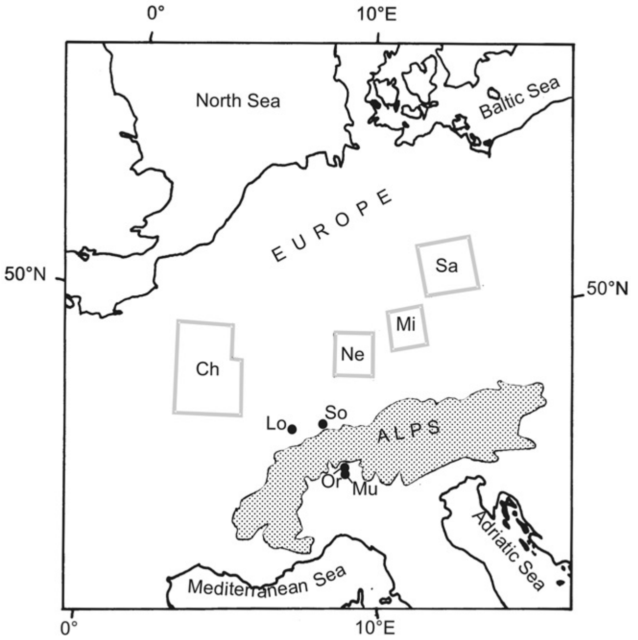

Fig. 1. Geographical map of Europe showing the location of the four study sites (So = Soppensee, Lo = Lobsigensee, Mu = Lago di Muzzano, Or = Lago di Origlio). The rectangles indicate areas with important decreases of archaeological findings during cold-humid climate periods at 800–600 BC (Mittelfranken and Sachsen) and 400–100 BC (Champagne and Neckarland) (Maise, 1998). Ch = Champagne, Ne = Neckarland, Mi = Mittelfranken, Sa = Sachsen.

Fig. 2. Bird-eyes view of Soppensee (596 m a.s.l.) and its surrounding landscape (central Swiss Plateau) north of the Alps characterised by intensive regional land-use (arable and pastoral farming). The rudimentary forests consist of *Fagus silvatica* and planted *Picea abies*.

Fig. 3. View of the landscape south of Lago di Origlio (416 m a.s.l., the lake on the left). Sweet chestnut (*Castanea sativa*, flowering) forests cover most of the area around the lake. Until 50 years ago chestnut forests were intensively used for human food, litter and pasture (chestnut orchards) or for wood production (chestnut coppices). In the background Monte Generoso (1701 m a.s.l., on the left) and Monte San Salvatore (912 m a.s.l., on the right).

respectively. At Lago di Origlio agriculture is only marginal and restricted to a gentle slope east of the lake, whereas at Soppensee, Lago di Muzzano and Lobsigensee present-day land-use is more intensive (see Figs. 2 and 3). Mean July temperature is about 18°C at Soppensee and Lobsigensee, whereas Lago di Muzzano and Lago di Origlio have markedly higher mean July temperatures of about 21–22°C. Mean annual precipitation is also higher in the south, reaching 1600–1700 mm in comparison with about 1250 mm at Soppensee and 950 mm at Lobsigensee. In both areas the precipitation maximum occurs during the summer. The incidence of summer rain in Insubria, a region south of the Alps characterised by over-average precipitation amounts (for geographical extent see Tinner et al., 2000), contrasts with the summer-dry Mediterranean climate of neighbouring regions. Despite the high summer precipitation (ca. 800 mm, of convective origin), total solar radiation is higher than north of the Alps (mean summer hourly power ca. 200 $\mathrm{W m^{-2}}$ at Soppensee, 220 $\mathrm{W m^{-2}}$ at Lobsigensee, 220 $\mathrm{W m^{-2}}$ at Muzzano and 240 $\mathrm{W m^{-2}}$ at Origlio; Zelenka, 2000). The sparse forests around Soppensee and Lobsigensee are dominated by spruce (*Picea abies*, planted) and beech (*Fagus silvatica*), whereas sweet chestnut (*Castanea sativa*) is the most prominent tree around Lago di Muzzano and Lago di Origlio. Remaining modern woodland vegetation around Soppensee and Lobsigensee is typical for Central Europe and differs greatly from that around Lago di Muzzano and Lago di Origlio, which is typical for sub-mediterranean (peri-adriatic) forests of southern Europe (Ozenda, 1988). For more detailed site descriptions see Ammann (1985), Lotter (1999), Tinner et al. (1999) and Gobet et al. (2000).

3. Material and methods

3.1. Coring and sediments

The core SO89-23 was taken with a Kullenberg piston corer in the deepest part of Soppensee (details in Lotter et al., 1997). Parallel cores were taken with a modified Livingstone piston corer (Merkt and Streif, 1970) from the deepest parts of Lobsigensee (LQ-90), Lago di Muzzano and Lago di Origlio. The water depth was 27 m at Soppensee, 3 m at Lobsigensee, 5 m at Lago di Origlio and 3 m at Lago di Muzzano. The sediments of Soppensee are partly laminated (Lotter, 1999), but in the period of interest they consist of homogenous fine-detritus gyttja. The sediments of Lobsigensee consist of calcareous gyttja and fine-detritus gyttja (Ammann, 1989). At Lago di Muzzano and Lago di Origlio the core sections analysed for this study consist of a homogenous slightly silty fine-detritus gyttja.

