



GLOBAL CHANGE IN THE HOLOCENE

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CHAPTER

25

MULTI-PROXY CLIMATIC RECONSTRUCTIONS

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Abstract: This chapter presents an overview of the potential of multi-proxy studies for Late Quaternary climatic reconstructions using lacustrine sediment records. Choice of sites, proxies and their climatic sensitivity, leads and lags of different proxies, and chronology are discussed and illustrated by three case studies of Late Glacial, Younger Dryas and Holocene multi-proxy summer temperature reconstructions. Common trends and consistencies in multi-proxy data make climatic reconstructions more credible, whereas differences among multi-proxy records call for a critical evaluation of the strengths and weaknesses of the proxies involved.

Keywords: Climatic reconstruction, Leads and lags, Reaction times, Transfer functions

This chapter deals with multi-proxy climatic reconstructions resulting from the study of biotic and abiotic materials preserved in continental lacustrine deposits. The focus and the selection of examples are the results of a personal bias. Other important types of environmental archives for multi-proxy climatic reconstructions are dealt with elsewhere in this book (e.g. marine deposits, historical records, glaciers and others).

The study of past and present global climatic change and the multiple interactions among geosphere, hydrosphere and biosphere call for a holistic approach to understand these complex and often non-linear relationships. Traditionally, every discipline in palaeoscience has concentrated on developing its own methods to reconstruct past climate. Depending on the specific proxy investigated the focus has usually been on one particular climatic variable. Biotic proxies such as vegetation or aquatic insects have mainly been interpreted in terms of the temperature of the growing season, whereas information from closed lake basins, raised mires, or abiotic archives such as glaciers and river deposits has focussed on precipitation. A wealth of mono-proxy climatic reconstructions go back to the early days of Quaternary science, such as the plant-indicator species approach of Iversen (1944). Even earlier, Gams and Nordhagen (1923) inferred major Late Quaternary climatic changes based on the combination of different types of evidence from European lacustrine deposits, an approach that today would be called a 'multi-proxy' study.

Such multi-proxy studies are becoming increasingly popular, not only in palaeoclimatology but also in palaeoecology and palaeolimnology including biotic assemblages (e.g. pollen, plant macrofossils, diatoms, ostracods, molluscs, chrysophytes, chironomids, cladocerans, coleopterans,

see relevant chapters in this book) and/or sedimentary variables (stable-isotopes, grain size, organic and inorganic geochemistry, mineralogy, loss-on-ignition, magnetic sediment properties, etc.). Such studies, however, are very labour-intensive and need careful planning. The major advantage that make multi-proxy studies attractive is the potentially independent lines of evidence they offer for environmental reconstruction. Every proxy has its own strengths and weaknesses, depending on such characteristics as its occurrence and abundance, temporal and spatial resolution, reaction and recovery time, and the climatic variables it approximates (e.g. Guiot, 1991, but see also chapters in this book). In a multi-proxy approach we seek to take advantage of the strengths and identify the weaknesses of each proxy with the aim of building on the consistencies and explaining the disagreement among proxies.

25.1 MULTI-PROXY STUDIES: TYPES AND TROI

In principle, two main approaches may be distinguished: single-site and multi-site studies. Observations and interpretations from single-site studies form the basis of any palaeoclimatic reconstruction. Depending on the sediment-sample size needed for analysis (e.g. $<1 \text{ cm}^3$ for most microfossils; several cm' for plant macrofossils; up to several kilograms for Coleoptera) the single-site approach may require the use of different cores from the same deposit. Such different stratigraphical sequences then need to be correlated on the basis of either conspicuous stratigraphical marker horizons (e.g. laminae, tephrae, etc.) or by using core-correlation techniques such as loss-on-ignition (LOI), magnetic susceptibility, or stable-isotopes. Different proxies may have dissimilar time resolution, so corresponding samples from different cores may represent unequal amounts of time. Depending on the importance of the temporal resolution of the study, this may create problems, e.g. a comparison of rates of change on a high-resolution time scale may be impeded. Preferably, however, all analyses should be carried out on the same core to minimize errors of stratigraphic correlation. Moreover, the sampling intensity and the sample intervals for all proxies should ideally be identical to avoid the above-mentioned difficulties.

Multi-site studies link different proxy data from single-site studies by using a common chronological framework to produce a climatic reconstruction in space and/or time. An example of such a multi-site approach is the reconstruction of European precipitation patterns for Holocene time-intervals by the combined use of lake-level and pollen proxies (Guiot *et al.*, 1993a). In another example, Huijzer and Isarin (1997) assembled botanical, zoological, periglacial, glaciological, aeolian, fluvial, lacustrine and pedological evidence in a multi-proxy database to reconstruct the Weichselian pleniglacial climate in northwestern and central Europe. A reliable chronology is of major importance in such an approach. In many cases, regional or even global overviews and reconstructions are hampered because of poor time control. This is especially the case for the Last Glacial and the Late Glacial periods or for sites in extreme settings such as high-altitude or high-latitude regions, where little suitable dateable organic matter is available for dating, even by accelerator mass spectrometry (AMS).

