Quaternary Science Reviews 200 (2018) 212–236

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Holocene vegetation history and quantitative climate reconstructions in a high-elevation oceanic district of the Italian Alps. Evidence for a middle to late Holocene precipitation increase

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ARTICLE INFO

Article history:
Received 13 July 2018
Received in revised form
2 October 2018
Accepted 2 October 2018

Keywords:
Holocene
Paleoclimatology
Europe
Vegetation dynamics
Stratigraphy
Timberline
Pollen Accumulation Rates

ABSTRACT

We reconstructed the vegetation and climate history during the last 10 ka in a high-elevation sedimentary record (Armentarga peat bog, 2345 m asl) on the southern flank of the European Alps through the study of paleoecological and sedimentary proxies. We included a specific elevational transect of modern Pollen Accumulation Rates for timberline-forming trees and shrubs (*Alnus viridis, Pinus sylvestris/mugo, Pinus cembra*). Quantitative reconstructions of July temperature and annual precipitation were obtained by applying numerical transfer functions built on an extensive pollen-climate calibration set from the European Alps. Changes in elevational vegetation arrangement were primarily driven by phases of precipitation increase, and to a lesser extent by millennial-scale temperature changes already known from glacier, timberline, chironomids and speleothem records at Alpine scale. Changes in pollen-inferred annual precipitation occurred in three main steps. An early Holocene moderately humid phase is mirrored by the early spread of *Alnus viridis* dwarf forests. Precipitation started to increase at 6.2 ka cal BP. A further, prominent step forward at the Middle to Late Holocene transition led to the high values of snowfall and runoff characterizing today's oceanic elevational climates of the outer Italian Alps. This change led to timberline depression and grassland expansion. Locally, human impact was weak at the Late Neolithic/Bronze Age transition. This event correlates with lake level oscillations in the northern Mediterranean borderlands, suggesting intensification of southern air masses conveyed by Tyrrhenian cyclones towards windward districts.

1. Introduction

Montane vegetation is traditionally known to be particularly sensitive to climate changes (Birks and Ammann, 2000; Wick, 2000). The strong elevational climatic gradient that characterises mountain areas results in a steep ecological slope, with several ecotones occurring in a small area. Regional climate signal is amplified with elevation (Beniston et al., 1997), and this effect is illustrated by the strong impact of recent climate variations on montane ecosystems (Houghton et al., 2001; Pepin et al., 2015; Qin et al., 2009). Being able to assess the impacts of climatic fluctuations on past biodiversity in mountain regions will help in choosing suitable management strategies in the near future. Pollen sequences investigated in or shortly above the modern timberline ecotone are ideal archives to analyze the relationships between climate and ecosystems, offering a millennial perspective to the ongoing trends and allowing to decouple the role of different predictors (e.g. July temperature, annual precipitation, pastoralism), acting at different time scales (Badino et al., 2018; Tinner and Theurillat, 2003).

A large number of independent natural archives and proxies complement palaeoecology in reconstructing the climate history of the high-elevation Alps during the present interglacial. The

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https://doi.org/10.1016/j.quascirev.2018.10.001
0277-3791/

sedimentary record of glacier activity, the most sensitive proxy of climate change, is well assessed but highly discontinuous, thereby making it difficult to decouple temperature and snowfall contributions to glacial advances or to the even more puzzling phases of glacier retreats (Holzhauser et al., 2005; Le Roy et al., 2015). Continuous isotopic and biological records can be obtained either from speleothems, lakes or peat bogs in high-elevation areas. However, a precipitation signal is hardly discriminated in isotopic records from Alpine speleothem (Fohlmeister et al., 2012), while most high-elevation biological proxies respond primarily to summer temperature modulations (e.g. chironomids and *Pinus cembra* timberlines) (Ilyashuk et al., 2011; Nicolussi et al., 2005; Wick et al., 2003). Up to now, available validated precipitation records derive from dendroclimatic series only (Büntgen et al., 2011).

Here we focus on a high-elevation site located in the outer Italian Alps (Armentarga peat bog), an area characterized by an oceanic climate with high precipitation (Fig. 2B), with snowfall and cloudiness significantly influencing ecological gradients (Belloni and Pelfini, 1990). An expanded array of biological proxies, including pollen and other microbiological particles (pteridophytes, bryophytes and fungal spores, algae, animal remains, etc.), pollen-slide microcharcoal, sieved charcoal, and biogeochemical proxies (water content, total organic matter, silicoclastic + oxides contents, magnetic susceptibility, phosphorus concentrations) was obtained from the study site. Pollen Accumulation Rates (PAR) were calculated to detect absolute pollen changes, which may reflect either population fluctuations (Badino et al., 2018; Tinner and Theurillat, 2003) or snowmelt runoff. Quantitative techniques were applied on fossil spectra to obtain estimates of past climate parameters (Birks and Seppä, 2004; Birks et al., 2010; Brewer et al., 2007; Juggins and Birks, 2012). Site-specific instrumental temperature and precipitation series and climatologies were obtained for the study site. Modern vegetation was surveyed and pollen deposition was studied in natural (mosses) and artificial pollen traps. Such modern references allow the so-called "site calibration" to be defined, accounting for site-specific features affecting either climate parameters and pollen deposition, such as local topography and sedimentary processes, and the local influence of runoff and, most conspicuously, snow runoff on PAR, barely considered in traditional palaeoecological studies. The methodology for site calibration is also inherent to the original procedure for climate reconstruction developed in the present paper.

