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ALNUS VIRIDIS A SENSITIVE SNOWFALL INDICATOR FOR PAST OCEANIC TIMBERLINES IN THE ALPS

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ABSTRACT: We analyse the modern ecological response of mountain alder (*Alnus viridis*) pollen proportions (%) to climatic parameters along altitudinal gradients in two contrasting climate regions of the European Alps and calculate pollen accumulation rates (PAR) to detect the effect of snowmelt runoff. We also compare independent sediment proxies for alluvial events in a high-altitude site of the outer Italian Alps (Armentarga peat bog, 2345 m a.s.l.), which was selected to investigate *Alnus viridis* response in the last 11000 years.

KEYWORDS: European Alps, Holocene, *Alnus viridis*, pollen accumulation rate, eHOF models, palaeoclimate

1. INTRODUCTION

Reconstructing the climate history of the high altitude Alps in the present interglacial relies on a large number of natural archives and proxies. The sedimentary record of glacier activity, the most sensitive proxy of climate change, is well stocked but highly discontinuous, thereby making it difficult to decouple temperature and snowfall contributions triggering glacial advances. Hopefully, plant and sediment deposition in high altitude areas, either from speleothems, lakes or peat bogs, provides continuous isotopic and biological records. However, in speleothem isotopic records (Fohlmeister et al., 2012) a precipitation signal is difficult to discriminate, while most high altitude biological proxies respond primarily to summer temperature modulations (e.g. chironomids and cembran pine (*Pinus cembra)* timberlines). Up to present, available validated precipitation records derive from dendroclimatic series only (Büntgen et al., 2011).

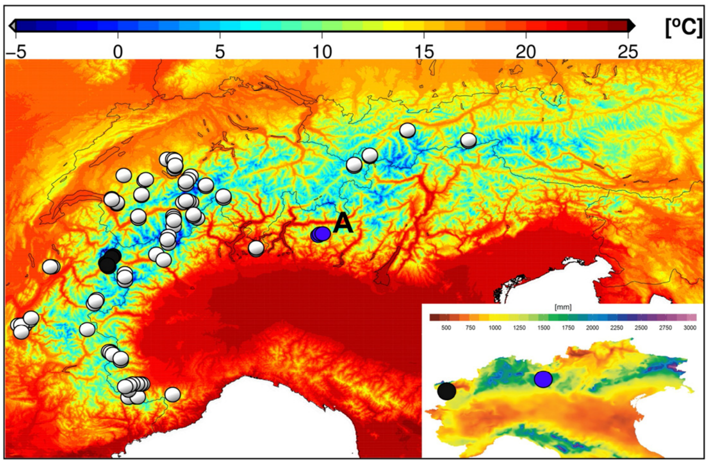

Fig. 1 - Map of July climatogy (1961-1990) with 170 EMPD sites (white dots), La Thuile Valley training set (black dots), Upper Brembana Valley training set (blue dots) and Armentarga fossil site (A) plotted. On the right map of annual precipitation (1961-1990) and the location of the two altitudinal training sets.

Here we propose to analyse the timberline record of *Alnus viridis* (mountain alder) in the oceanic climate regions of the Alps to reconstruct Holocene oscillations in precipitation, mostly referred to snowfall. Mountain alder is a deciduous shrub needing continuous water supply during the growing season, enhanced either by climatic - high annual snowfall rate - or by edaphic wetness (Richard, 1968,1969; Mauri & Caudullo, 2016). Extensive mountain alder shrublands develop in the subalpine altitudinal belt under oceanic, cool temperate climates that hinder cembran pine fitness. Edaphic geodiversity allows mountain alder to compete with dwarf pine (*Pinus mugo*), the latter also tolerating oceanic climates, but escaping edaphic wetness. Apart from snowfall, timberline forests formed by these Alpine dwarf shrubs are controlled by historical biogeography (range dynamics of refugial populations since the last glaciation) and human impact (human fire set to clear forests for pastoralism and mining).