25.2 ABIOTIC AND BIOTIC PROXIES

The benefit of combining two or more proxies, preferably from the same sediment core, to reconstruct past climate is evident from the wealth of scientific literature. Among abiotic climatic proxies, stable-isotopes play a prominent role (see Leng, pp. 124—139 in this volume). Since the

1970s numerous studies have stressed the potential of combining oxygen isotope analyses with pollen-analytical studies (e.g. Eicher and Siegenthaler, 1976; Lotter and Zbinden, 1989; Ralska-Jasiewiczowa *et al.*, 1992; Andrieu *et al.*, 1993; Hammarlund and Buchardt, 1996; Ahlberg *et al.*, 2001; Tinner and Lotter, 2001). Most of these studies have been carried out in Europe and focus on the Late Glacial period. Nevertheless, there are also such combined studies from North America (e.g. Fritz *et al.*, 1987; Lewis and Anderson, 1992; Yu and Eicher, 1998) as well as from the Holocene of Turkey (e.g. Lemcke, 1996; Reed *et al.*, 1999) and Africa (e.g. Lezine *et al.*, 1990). Close similarities among lacustrine lake marl and ostracod $\delta^{18}\text{O}$ records, and oxygen isotope variations in Greenland ice-cores suggest that the lake records are sensitive and respond rapidly to broad climatic shifts (Siegenthaler *et al.*, 1984; von Grafenstein *et al.*, 1999). The major and minor shifts recorded in the Late Glacial $\delta^{18}\text{O}$ curves (see Lotter *et al.*, 1992; Bjorck *et al.*, 1998) reflect changes in the North Atlantic thermohaline circulation that eventually led to climatic oscillations (e.g. Broecker, 2000). It is thus attractive to use the $\delta^{18}\text{O}$ signal as proxy for climatic change and then to observe the reaction of biotic and abiotic systems on both sides of the Atlantic (e.g. Bjorck *et al.*, 1996c; Yu and Wright, 2001). Several studies using stable-isotope records as a proxy for climatic change and pollen as a proxy for vegetation show no substantial lag of vegetation response to major climatic oscillations (e.g. Lotter *et al.*, 1992; Ammann *et al.*, 2000; for further discussion see below).

With biotic climatic proxies, one of the major points of discussion still is whether the organism of interest reacts directly or is triggered by climate-induced changes of habitat or substratum or, mainly in the case of aquatic organisms, is mediated through changes in the lake (e.g. length of ice-cover, mixing regime, anoxia, etc.) as well as in the catchment (e.g. vegetation cover, erosion, nutrient export, etc.). Furthermore, because different organisms have dissimilar ecological and climatic thresholds, it is also important to assess biota-inherent tolerances to particular climatic variables. In recent years, quantification of biotic proxies in terms of climatic variables has helped to elucidate some of these issues. Empirical regression models (transfer functions; see Birks, pp. 107-123 in this volume) infer climatic variables based, for example, on estimates of optima and tolerances of different taxa. Different organisms have been numerically related to one or more environmental variables that are directly (e.g. temperature, precipitation) or indirectly (e.g. lake-water salinity, pH) linked to climate. Applications of such transfer functions to downcore biotic assemblages allow quantitative reconstructions of past climatic variables. Nevertheless, climate as well as other environmental factors can produce similar signals in a proxy record, and it is therefore essential to evaluate the results of such quantitative climatic reconstructions critically. Pienitz *et al.* (2000) give an example of an indirect multi-proxy climatic reconstruction. By applying diatom, fossil-pigment and mineralogical analyses to a sediment core from a lake in the Canadian subarctic, they inferred changes in the salinity of this high-latitude lake that also reflect Holocene changes in effective moisture. Using pollen, plant-macrofossil, diatom and sedimentological analyses in combination with chironomid-inferred temperatures, Levesque *et al.* (1994) and Mayle and Cwynar (1995) estimated summer cooling in Atlantic Canada for the Younger Dryas.

25.3 CASE STUDIES OF LATE QUATERNARY MULTI-PR CLIMATIC RECONSTRUCTIONS

In the following section three case studies of multi-proxy climatic reconstructions are discussed. Most multi-proxy climatic reconstructions in the literature deal with the Late Glacial period, as

this period gives evidence for the highest amplitude of climatic and environmental change since the end of the last ice-age, whereas Holocene climatic changes are smaller and therefore more difficult to detect. The choice of the three case studies reflects this situation: the first two examples deal with Late Glacial and Early Holocene climatic reconstructions, whereas in the third example multi-proxy climate inferences for the Holocene are discussed.