2. Physical setting, modern climate, and elevational ecological gradient

We selected a high-elevation site (Armentarga peat bog, 2345 m asl, N 46° 2′ 26.642"; E 9° 52′ 44.263") on the headwall of a main valley cutting N-S and draining the external belt of the Alpine edifice in front of the Po Plain (Orobie Alps, Fig. 1). The bedrock geology is characterized by a low-permeability sedimentary and volcano-sedimentary sequence of claystone, siltstone, sandstone and tufites of Permian age. The area was occupied by valley glaciers during the last glaciation, while highest peaks preserve a horn-shape typical for nunataks emerging from cirque glaciers (Forcella, 1988; see Fig. 3E). Deglaciation age will be determined in the present paper for the first time. Several lakes and peat bogs developed since then. The modern setting of the Armentarga peat bog (Fig. 3C,E) results from the infilling of a small lake either by an inlet on its NE side and by biogenic-biochemical deposits. The basin is surrounded by a roche moutonnées landscape (see Fig. 3E).

This region is marked by a *Dfc* climate (Köppen, 1923), i.e. nival, persistently wet throughout the year (Fig. 2B); locally, the annual temperature is 1.3 °C (Fig. 3B) and lapse rate ranges from 0.56 °C/100 m in the mountain belt to 0.77 °C/100 m above the open forest limit. Mean annual precipitation (Pann, 1838 mm at the study site) is not significantly related with elevation. The site actually represents a snowfall extreme in the entire Alps (Fig. 2B), snow accumulation being concentrated in late winter and spring, and net snow accumulation summing up to 7 m at 1950 m asl (1964–1973 period, Belloni and Pelfini, 1990). The glacier Equilibrium Line Elevation under current climate conditions exceeds the mountain peaks; it was about 2600 m in 1994 AD (Caccianiga et al., 1994). The pollen-climate elevational transect (see section 4.5.) specifically designed for this area extends along the uppermost section of a typical prealpine valley open to moist southern winds orographically forced uphill, between 1100 m and the headwalls at 2500–2700 m asl.

The vegetation of the area provides a representative example of elevational ecological gradient in an oceanic climatic regime (Fig. 3A–B) common in the Eastern and Northern Alps, and heavily affected by pastoralism. Deciduous broad-leaved forests (mainly *Acer pseudoplatanus* and *Corylus avellana*) extend between 1100 and 1400 m on sunny aspects, being fragmented by clearings, mowed meadows and human settlements. Chestnut and walnut trees (*Castanea sativa* and *Juglans regia*) grow up to an elevation of 1100 m asl on sunny slopes, i.e. up to a Tjuly limit of about 17 °C. Patches of dark coniferous forest (*Picea abies, Abies alba, Larix decidua*) occupy shadow slopes only, while large areas in the subalpine belt (1400–2200 m asl) are covered by a low-pollen producer larch forest. Here, low canopy density allows for a massive development of *Alnus viridis* understory thickets. The timberline is very complex due to the disruption of pristine subalpine forest by shepherds and miners, especially on sunny slopes (see Fig. 3A). A field survey of the 20 km^2 area partly included in Fig. 3A shows the following elevational timberline thresholds. The open forest upper limit and dwarf forest limit are formed either by larch or by *Alnus viridis* groves at 2140 m asl on bedrock conductive to fine-grained regolith and by *Pinus mugo* (mountain dwarf pine) scrub at 2130 m on massive bedrock conductive to coarse regolith (dry edaphic sites). Here, isolated stands of *Pinus mugo* form part of the timberline structure at 1800–2130 m asl. Current larch treeline extends farther up to 2220 m on rock emergencies at about 11 °C Tjuly and 1860 mm Pann. Only larch individuals with >2 m erect stems less than 50 yrs old occur above 2130 m, suggesting treeline expansion uphill in recent decades, most probably in the postwar period. Swiss stone pine (*Pinus cembra*) is present but extremely rare (Andreis et al., 2005, Fig. 3A); its crown cover in the pollen source area is negligible. The wide development of alpine pastures and of xerophytic grasslands at timberline elevations and between 1800 and 2600 m asl is driven primarily by oceanic climate and human impact. For details on grassland ecology at the elevation of the study site see Fig. 3E.

2.1. Archaeological and documentary evidence

The studied mountain region is lying 25–30 km NW of the Valcamonica, the famous rock-art valley which become inhabited since the Middle Neolithic (Poggiani, 2010), after an earlier Paleolithic-Mesolithic peopling (Pini et al., 2016b). Despite extensive surveys so far carried out (Poggiani, 2007), earliest evidence for human presence in a radius of 5 km around the Armentarga peat bog is starting with rock engravings from the late Iron Age, III century BC (Casini et al., 2010, see Fig. 3A,C). A mining village dating back to the early Middle Ages (Longobard Age) has been recently discovered and excavated (Museo Archeologico di Bergamo, unpublished data, see Fig. 3A). The name "Armentarga" means "site of herds", and indeed the existence of summer pastoralism here in the Middle Ages is testified by a written document dating back to AD 1148 (Zonca, 1998).