3.2. Palynology

For pollen analyses 1 $\mathrm{cm^3}$ of wet sediment was used. *Lycopodium* tablets (Stockmarr, 1971) were added for estimation of pollen concentration (pollen grains $\mathrm{cm^{-3}}$) and pollen accumulation rates (pollen grains $\mathrm{cm^{-2}\,yr^{-1}}$). The standard chemical procedure included treatment with 10% HCl, 10% KOH, 40% HF, acetolysis, mounting in glycerol and staining with Fuchsine. Pollen grains were identified under a light microscope using the reference collection of the Institute of Plant Sciences at the University of Bern and the standard determination keys (e.g. Moore et al., 1991) and the photo volumes of Reille (1992, 1998). Pollen identification and

Table 1
AMS-radiocarbon dates

Lab-number	Depth (cm)	Years BP, conv. uncal. radio-carbon dates	AD/BC 95% limits, CALIB 4.1.2. (Stuiver and Reimer, 1993)	AD/BC age in diagrams[a]
Soppensee	218–220	1495±55	428–658 AD	623 AD
	243.5	2145±50	362–5 BC	5 AD
	260.5	2365±55	758–262 BC	446 BC
	292–293.5	3310±70	1744–1431 BC	1541 BC
	309.5	3810±65	2465–2110 BC	2192 BC
	330–332	4435±60	3351–2907 BC	3007 BC
Lobsigensee				
UtC-4102	95–100	590±60	1286–1437 AD	1358 AD
UtC-4105	160–164	1580±50[b]	385–601 AD[b]	940 AD
UtC-4106	250–253	1535±35	428–619 AD	528 AD
UtC-4103	320–325	2045±35	167 BC–50 AD	38 BC
UtC-4104	403–408	3200±50	1601–1323 BC	1468 BC
UtC-4101	448–452	3915±45	2556–2212 BC	2399 BC
UtC-4108	507–509	4740±45	3642–3373 BC	3503 BC
Muzzano				
UtC-5620	237	1000±60	898–1185 AD	1028 AD
UtC-4977	471–472.5	2010±40	107 BC–77 AD	49 BC
UtC-4978	597.5	2800±40	1046–833 BC	917 BC
UtC-5271	762.5	3820±40	2457–2140 BC	2087 BC
UtC-4979	963.5–965	4600±60	3519–3100 BC	3434 BC
Origlio				
UtC-5621	186	810±90	1023–1385 AD	1220 AD
UtC-4984	285.5	1620±40	342–539 AD	429 AD
UtC-4985	396.5	2210±35	386–171 BC	286 BC
UtC-4986	422–424	2270±40	400–203 BC	376 BC
UtC-4987	479.5	2460±45	787–402 BC	672 BC
UtC-4988	591.5	2780±40	1008–829 BC	1012 BC
UtC-4989	680.5	3390±45	1862–1527 BC	1742 BC
UtC-4990	757	4120±40	2876–2501 BC	2578 BC

[a] For age-depth models of Soppensee see Lotter (1999), for Origlio and Muzzano see Tinner et al. (1999). The age-depth model of Lobsigensee is based on linear interpolation (see also van der Knaap and Ammann, 1997).

[b] Excluded date in the age-depth model. Radiocarbon-sample thickness is 1 cm, except otherwise indicated.

enumeration were made by A.F. Lotter at Soppensee, B. Ammann and J.F.N. van Leeuwen at Lobsigensee, P. Hubschmid and M. Wehrli at Lago di Muzzano and W. Tinner at Lago di Origlio. Minimal pollen sums counted ($\sum$ AP + NAP) were 500 at Soppensee, 1000 at Lobsigensee and 700 at Lago di Muzzano and Lago di Origlio. In this study, we focus on the period between 2300 BC and 800 AD (i.e. 4250–1150 cal. BP) because before 2300 BC pollen of Cerealia and *Plantago lanceolata* occurred only sporadically. After 800 AD historical sources may contain better information about land-use intensity and harvest success than pollen indicators. We have chosen Soppensee and Lobsigensee because their vegetation history is typical for the Swiss plateau and they are among the diagrams with the most reliable chronology and the highest sample resolution for the Swiss Plateau for the period 2300 BC–800 AD (mean sample resolution 69 cal. yr ±19 at Soppensee). At Lobsigensee we increased the original sample resolution (see Ammann, 1989) by processing and analysing 30 additional samples (new mean sample resolution 55 cal. yr ±25). The pollen stratigraphy of Lago di Origlio is typical for Insubria, and its chronological reliability and resolution are comparable to Soppensee (Table 1, mean sample resolution 51 cal. yr ±33). Lago di Muzzano was chosen for comparison with Lago di Origlio and because its sample resolution is close to that of the other sites (80 cal. yr ±42). We have chosen three pollen indicators to assess human influence: the sum of tree pollen (shrubs excluded), *Plantago lanceolata* (plantain) and the Cerealia (Cereals with exception of *Secale*). During the study period the latter two pollen types are reliable representatives of other pollen types indicating human impact (e.g. *Rumex* t., Cichorioideae, *Centaurea nigra* t., *Ranunculus* t., *Urtica*, *Trifolium*, see Ammann, 1989; Lotter, 1999; Tinner et al., 1999; Gobet et al., 2000). Most likely, *Plantago lanceolata* and Cerealia are not native species in the study regions. Since the cereals producing the Cerealia pollen type have a poor pollen dispersal capacity, *Plantago lanceolata* is considered to be the most reliable indicator of farming, including both pastoral and arable farming (Behre, 1988).

3.3. Radiocarbon dating

Plant macrofossils of terrestrial origin from the cores of Soppensee, Lobsigensee, Lago di Muzzano and Lago di Origlio were dated by AMS-radiocarbon techniques. The chronology for the period of interest (2300 BC–800 AD) is based on six AMS-radiocarbon dates for Soppensee, six for Lobsigensee, five for Lago di Muzzano and eight for Lago di Origlio (Table 1). The radiocarbon ages were calibrated as years AD/BC by the program CALIB Rev. 4.1.2. (Stuiver et al., 1998). Table 1 shows the position of the depth-age modelled calibrated ages in relation to the 95%-limits of calibrated ages. For more details on depth-age models see Lotter (1999), Tinner et al. (1999) and Tinner et al. (2000). At Lobsigensee we omitted the date 1580 ± 50 BP (Table 1), because in comparison with the adjacent dates it is apparently too old. To provide a chronology consistent with the other study sites, only terrestrial plant macrofossils were considered in the case of Lobsigensee, and the chronology used here (Table 1) therefore differs from the one presented by van der Knaap and Ammann (1997).