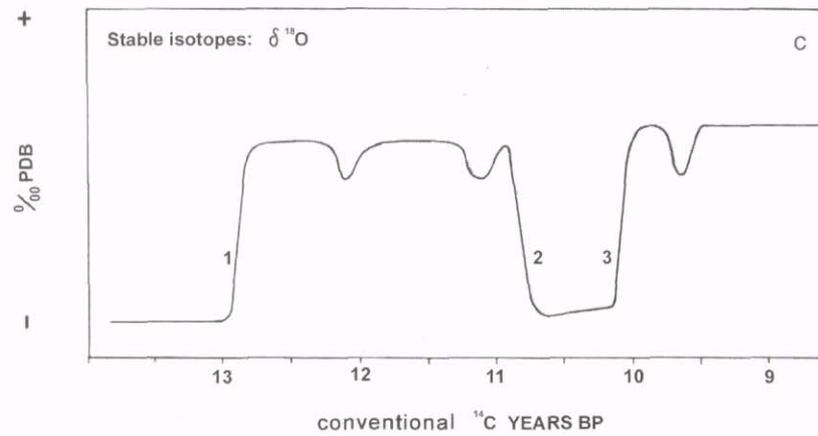
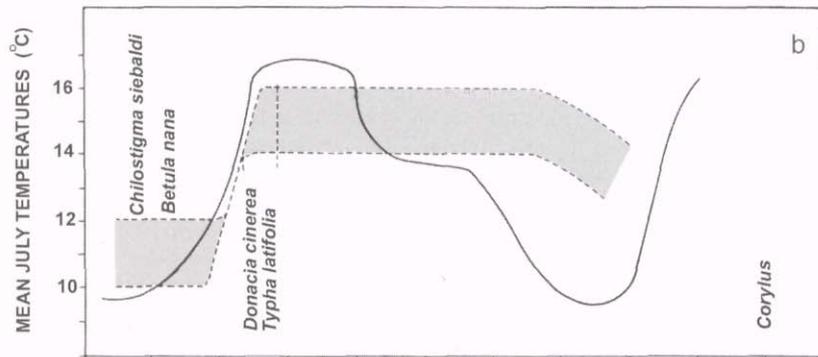
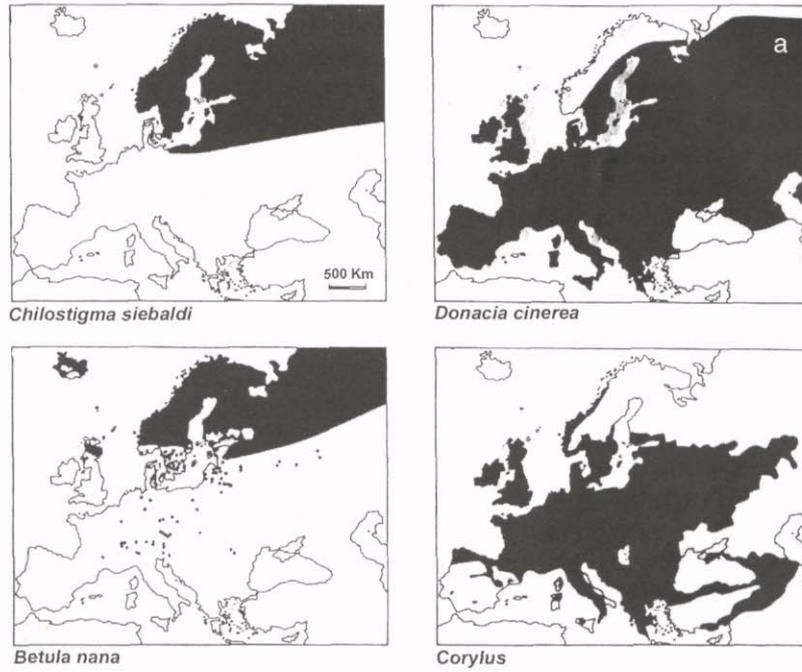
25.3.1 Lobsigensee: Late Glacial Climatic Change

Lobsigensee is a small kettle-hole lake on the Swiss Plateau where Ammann (1989b) used more than a dozen cores for pollen and other biotic and abiotic proxies. A littoral core was analysed for Coleoptera (beetles) and Trichoptera (caddis flies; Elias and Wilkinson, 1983) as well as stable oxygen isotopes (Eicher and Siegenthaler, 1983). More than three dozen macrofossil samples of terrestrial vegetation radiocarbon-dated by AMS provided an excellent high-resolution Late Glacial and Early Holocene chronology (Ammann and Letter, 1989).