Given these ecological constraints, we analyse the modern ecological response of mountain alder pollen proportions (%) to climatic parameters along altitudinal gradients in two contrasting climate regions of the Alps, and we calculate pollen accumulation rates (PAR) to detect absolute pollen changes, which may reflect either population fluctuations or snowmelt runoff. We also compare independent sediment proxies for alluvial events in a high-altitude site of the outer Italian Alps (Armentarga peat bog, 2345 m a.s.l., Fig. 1), which was selected to investigate *Alnus viridis* response in the last 11,000 years.

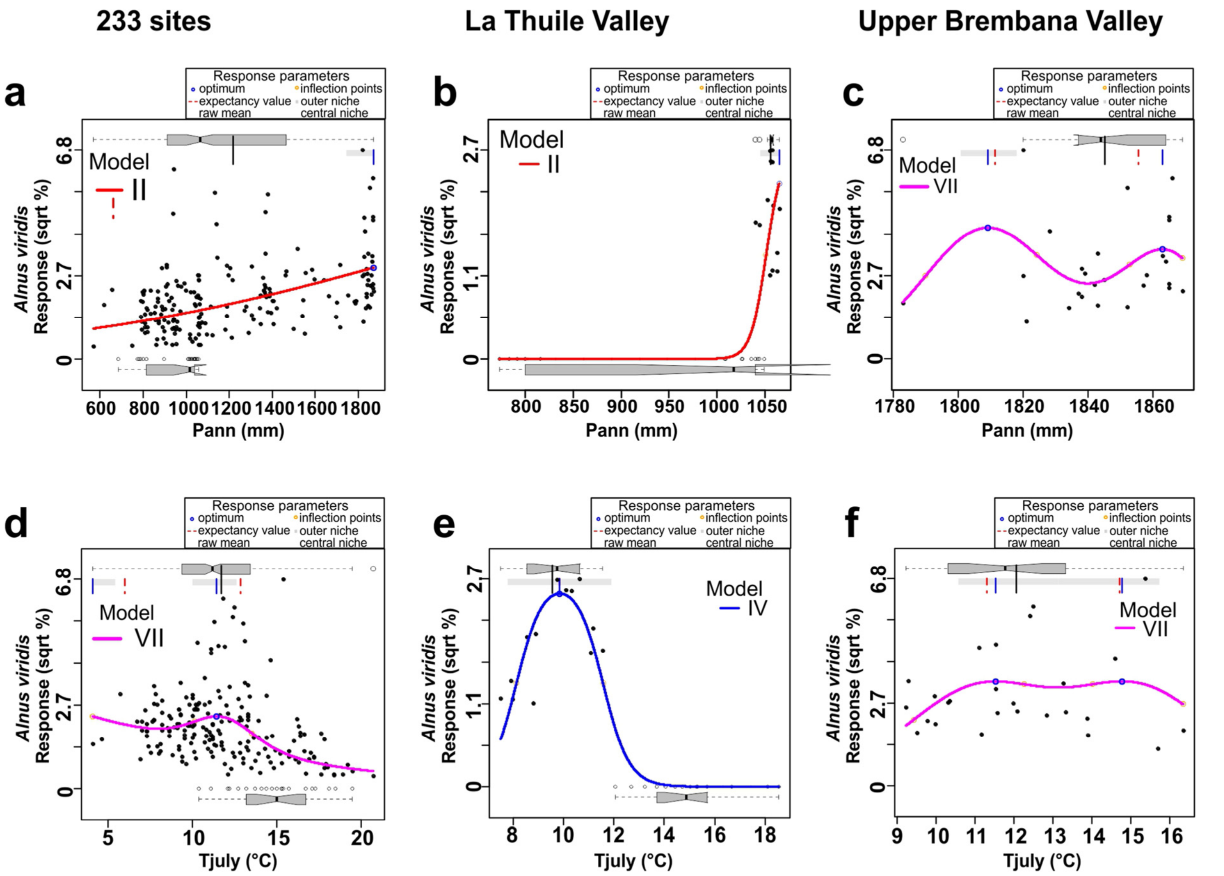

Fig. 2 - Diagrams showing the simplest statistically significant response model for *Alnus viridis* from the 233 sites and the two single training sets (La Thuile Valley and Upper Brembana Valley) in relation to a) annual precipitation and b) July temperature as assessed by a hierarchical set of taxon response models within the framework of generalized linear modelling.