3.4. Climatic reconstruction

LOWESS-smoothed (Cleveland, 1981) GRIP oxygen isotope values with span 10% were used as a climate proxy in this study (Fig. 4A). For comparison with the GRIP record we applied the same smoother with the same span to the GISP 2 stable-isotope record and the residual Δ^{14}C data (Fig. 4B–D). Span 10% was selected after comparison with reconstructed summer temperatures by Jones et al. (1998), because it gave the best common fit (Fig. 5A) with this palaeoclimatic record. To verify if the GRIP-inferred climatic variability in Greenland had a counterpart in continental Europe, we used a series of tree-ring density curves (Bircher, 1982, 1986; Renner, 1982) (Fig. 5B), which are in agreement with other climatic reconstructions from the Alps (glacier oscillations, palaeobotanical timberline studies; see Wick and Tinner, 1997). The chronology of the tree-ring density curves is fixed by numerous radiocarbon dates and is reliable to about ±100 years. Attempts to reduce dating errors by wiggle matching were not successful, because the relationship between radiocarbon dates and the tree-density curves is only poorly documented in the original studies (Maradi, 1999). Furthermore, we compared the GRIP and GISP2 record with residual Δ^{14}C (Stuiver and Braziunas, 1991), because strong connections between past Δ^{14}C-variations, solar activity and Holocene climatic oscillations have been suggested (e.g. Magny, 1993b; van Geel et al., 1999; Bond et al., 2001).

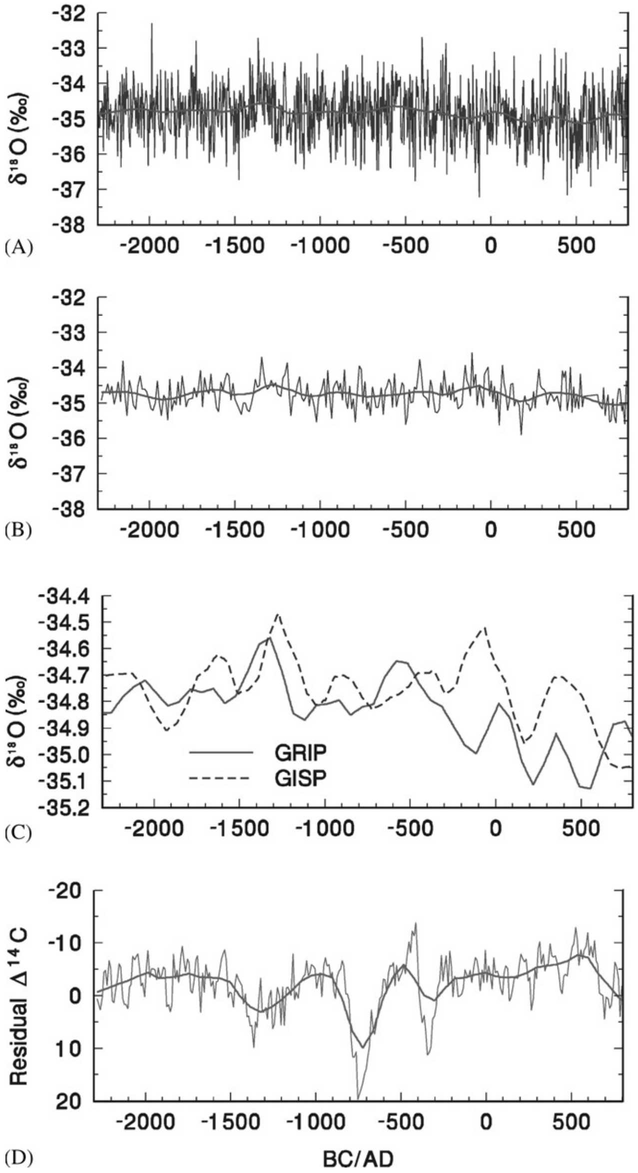

Fig. 4. Comparison of Holocene climate proxies for the period 2300 BC–800 AD (all LOWESS curves with span = 10%). (1A) GRIP (European Greenland ice-core project) stable oxygen isotope record (Dansgaard et al., 1993), the line indicates LOWESS-smoothing. (B) GISP2 (US Greenland ice Sheet Project 2) stable oxygen isotope record (Grootes et al., 1993), the line indicates LOWESS-smoothing. (C) Comparison between LOWESS-smoothed GRIP and GISP2 oxygen isotope values. (D) Variation of residual Δ^{14}C (Stuiver and Braziunas, 1991), the heavy line indicates LOWESS smoothing.

4. Results: vegetation and land-use history

Rather low vegetational dynamics and the dominance of *Fagus* and *Abies* characterise the period between 5000

BC and 800 AD on the entire Swiss Plateau (Ammann et al., 1996). In contrast, south of the Alps the Insubrian woodland vegetation was strongly altered by man since the Neolithic. Due to agricultural activities the mean fire periodicity decreased from natural levels of about 1500 years to a maximum of 50 years between 5100 and 2150 BC (Tinner et al., 1999). As a consequence, fire-sensitive arboreal taxa (e.g. *Abies*, *Hedera*, *Ilex*, *Tilia*, *Ulmus*, *Acer*, *Vitis*, *Fagus*) were successively eliminated from the mixed deciduous forests. Only impoverished and fire-adapted oak-alder forests survived human pressure after 2150 BC (Tinner et al., 2000). After 200 AD these stands were on their part replaced by *Castanea sativa* woodlands. The replacement process was rather fast (200 years; Gobet et al., 2000) and mainly induced by humans for wood and food (Conedera and Tinner, 2000a). Paradoxically, after 200 AD, maxima in pollen of *Castanea sativa* were often correlated with decreases of pollen indicative of human impact in the Swiss and Italian southern Alps (Tinner et al., 1999; Gobet et al., 2000). A possible explanation might be that only wild forms of *Castanea sativa* produce notable amounts of pollen (Rudow and Conedera, 2001). In addition, *Castanea sativa* probably invaded formerly cultivated areas during periods of land abandonment.