The sediments older than 12,700 (conventional radiocarbon years) BP contain pollen of heliophilous herbs such as grasses and *Artemisia* as well as pollen and macrofossils of willows and dwarf birch (*Betula nana*). The vegetation during this period consisted of shrub tundra. Beetles and caddis flies of modern boreo-montane distribution such as *Chilostigma siebaldi* present in these sediments, suggesting mean July temperatures between 10 and 12 °C according to modern analogues (Elias and Wilkinson, 1983). Figure 25.1a shows the similar modern distributions for *C. siebaldi* and *B. nana* (mean July temperature >7 °C, see Huijzer and Isarin, 1997 and references therein). At 12,700 BP a first sharp increase in $\delta^{18}\text{O}$ values indicates climatic warming (Lotter *et al.*, 1992). Both pollen and macrofossils of dwarf birch decreased as well as remains of cold-indicating caddis flies. Simultaneously, the first records of *Typha latifolia* pollen and of the temperate plant-independent beetle (*Donacia cinerea*) occur (see Fig. 25.1). The Boiling and Allerød vegetation is characterized by open birch woodland and pine-birch woodland, respectively. According to the insect assemblages the mean July temperature was between 14 and 16 °C, whereas *T. latifolia* may grow at temperatures of 12–14 °C today, but is more common when mean July temperatures are >15 °C. However, the temperature estimates based on such plant-indicator species have to be considered merely as threshold values, and the occurrence of such indicator plants will not give any information as to the extent to which this threshold had been crossed (see also discussion in Birks, 1981).

Whereas the climatic cooling of the Younger Dryas is evidenced by a decrease in the $\delta^{18}\text{O}$ values (Fig. 25.1c) and a renewed increase of heliophilous herb pollen, indicating an opening of the pine-birch woodland around 10,800 BP, the insect assemblages at Lobsigensee give no evidence for cooling (Fig. 25.1b). This contrasts markedly with results from Britain (see Fig. 25.1b) and

Figure 25.1 Multi-proxy climatic reconstruction for the Late Glacial period at Lobsigensee (Central Swiss Plateau). Modified after Ammann (1989a). (a) Comparison of modern biogeographical ranges of the caddis fly *Chilostigma siebaldi*, the beetle *Donacia cinerea*, the dwarf birch (*Betula nana*), and hazel (*Corylus*), (b) Insect-inferred Late Glacial July temperatures for Lobsigensee (grey band, according to Elias and Wilkinson, 1983) and for Britain (solid line, according to Coope, 1977). The timings of occurrence or immigration of constituents of the insect and vegetation assemblages are also shown, (c) Simplified oxygen isotope curve for the Swiss Plateau showing the three major shifts in bulk-carbonate $\delta^{18}\text{O}$ (after Lotter *et al.*, 1992). The time-scale refers to conventional (uncalibrated) radiocarbon years BR



Scandinavia (e.g. Coope, 1977; Coope *et al.*, 1998), where a substantial coleopteran-inferred cooling is indicated. The transition between the Younger Dryas and the Pre-Boreal at 10,000 BP (i.e. the onset of the Holocene) is marked by another major increase in oxygen isotopes (Fig. 25.1c) together with a decrease in herb pollen. During the Pre-Boreal the pine-birch woodland in all of Central Europe was rather rapidly replaced by hazel (*Corylus*) and some centuries later by other temperate deciduous trees. *Corylus* has a modern distribution somewhat similar to that of *D. ctnerea* (see Fig. 25.1a). It is noteworthy that the arrival and expansion of this shrub, which today occupies a climate space similar to that of the temperate beetle (*D. cinerea*), took more than 3500 years, whereas the arrival of the reed-plant *T. latifolia* was contemporaneous with that of the beetle.

This example demonstrates the advantage of insects and aquatic organisms as climate proxies, or the possible disadvantages of trees. Once climatic conditions are favourable, the amount of time needed for organisms to migrate depends on factors such as the distance from refugia, their dispersal abilities and the availability of suitable habitats in the region to be **colonized**. Moreover, changes in productivity (e.g. annual seed or pollen production) in response to climatic change may also play an important role for long-lived organisms such as trees (Ammann *et al.*, 2000). According to Iversen (1954, 1964; but see also Ritchie, 1986) water plants may react fast to climatic change because of their short life-cycle, efficient dispersal and their pedogenic independence. These reasons are also valid for (vegetation-independent) insects (e.g. Coleoptera, Trichoptera, chironomids) and aquatic organisms (e.g. water plants, Cladocera, algae such as diatoms and chrysophytes). These short-lived organisms are therefore most likely to be the best fossil biomarkers for Late Glacial climatic change. If vegetation is used as a climatic proxy, it is important for it to be in equilibrium with climate (see e.g. Birks, 1981; Davis, 1984; Prentice, 1986; Webb, 1986). In the case of the lagged reaction of hazel, Ammann (1989a) favours the hypothesis of a migrational lag because of poor seed dispersal and life-cycle characteristics. Furthermore, increased seasonality and continentality during the Younger Dryas, with very cold winters and late frost, may have inhibited or delayed the expansion of the frost-sensitive hazel, whereas the onset of milder winters during the Holocene may have favoured its rapid expansion throughout Europe during the Early Holocene.