Single scattered findings of Cerealia pollen and other anthropogenic indicators at Soppensee, Lobsigensee, Lago di Muzzano and Lago di Origlio suggest constant but low human impact before 2300 BC. The beginning of continuous curves of cultural indicators (CI, sum of Cerealia and *Plantago lanceolata* pollen, Fig. 5D) indicating first enduring increases of human influence

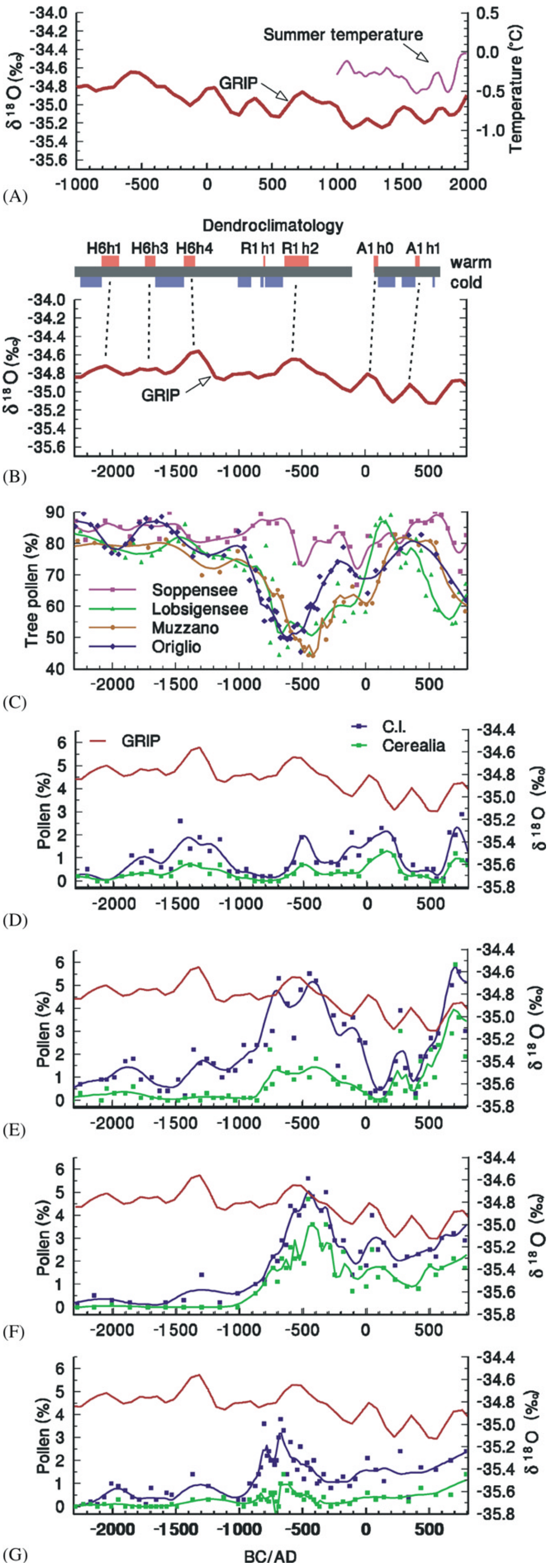

Fig. 5. Holocene climatic proxies and lowland pollen records located north and south of the Alps. For better comparison of common trends all data were LOWESS-smoothed (tension 10%). The scatterplots show the original pollen percentage values. The lines indicate LOWESS smoothing. Chronologies for pollen records were assessed by radiocarbon dating (see Table 1) and correlated with Greenland oxygen isotope records according to their absolute ages. (A) Comparison between GRIP stable oxygen isotope records (Dansgaard et al., 1993) and northern-hemisphere summer temperature reconstructions (Jones et al., 1998). (B) Comparison between dendroclimatological records from the Alps and GRIP stable isotope records. The abbreviations denominate warm phases in the Alps according to Bircher (1986). For comparison ^{14}C BP yr ages were calibrated to BC/AD ages. A1h0 is a pronounced warm phase (1940–1890 ^{14}C yr BP; see Bircher, 1986) which is unnamed in the original studies. For abbreviations of cold phases see Bircher (1986). (C) Tree pollen percentages at Soppensee, Lobsigensee, Lago di Muzzano and Lago di Origlio. (D) Comparison between the GRIP stable isotope record and pollen records of Soppensee. (E) Comparison between the GRIP stable isotope record and pollen records of Lobsigensee. (F) Comparison between the GRIP stable isotope record and pollen records of Lago di Muzzano. G: Comparison between the GRIP stable isotope record and pollen records of Lago di Origlio. (D–G) The green LOWESS curve indicates the Cerealia pollen percentages and the blue LOWESS curve the percentage sum of Cerealia and *Plantago lanceolata* (=cultural indicators, CI).

is dated at ca. 2300 BC at Lobsigensee, at ca. 1950 BC at Soppensee and at ca. 2250 BC at Lago di Muzzano and Lago di Origlio and falls into the End Neolithic or the Early Bronze Age period. First relevant deforestations indicated by tree pollen percentages <80% started ca. 2000 BC (Early Bronze Age) at Lobsigensee and Lago di Origlio. Noticeable peaks of Cerealia and *Plantago lanceolata* pollen (ca. 1%) at 1950–1900 BC point to intensified agriculture at these two sites (Fig 5E and 5G). A similar CI peak seems slightly delayed at Soppensee (1800 BC). The first coeval decrease of tree pollen recorded at all four sites reached its apex at around 1350 BC and was accompanied by peaks of Cerealia and *Plantago lanceolata* suggesting a temporary expansion of arable and pastoral farming during the Late Bronze Age.

During the Iron Age at around 650–400 BC tree pollen percentages reached a further minimum (<55% at Lobsigensee, Lago di Muzzano, Lago di Origlio; <75%, at Soppensee), suggesting substantial deforestations around these lakes. Forest disruptions went together with strong peaks of CI (>5% at Lobsigensee and Lago di Muzzano), pointing to intensive agricultural activities. Apparently, the onset of this phase of land-use intensification was delayed at Soppensee by about 300 years (600 vs. 900 BC at Lobsigensee, Lago di Muzzano and Lago di Origlio). A minimum of Cerealia at around 800–700 BC was detected only at Soppensee and Lago di Origlio. South of the Alps agricultural intensification during the Iron Age was accompanied by a substantial expansion of meadow and ruderal species (e.g. *Artemisia*, Caryophyllaceae, *Rumex acetosella* t., *Teucrium*, Asteroideae, Cichorioideae, *Centaurea jacea* t., *Jasione* t., *Potentilla* t., Rosaceae, *Trifolium repens* t., *Urtica*, *Polygonum aviculare*; see Conedera and Tinner, 2000b) as well as fire-adapted *Calluna* heathlands and *Pteridium* thickets (Tinner et al., 1999). At Lobsigensee a similar development was characterised by the expansion of *Artemisia*, Chenopodiaceae, Asteroideae, Cichorioideae, Apiaceae, Fabaceae, Brassicaceae, *Ranunculus* t., *Rumex* t. and *Pteridium* (Ammann, 1989).

Only minor peaks of CI and of non-tree pollen are characteristic for the Roman Period (15 BC–400 AD). A first maximum falls into the period after the Roman occupation and is detectable at Soppensee, Lago di Muzzano and Lago di Origlio (ca. 1–150 AD, see Fig. 5E and 5G), but not at Lobsigensee (Fig. 5E), whereas at around 300 AD a land-use intensification is only recognisable at Lobsigensee, although it is possibly hinted at Soppensee by a minor decrease in tree pollen percentages. The low values of CI during the Roman period are only in part compensated by the introduction of new crops such as *Castanea sativa*, *Juglans regia*, *Vitis vinifera* and *Secale cereale.* Our findings therefore seem to be in contrast with the conventional opinion that human impact was higher during the Roman Period than before (see Behre, 1988). In fact, only during the Early Middle Ages at ca. 700 AD the CI and non-tree pollen increased again to the levels reached during the Iron Age (Conedera and Tinner, 2000b, and Fig 5D–G).

5. Discussion

5.1. *Synchronous land-use fluctuations north and south of the Alps*

The general vegetation histories north and south of the Alps are distinctly different. It is therefore striking that despite the considerable physical barriers of the Alps (Fig. 1) all sites have nearly identical trends in the tree-pollen percentage curves (Fig. 5C), suggesting coeval deforestation phases over large areas. Although minor discrepancies among the sites certainly exist, peaks of CI occurred at around 1350 BC, 650–400 BC, 1–150 AD and 700 AD. In general, CI values are higher at Lobsigensee than south of the Alps, where climate is considerably warmer during the growing season. This may be attributed to the favourable location of Lobsigensee at the eastern limit of the largest grain-field area of Switzerland (Plaine de l'Orbe-Seeland; AdS, 2000). Surprisingly, Lobsigensee has more long-term trends of CI in common with the sites south of the Alps than with Soppensee. Throughout the period of investigation, pollen values of Cerealia and *Plantago lanceolata* are higher at Lago di Muzzano than at Lago di Origlio, probably reflecting more favourable conditions for agriculture. Nevertheless, the similarity among the four tree and cultural pollen records is pronounced and suggests the presence of a common driving factor, which may account for the palaeovegetational patterns observed. If this is true, it may be appropriate to ask how far such large-scale changes may have been driven by cultural and/or climatic factors.

5.2. *The archaeological, historical and cultural context*

5.2.1. *Autarky and contacts*

During the Bronze and Iron Age (Table 2) the four study sites were situated in different cultural settings (Rychner et al., 1998; Müller, 1999). Only the two sites south of the Alps were probably exposed to common cultural influences throughout the whole period. Already before the Bronze Age cultural contacts existed between the regions north and south of the Alps, as documented by many archaeological findings (Stöckli, 1995). Contacts and exchanges increased during the Bronze and Iron Ages (Hochuli et al., 1998; Müller et al., 1999). However, European prehistorical and early historical economies were mainly based on autarky (Müller, 1999), and hence on local agricultural production. Moreover, already during the Neolithic western

Switzerland (Lobsigensee) was culturally oriented to west and south-west (southern France), whereas central Switzerland (Soppensee) and southern Switzerland were more influenced by eastern (Germany, Austria) and southern cultures (Italy), respectively (Stöckli, 1995). Generally, this pattern persisted until the La Tène period, although after 1550 BC the region north of the Alps was increasingly joined by common influences from western and central Europe (Rychner et al., 1998; Dunning et al., 1999; Table 3). During the La Tène period the regions north and south of the Alps were exposed to an increasing "internationalisation" of the material culture (Table 3). The Roman occupation of the Alps and of the southern part of central Europe (ca. 15 BC) reinforced this process. Given the autarky-based economy as well as the cultural heterogeneity it seems unlikely that the similar patterns observed in the tree and CI pollen percentages (Fig. 5) could be the result of common economical expansion and contraction patterns alone.

5.2.2. Technological innovations and population changes

Despite autarky and cultural heterogeneity, technological innovations may have influenced human impact on vegetation and thus its imprint on pollen curves. It is striking that the CI-curves became continuous for the first time during the transition from End Neolithic to the Early Bronze Age (2300–1950 BC) at all four sites. Similarly, at the beginning of the Iron Age (800 BC) the CI increased markedly. South of the Alps, values of CI never fell back to the low levels observed before the onset of the Iron Age. In fact, archaeologically documented innovations in agriculture coincided with changes in pollen indicators. Bronze tools (e.g. sickles) and efficient ox-pulled ploughs increased agricultural productivity during the Bronze Age (Jacomet, 1998). The use of dung as fertiliser and the production of hay as well as the use of iron ploughs and scythes also led to higher yields during the Iron Age (Müller, 1999). The adoption of innovations is likely to be responsible for the increasing long-term trends observed in our data. However, they do not explain the synchronous oscillations of pollen indicative of agricultural activities.