25.3.2 Gerzensee And Krakenes: High-Resolution Climatic Change of the Younger Dryas

Two independent high-resolution studies from Switzerland and Norway focus on the Younger Dryas as an example of an abrupt, high-amplitude climatic change. Both studies illustrate very elegantly the use of quantitative multi-proxy climatic reconstructions to assess the magnitude and rate of climatic change.

Gerzensee is a small kettle-hole lake located in the sub-montane belt of the Swiss Plateau. An oxygen isotope oscillation of Allerød age was named after this site (Eicher and Siegenthaler, 1976; Lotter *et al.*, 1992). This oscillation has not only been found in the Greenland ice-cores (Björck *et al.*, 1998) but also in LOT stratigraphies and chironomid-inferred temperatures from Atlantic Canada, where it is called the Killarney oscillation (Levesque *et al.*, 1993a, 1993b). A multi-proxy investigation of biotic response to climatic change was undertaken on a core consisting of Late Glacial lake marl (Ammann, 2000). At Krakenes, a small coastal lake close to a former cirque glacier in west central Norway, a similar study was carried out (Birks *et al.*, 1996a). An extensive series of radiocarbon dates on terrestrial macrofossils was calibrated to

produce a calendar-year chronology for Krakenes (Birks *et al.*, 2000), whereas at Gerzensee a high-resolution chronology was derived by synchronizing the detailed lake-marl oxygen isotope stratigraphy with the GRIP 8^{18}O record (Schwander *et al.*, 2000). This oxygen isotope stratigraphy is assumed to record the hemispheric temperature changes without lag and is used to indicate the commencement of the climatic change at the beginning and end of the Younger Dryas (see Fig. 25.2).

At both sites quantitative temperature reconstructions based on weighted averaging partial least squares (WA-PLS) regressions and calibrations (see Birks, pp. 107-123 in this volume) were carried out. At Gerzensee pollen and benthic cladoceran WA-PLS reconstructions were used to infer mean summer temperatures (average of June, July and August) (Lotter *et al.*, 2000). At the onset of the Younger Dryas the pollen-inferred mean summer temperatures dropped by 2–3 °C over *c.* 135 years, whereas the cladoceran-inferred temperatures decreased by 2–4 °C over *c.* 225 years. At the end of the Younger Dryas the pollen-inferred temperatures increased by 2–3 °C over *c.* 160 years, while the Cladocera imply an increase of 5–6 °C in *c.* 400 years (see Fig. 25.2). At Gerzensee the inferred rates of temperature change are thus about 0.6 °C per 25 years at the beginning and about 0.3 °C per 25 years at the end of the Younger Dryas. At Krakenes pollen, cladoceran and chironomid WA-PLS models as well as plant-macrofossil reconstructions based on modern analogues were adopted to infer mean July temperatures (Birks and Ammann, 2000). Although all the investigated organisms exhibited high rates of change (Birks *et al.*, 2000), it is only the plant macrofossils and chironomids that show a marked fall in Younger Dryas mean July temperatures (Fig. 25.2). At the end of the Younger Dryas all organisms imply a steep rise in temperature of 4–6 °C. At Krakenes the rates of temperature change are about 0.7 °C per 25 years at the onset and between 0.2 (chironomids) and 0.3 °C per 25 years (Cladocera) at the end of the Younger Dryas.

This example demonstrates how independent climatic reconstructions based on terrestrial and aquatic biota may complement each other. The ranges and rates of temperature increase and decrease revealed at these two sites more than a thousand kilometres apart are, within the chronological constraints, surprisingly comparable and reflect rates comparable to those observed in the Greenland ice-cores. However, differences between the two reconstructions do exist. The inferred Allerød summer temperatures at Gerzensee were generally 2–4 °C warmer than at Krakenes, whereas the Younger Dryas was up to 4 °C colder in western Norway. Here, the comparison with the temperature inferences by aquatic organisms and with plant macrofossils (tree birches established locally around 10,900 cal yr BP) point to the fact that the pioneer Allerød tree-less vegetation was not yet in equilibrium with climate. If the steeply increasing cladoceran-inferred temperatures for the Early Holocene at Gerzensee were real, then the pollen-inferred temperatures that levelled off around 11 °C would point in the same direction.