Table 2
Chronology of cultural periods

Age	Cultural period
After 568 AD	Middle Ages
375 AD–568 AD	Migration Period
15 BC–375 AD	Roman Period
450–15 BC	Late Iron Age
800–450 BC	Early Iron Age
1350–800	Late Bronze Age
1550–1350 BC	Middle Bronze Age
2200–1550 BC	Early Bronze Age
5500–2200 BC	Neolithic

Sources: Hochuli et al. (1998), Müller et al. (1999).

Decreases in pollen of cultivated plants and weeds could be caused by the abandonment of settlements as well as by migration of people. Because of rising lake-levels (Magny et al., 1998), Bronze Age lake-shore settlements were displaced or abandoned around 1500 and 850 BC (Rychner et al., 1998). Celtic tribes migrated south at around 400 BC, leaving central Europe and invading Northern Italy. In *De Bello Gallico* Julius Caesar reported that at 58 BC the tribe of the *Helvetii* left the Swiss Plateau for France, destroying their 12 cities, 400 villages, and many farms (Jud, 1999). After being defeated by the Roman army, the survivors were forced to resettle on the Swiss Plateau. Finally, after the year 375 AD many Germanic tribes left their northwestern and central European homesteads and eventually provoked the collapse of the Western Roman Empire in 476 AD.

Such large-scale population changes must have influenced agricultural yields substantially over the years. However, because of radiocarbon dating errors

Table 3
Cultures on the Swiss Plateau and in the Swiss southern Alps (2300–800 AD)

Western Swiss Plateau		Eastern Swiss Plateau		Swiss Southern Alps	
Age	Culture	Age	Culture	Age	Culture
400–800 AD	Romanic and Germanic	540–800 AD	Germanic	400–800 AD	Romanic and Germanic
		400–540 AD	Romanic		
15 BC–400 AD	Roman Empire	15 BC–400 AD	Roman Empire	15 BC–400 AD	Roman Empire
450–15 BC	La Tène	450–15 BC	La Tène	250–15 BC	La Tène
800–450 BC	Hallstatt	800–450 BC	Hallstatt	800–250 BC	Golasecca
1350–800 BC	Urnenfelder	1350–800 BC	Urnenfelder	1200–800? BC	Protogolasecca
				1350–1200 BC	Canegrate
1550–1350 BC	Hügelgräber	1550–1350 BC	Hügelgräber	1550–1350 BC	Viverone
2200–1550 BC	Rhone	1800–1550 BC	Arbon	2200–1550 BC	Rhone/Polada?
		2200–1800 BC	Singener?		
2450–2200 BC	Bell Beaker	2450–2200 BC	Bell Beaker	2450–2200 BC	Bell Beaker?

Based on various archaeological evidences, it has been hypothesised that the Bell Beaker culture delineates the first expansion of central-European Celtic cultures in western Europe (Stöckli, 1991). Sources: Hochuli et al. (1998), Müller et al. (1999).

(Table 1) and of sample resolution (50–80 years) it is not possible to address events shorter than 50–100 years with the methods used in this work. The only well-documented century-scaled migration period occurred between 375 (destruction of the East-Gothic Kingdom by the Huns) and 568 AD (Lombardic landnam in Italy). Pollen data suggest that during this time the reduction of agricultural activities (maximum of tree pollen, minimum of Cerealia, and *Plantago lanceolata* pollen, Fig. 5C–G) north and south of the Alps was accompanied by natural afforestation (see also Rösch, 1992 for southern Germany and Jacomet et al., 1999 for northern Italy).

Most of these population discontinuities are considered to be closely related to climatic change (e.g. Magny et al., 1998; Maise, 1998, 1999). We therefore compare the observed patterns in pollen curves with climatic proxies to address possible causal relationships between climatic forcing and the history of agriculture with its impact on vegetational development.

5.3. Climatic oscillations 2300 BC–800 AD

5.3.1. The Greenland records

Different proxies such as marine sediment records (Bond et al., 1997, 2001), oxygen isotope records in lacustrine and ice cores (Dansgaard et al., 1993; von Grafenstein et al., 1999; Johnsen et al., 2001), residual $\Delta^{14}C$ (Magny, 1995; van Geel et al., 1999) and dendroclimatological records (Bircher, 1986; Jones et al., 1998; Mann et al., 1999; Mann, 2000) are widely used to infer past Holocene climatic changes. Johnsen et al. (2001) found good correspondences among six different Holocene stable isotope records from Greenland, suggesting that the dominant influence on oxygen isotope variations was regional climatic change. The agreement for the Holocene comparison between GRIP and NorthGRIP is particularly good for the period of interest (2300 BC–800 AD, Johnsen et al., 2001), and in general it is assumed that changes in $\delta^{18}O$ mainly reflect past mean annual air-temperature variations.

Oxygen isotope records from Greenland show conspicuous peaks suggesting warmer climate at around 2100–1900 BC, 1450–1250 BC, 650–450 BC, 50 BC–100 AD, 350–400 AD and 700–1000 AD and a general decreasing temperature trend after 450 BC (Figs. 4C, 5A and B). Sediment properties (loss on ignition) for arctic lakes in West Greenland faithfully follow the fluctuations in the GRIP core for millennia, suggesting a close link between lacustrine palaeoproductivity and temperatures (Willemse and Törnqvist, 1999). Positive and negative excursions of the smoothed GRIP oxygen-isotope values have equivalents in the GISP2 record (Willemse and Törnqvist, 1999 and Fig. 4). With the exception of the period 1100–300 BC, however, they do not match the residual $\Delta^{14}C$ variations (Fig. 4). In some cases (e.g. positive excursions at about 1300 and 500 BC), the GRIP and GISP2 oscillations seem to be shifted by about 50–150 years (Fig. 4C). Southon (2001) noticed similar discrepancies and Willemse and Törnqvist (1999) emphasised that their data matched the GRIP better than the GISP2 record.

Positive and negative oscillations in the oxygen isotope records are comparable to those of the Little Ice Age (LIA, 1500–1900 AD, Fig. 5A and B), although they are of minor amplitude if compared to the Lateglacial and early Holocene oscillations. On the basis of the relationship of 3°C/‰ $\delta^{18}O$ for Greenland and 1.7°C/‰ in central Europe (see discussion in von Grafenstein et al., 1998), mean annual air temperatures between 2300 BC and 800 AD may have oscillated by ±0.3–0.6°C in Greenland and ±0.2–0.3°C (±0.1–0.2‰ $\delta^{18}O$) in central Europe.

5.3.2. Northern hemisphere and European climate proxies

For the past millennium mean annual air temperature inferred from oxygen isotope variations in Greenland are in agreement with northern hemisphere summer temperature oscillations reconstructed by means of other proxies (e.g. Jones et al., 1998; Jones et al., 2001; see Fig. 5A). For the time before 1000 AD it is possible to compare the Greenland oxygen-isotope variations with temperature proxies from central Europe. A good correspondence between oxygen isotope oscillations and the increases and decreases of temperature as inferred from tree-ring density variations (Bircher, 1982, 1986; Renner, 1982; Fig. 5B) can be observed. Tree-ring results were corroborated by palaeobotanical analyses (see Wick and Tinner, 1997) and glacier fluctuations in the Alps (Bircher, 1986) and suggest an additional warm phase around 1750 BC, when only a minor peak is present in the GRIP oxygen isotope values.

A trend to cooler climatic conditions similar to that in the Greenland ice-core record during the last two millennia is documented by more frequent and more marked advances of the Aletsch Glacier, the largest Alpine glacier (Wanner et al., 2000). For example, two Aletsch Glacier advances at around 1150 and 1350 AD are in agreement with the GRIP record and a new tree-ring series (Esper et al., 2002) suggesting relatively cool conditions between 1100 and 1400 AD. Moreover, all major peaks in the $\delta^{18}O$ values of the GRIP record are approximately synchronous with glacier retreats (before 1900 BC, see Maisch et al., 1999; around 1450 BC, 650 BC, 1 AD, 750 AD, see Wanner et al., 2000).

On the clear basis of the physical link between stable isotope and temperature variations and the good match with independent Greenland and Alpine climatic proxies, we have chosen the GRIP record for comparison with our pollen data in the following discussion. Since the GRIP oxygen isotope curve is correlated with tree-ring density variations (reflecting changing tree growth conditions during the vegetation period), we assume a rather close relationship between annual and summer climates.

5.4. Climate change and cultural phases

Warm periods at around 2100–1900 BC, 1450–1250 BC, 650–450 BC, 50 BC–100 AD, 350–400 AD and 700–1000 AD correspond to tree-pollen minima indicating coeval forest clearances north and south of the Alps (Fig. 5C, Table 4) within respective dating uncertainties. In addition, they generally coincide with maxima of CI, indicating more intensive agricultural activities. The closest matches are given at 1450–1250 BC, 650–450 BC, 50 BC–100 AD and around 700 AD (Fig. 5D–G). This close agreement is not confined to Switzerland. Marked peaks of CI (Cerealia, *Plantago lanceolata*) at around 1500 BC, 600 BC, 250 BC, 100 AD, 400 AD and 700 AD are also documented for southern Germany (Hornstaad, Durchenbergried: Rösch, 1992; Rösch, 1993). In nearly perfect match with Lago di Origlio (Fig. 5G), pronounced peaks of Cerealia and *Plantago lanceolata* are documented for Lago di Annone in northern Italy at 1900 BC, 1400 BC, 650 BC, 1 AD and 650 AD (Jacomet et al., 1999).

At some sites peaks of CI pollen are present around 1750 BC (Soppensee, Lago di Origlio) and 800 BC (Lobsigensee, Lago di Origlio), but they do not correspond to major peaks in the GRIP oxygen isotope record. A comparison with the dendroclimatological records show that they fell into minor or short warm phases in the Alps (H6h3, R1h1, Fig. 5).

Aside from the temporal distribution of maxima and minima (Fig. 5, Table 4), common trends exist between the GRIP and pollen records as illustrated by the course of the smoothed oxygen isotope and pollen curves. A pronounced trend to more negative values in the GRIP oxygen isotope record is noticeable between 500 BC and 500 AD. Tree-pollen curves of Soppensee, Lago di Muzzano and Lago di Origlio show increasing trends indicating afforestations between 500 BC and 500 AD (Fig. 5C). At Lobsigensee a similar development occurred between 400 BC and 200 AD. At the same time, pollen indicating anthropogenic activities and especially field cultivation show decreasing trends (Fig. 5D–G).

With the exception of the period 1100–300 BC no convincing match could be found between pollen and residual $\Delta^{14}C$ data. Recent studies (e.g. van Geel et al., 1999; Magny, 1999; Bond et al., 2001) suggest a close link between changes in solar activity and past climatic changes over the North Atlantic and Europe. It is evident that marked discrepancies exist between the Greenland records and the residual $\Delta^{14}C$ curve throughout the Holocene (Fig. 4, see also Stuiver et al., 1995). For example, the most prominent Holocene climatic reversal in the Greenland records at 8200 cal. BP was at least of northern hemisphere extent (e.g. von Grafenstein et al., 1998; Hu et al., 1999), but it is hardly detectable in the residual $\Delta^{14}C$ curve or other proxies of solar radiation (e.g. Magny, 1999; Bond et al., 2001). Our results as well as dendroclimatological and glacier records from the Alps suggest that climatic changes between 2300 BC and 800 AD recorded in the GRIP ice core were of great relevance for the European climate system. The differences between the Greenland climatic records and the residual $\Delta^{14}C$-curve may be either due to: (1) climatic changes generated by factors other than solar activity (see Bond et al., 2001), (2) factors other than solar activity influencing the $\Delta^{14}C$ record (see Stuiver and Braziunas, 1991) or (3) discrepancies in the chronological systems. Since chronological discrepancies exist between the GRIP and GISP2 records, presently the three explanations seem equally plausible.