25.3.3 Sjuodjjaure: Holocene Climatic Change

An increasing number of quantitative reconstructions based on transfer functions give evidence for large temperature changes for the Late Glacial and Early Holocene periods. For the Holocene period, however, only a few quantitative reconstructions and hardly any multi-proxy reconstructions are available. The smaller amplitude of climatic change during the Holocene is usually close to the limits of the prediction errors of the inference models. A multi-proxy approach providing independent reconstructions is therefore of great importance.

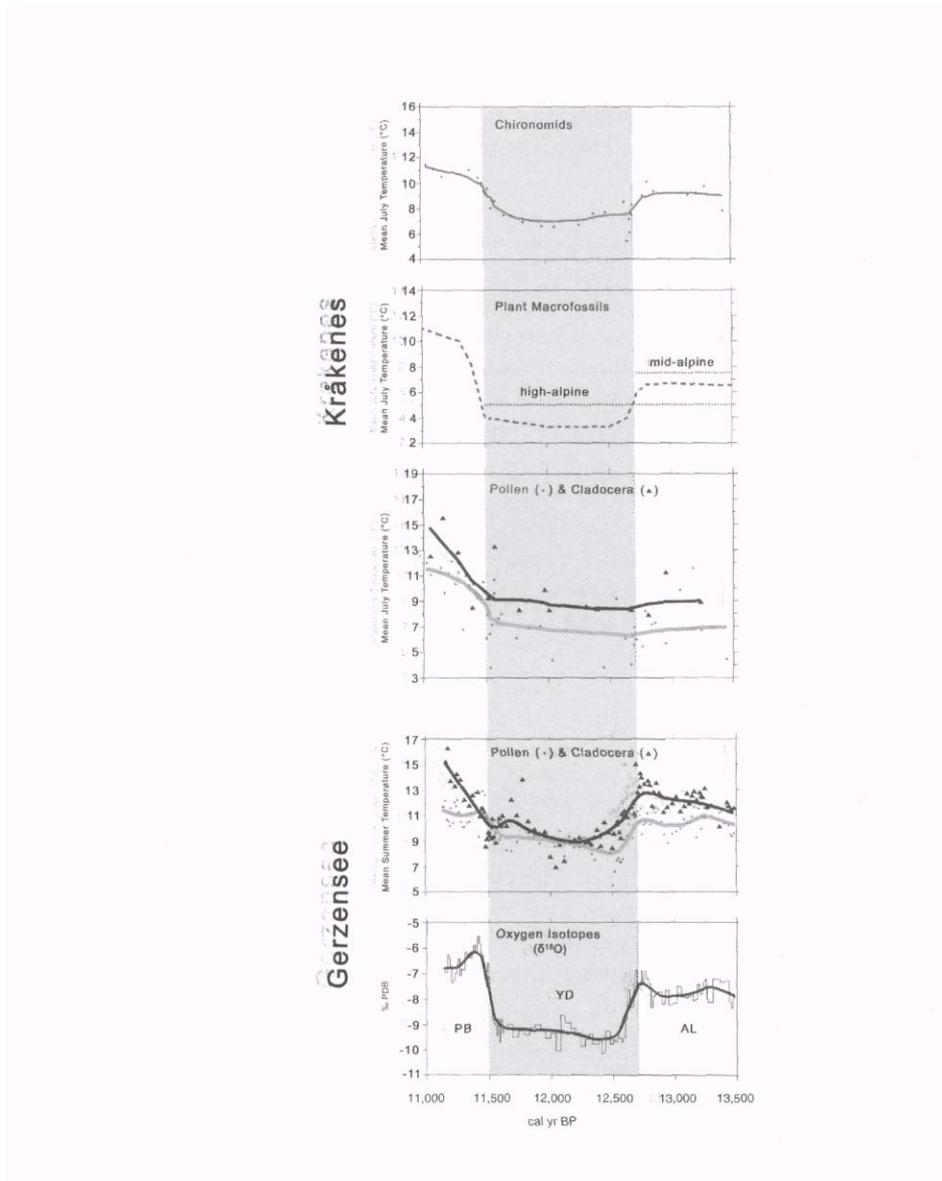


Figure 25.2 Multi-proxy climatic reconstructions at Gerzensee (Switzerland, data from Letter et al., 2000) and Krakenes (western Norway, data from Birks and Ammann, 2000). The Gerzensee chronology refers to GRIP ice-core years *BP*, whereas the Krakenes chronology is based on calibrated radiocarbon dates. The mean summer (average of June, July, August) and mean July temperatures were inferred from weighted averaging partial least squares regression and calibration models. For plant-macrofossil temperatures modern vegetation analogues were used, and the horizontal dotted lines delimit the mean July temperatures for mid- (5–7.5 °C) and high-alpine vegetation zones (<5 °C). The lines drawn through the individual estimates are LOWESS smoothers (span: 0.25). AL = Allerad; YD = Younger Dryas; PB = Pre-Boreal.

Rosen *et al.* (2001) investigated sediments of Sjuodjijaure, a small lake above tree-line in the Scandes Mountains of northern Sweden. The lake is located in an ecotonal area where small climatic changes may trigger large biotic reactions. The chronology of the core is based on five AMS radiocarbon dates on terrestrial plant remains. Regional WA-PLS transfer functions were used to infer mean July temperatures for the past 9300 years from diatoms, chironomids, pollen and near-infrared spectroscopy (NIRS) of organic sediment. The inferred Holocene temperatures based on these four proxies show a generally similar development (see Fig. 25.3).

Between 9300 and 7300 cal yr BP all reconstructions indicate short-term temperature variations. These are well within the model-inherent errors of prediction (0.9-1.7 °C). However, some of these rapid oscillations are simultaneously manifested by different proxies and can thus be accepted with more confidence: the decreases in LOI values around 8500 and 7600 cal yr BP are concurrent with oscillations in the diatom- and chironomid-inferred temperatures of 0.6-1.7 °C. The LOI decrease around 8200 cal. BP is contemporaneous with the pollen-inferred temperature oscillation (cooling of 0.8 °C and subsequent warming of 1.7 °C) and, to a lesser degree, those evidenced by diatoms and chironomids (0.5-0.6 °C). Depending on the proxy, however, only few or no convincing modern analogues exist in the calibration datasets for the Early Holocene. Rosen *et al.* (2001) are rightly cautious about the interpretation of the reconstructions for this period. The analogues are considerably better after ca. 7300 cal yr BP and may therefore be more reliable.

Around 7300 cal yr BP, a major increase of between 1.5 and 1.7 °C in mean July temperature is indicated by all proxies except the pollen, which may be affected by a migrational lag of the vegetational constituents. Subsequently, the inferred temperatures began to decrease gradually, and lower temperatures then characterize the Late Holocene. Considering the chronological uncertainties, the inference that the climate was warmest during the Mid-Holocene compares well with other investigations from northern Scandinavia.

Correlations among the different proxy-based temperature inferences for the entire Holocene are highest between chironomids and NIRS ($r = 0.92$) and lowest for pollen and NIRS ($r = 0.32$), whereas for the period from 7300 cal yr BP to today they are highest between diatoms and chironomids ($r = 0.84$) and diatoms and pollen ($r = 0.83$) and lowest for NIRS and pollen ($r = 0.45$). The differences in correlation between the different proxy-derived mean July temperatures is not surprising because each of these biotic and abiotic proxies reacts with a different time lag to climatic change. Moreover, July air temperature is not the only controlling factor, for it is correlated with several other climate-related and limnological factors.

To assess Holocene climatic change on a regional or even continental scale, more such multi-proxy studies are needed. By comparing similarities in the different proxy-inferred climatic parameters (see e.g. Rosen, 2001), such studies will eventually not only allow one to assess long-term climatic change but also, given the necessary time-resolution, short-term trends.