Table 4
Cultural phases, regional differences, climate and innovations

Age (±100 yr)	CI	Site, region	Climate	Innovation, history
2300–2100	Low	S, L, M, O	Cold, humid	
2100–1900 BC	↑, low-medium	L, M, O,	Warm, dry	Bronze tools, ox pulled ploughs
1750–1650 BC	↑, medium	S, O	Warm, dry	
1650–1450 BC	↓, low	S, L, M, O	Cold, humid	Bronze sickles
1450–1250 BC	↑, low-medium	S, L, M, O	Warm, dry	
1000–950 BC	↓, low-(medium)	S, L, M, O	Cold, humid	
800 BC	↑, medium-high	L, M, O	Unstable	Iron ploughs, scythes, dung fertiliser, hay production
700 BC	↓, low-medium	S, O	Cold, humid	
650–450 BC	↑, high	S, L, M, O	Warm, dry	
200 BC	↓, medium-high	S, L, M, O	Cold, humid	
50BC–100 AD	↑, medium, high	S, L, M, O	Warm, dry	New crops (e.g. *Juglans*)
150–350, 500 AD	↓, low-high	S, L, M, O	Cold, humid	Migrations
700 AD	↑, high	S, L, M, O	Warm, dry	

↑ = maximum of cultural indicators (CI), ↓ = minimum of CI. CI < 1% = low, CI 1–2% = medium, CI > 2% = high. S = Soppensee, L = Lobsigensee, M = Lago di Muzzano, O = Lago di Origlio. The climate deviation from the average is based on comparisons between Alpine dendroclimatological series (Bircher, 1986) and the GRIP record (Dansgaard et al., 1993; see Fig. 5).

5.5. Effects of climate change on prehistoric agriculture and population

The good match between the GRIP data and our pollen data suggest that agricultural yields and land-use were to a large extent climatically controlled, and it seems that crop failures due to climatic deterioration were drastic enough to overrule technical progress at least in part. But what happened exactly when the climatic deterioration set in? It seems highly unlikely that temperature decrease alone could have led to harvest failures. After 2200 BC grain fields existed at altitudes of 1630–1700 m a.s.l. in the central Alps of Switzerland (Zoller and Erny-Rodman, 1994). Assuming temperature lapse rates of about $6^\circ\mathrm{C\,km^{-1}}$, summer temperatures were about 6–7°C cooler at these elevations than at the lowland study sites north of the Alps. Nevertheless, cultivation of *Triticum* and *Hordeum* was successful, considering that pollen of Cerealia reached peak values of more than 5% in deposits at these elevations (Zoller and Erny-Rodman, 1994). In the Alps most Holocene cool periods were characterised by higher amounts of precipitation and were therefore comparable to the LIA period (Wanner et al., 2000; Tinner and Ammann, 2001). Thus it seems more plausible that prolonged humid conditions during the growing season favoured parasite attacks and provoked substantial harvest losses. This would also explain why, despite markedly higher summer temperatures, harvest losses also occurred in the sub-mediterranean region south of the Alps. Land abandonment in marginal areas may have led to famines and migration to more favourable areas. Subsequently, *Plantago lanceolata* and other weeds and meadow plants (e.g. as represented by pollen of *Artemisia*, Caryophyllaceae, *Rumex acetosella* t., *Teucrium*, Asteroideae, Cichorioideae, *Centaurea jacea* t., *Jasione* t., *Potentilla* t., Rosaceae, *Trifolium repens* t., *Urtica*, *Polygonum aviculare*; see Conedera and Tinner, 2000b) were rapidly displaced by successional processes involving the reestablishment of woodlands. Only when climate changed again to more favourable conditions for cereal-based agriculture a new wide-spread phase of forest clearances and field extensions was possible, allowing a new cycle of landnam and thus population growth.

The frequency of archaeological findings through time has been compared with residual Δ^{14}C (Magny, 1993a; Gross-Klee and Maise, 1997; Maise, 1998). For different reasons archaeological findings were more frequent when residual Δ^{14}C was low or near the average, indicating elevated solar activity. Explanations include lake-level changes influencing the location of lake dwellings (Magny, 1993a; Gross-Klee and Maise, 1997) and climatically caused human-population collapses in Europe (e.g. Champagne, Neckarland, Mittelfranken, Sachsen, Fig 1, see Maise, 1998). The two phases (800–650 BC and 400–100 BC) of land abandonment observed by Maise (1998) are best depicted at Soppensee. Historical records show that the region around Soppensee is located in the most marginal area for cereal production (AdS, 1977), and it is hence likely that climatic reversals had the biggest effect on this site. This sensitive position of Soppensee may also explain why the site shows the best match with the GRIP data.

Recently, cultural shifts, population dislocations, urban abandonment and state collapses in dry regions of North and South America and Asia have been attributed to droughts lasting decades or centuries (deMenocal, 2001; Polyak and Asmerom, 2001). Our results imply that early European societies north of the Mediterranean Basin were more endangered by prolonged humid-cool periods. However, in central Europe, archaeological data suggest cultural continuity for thousands of years (Stöckli, 1991). This illustrates that despite considerable cycles of spatial and demographic reorganisations (repeated land abandonments and expansions, as well as large-scale migrations and population decreases), human societies were able to shift to lower subsistence levels without dramatic ruptures in cultural elements.

6. Conclusions

Our results suggest a high climatic dependence of human prehistorical and historical activities during many millennia. The resulting patterns of vegetational change cannot be explained neither by cultural developments nor by human impact alone. However, cultural persistence as indicated by uninterrupted evolution of material culture for thousands of years as well as the successful adoption of yield-increasing advances argue against a simplistic model of climatic determinism. Instead, human societies developed in interaction with their environment, and it is likely that technical advances allowed increasing growth of a vulnerable population, as evidenced by the positive trends in the CI of our study sites that persisted for millennia. Our model of climatically driven phases of expansions and contractions of cultivated land is supported by many archaeological evidences over Europe. However, to address this topic by means of pollen analysis more effectively, chronological control and sample resolution of standard pollen diagrams have to be improved. This will eventually permit better comparison with independent climatic proxies.

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