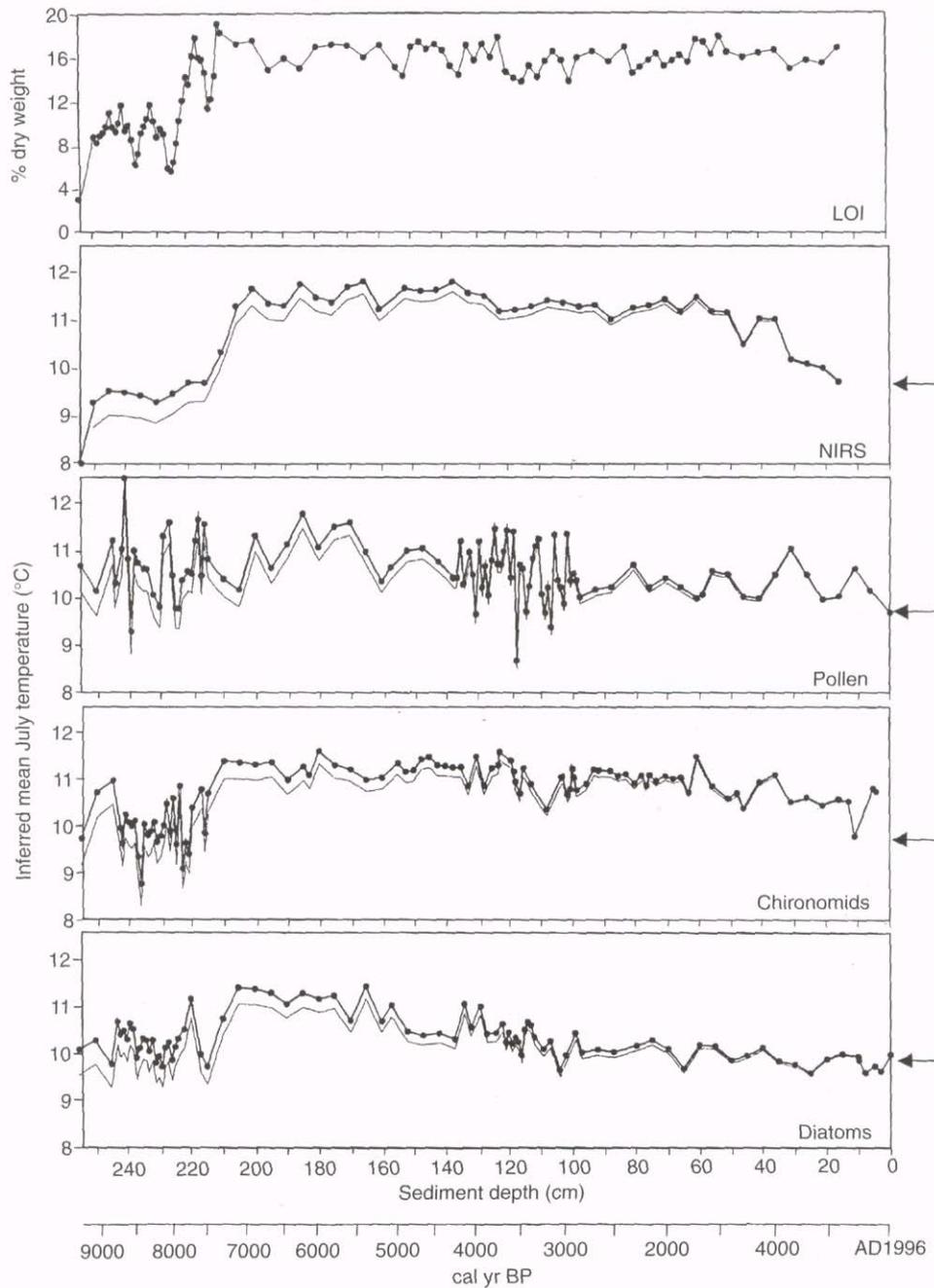


Figure 25.3 Loss-on-ignition (LOI) data and multi-proxy mean July temperature reconstructions from diatoms, chironomids, pollen and near infrared spectroscopy (NIRS) for a sediment core of Sjudjijaure (northern Sweden). The arrows indicate the modern mean July temperature (9.8 °C) at the lake and the dotted lines represent the inferred July temperatures corrected for land uplift. Data from Rosen et al. (2001).

25.4 CONCLUSIONS

Multi-proxy studies are increasingly popular to reconstruct past environmental change at different spatial and temporal scales. As such studies are extremely laborous and time-demanding they need a rigorous design, careful planning and meticulous site selection.

The choice of proxies for such studies is paramount. They should be sensitive climatic indicators (i.e. their variations in the fossil record should be attributable to climate change) and complementary in their ability to reconstruct climate. Fast-reacting proxies such as e.g. stable-isotopes, insects, or aquatic organisms may help to extract the climatic signal directly, whereas long-lived proxies such as upland vegetation and especially trees may show delayed reactions. The combination of these types of proxy may help register leads and lags in the reaction of different biotic and abiotic systems to climatic change and thus enhance our 'understanding of community ecology under a changing climate, including equilibrium or disequilibrium between communities and climate' (Ammann, 1989a). Detecting common trends between independent proxies may make reconstructions more credible, whereas identifying differences calls for critical evaluations.

The chance of detecting past climatic change, especially during the Holocene, is highest at sites that are located at ecotones. Here small changes in climate are likely to lead to biotic response that may be traced in the sedimentary record. However, during times of low-amplitude climatic change such as the Holocene, one of the drawbacks of the multi-proxy approach may be that ecotonal situations are organism-specific, i.e. some biota may react at a site, whereas others are not affected (Letter and Birks, unpublished data).

Ideally, all proxies should be studied on the same sediment core to minimize the necessity of core correlation and problems of comparison of the observed changes. If fast climatic changes are to be studied, cores with high sediment-accumulation rates that allow fine-resolution studies are preferable. Particular attention must always be paid to chronology. A reliable time-scale (preferably in calendar years) is not only of paramount importance for unambiguous long-distance comparison of climatic reconstructions but also for the estimation of rates of change. Multi-site studies will eventually help in assessing trends and interpretations of climatic reconstructions on a broader spatial scale. More such multi-proxy climatic reconstructions are needed to elucidate geographical patterns of climatic change that may be used as boundary conditions to constrain climate models or as a means of validating Earth System model results.

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