2. MATERIAL AND METHODS

A modern pollen-climate calibration dataset for *Alnus viridis* was created selecting one hundred and seventy alpine sites from the EMPD-European Modern Pollen Database (Davis et al., 2013) in which *Alnus viridis* was kept distinguished and adding fifty-three plots from the two new altitudinal training sets, respectively in an oceanic, outer district of the chain in the Central Alps (Upper Brembana Valley training set; Furlanetto et al., unpublished data) and in a continental inner valley of the Western Alps (La Thuile training set; Badino et al., 2018; Furlanetto et al., unpublished data) (Fig. 1). Site-specific temperature and precipitation series, covering the 1951-2010 period, were reconstructed for each sampling site, by means of the anomaly method as described in Brunetti et al. (2012). From these monthly series, mean temperature of the warmest month (TJuly) and the total annual precipitation (Pann) were calculated. *Alnus viridis* individual response (Fig. 2) was obtained using the Extended Huisman-Olff-Fresco fitting method using R 3.2.3 version and eHOF package (Jansen & Oksanen, 2017).

Sixty-two fossil samples from a lake - peat bog record in an outer oceanic district of Central Alps (Armentarga record, Fig. 1) were processed following standard methods at the Laboratory of Palynology and Palaeoecology of CNR-IDPA in Milano, and identified at the optical microscope, reaching a minimum pollen sum of six hundred pollen grains x sample. Eight ^{14}C dates were obtained on upland plants remains samples from the study deposits. Radiocarbon ages were calibrated and deposition rates were modelled (Fig. 3).

The calculation of PAR values for a specific *taxon* in a sample is not dependent on other *taxa* occurring in the same sample (Birks & Birks, 1980). *Alnus viridis*, one of the main timberline ecotone shrub species in the outer oceanic districts of Central Alps, shows a specific altitudinal PAR arrangement under modern climate conditions (Tab. 1). These PAR measurements have been used as a modern reference to estimate past plant population densities.

Pollen-climate transfer functions were derived from weighted averaging partial least squares (WA-PLS) regressions (Ter Braak & Juggings, 1993) using a calibration set of two hundred thirty-three modern pollen samples; a 2-component WA-PLS model was selected.

3. RESULTS

In the calibration dataset of two hundred thirty-three modern pollen samples eHOF fitting shows that *Alnus viridis* has a significant relationship with annual precipitation being monotonic (optima of ca. 1800 mm at the gradient extreme) and with July temperature being skewed bimodal, with the main optima at ca. 12 °C (Fig. 2a, d). In the La Thuile Valley training set *Alnus viridis* has an estimated optimum of 10 °C and 1050 mm (Fig. 2b, e), while in the Upper Brembana Valley training set it has a double optimum with higher temperature and precipitation (respectively 11.5 and 15 °C, 1810 and 1870 mm) (Fig. 2c, f).

Alnus viridis, the main timberline ecotone shrub species in the Upper Brembana Valley, shows a specific altitudinal PAR arrangement under modern climate conditions (Tab. 1). The highest PAR values in the Upper Brembana Valley training set are observed in the plots L2 and L5 located at mountain altitude (respectively at 1420 and 1940 m a.s.l.) in river corridors and waterfalls with mountain alder scrub with PAR values of 2400 and 3100 pollen grains cm^{-2} yr^{-1} (Tab. 1, TL2 and TL5). In the pollen traps at subalpine altitude (Tab. 1, TL15, TL14; respectively 2100 and 2180 m a.s.l.), located at the border of mountain alder scrub with continuous understory of Ericaceae, PAR values are about 700 pollen grains cm^{-2} yr^{-1}. Modern PAR data from Armentarga peat bog show values that range from 100 to 400 pollen grains cm^{-2} yr^{-1} (Tab. 1, TL10 and TL10 lt). These PAR measurements have been used as a modern reference to estimate past plant population densities (Fig. 3).

Palaeoecological data from the Armentarga peat bog (Fig. 3) show a general increase of *Alnus viridis* from ca. 7,000 years cal BP (*Alnus viridis* % and PAR) and a concurrent increase of lithic fragments concentration and of silicoclastic + oxides contents with an opposed decrease of *Pinus sylvestris/mugo* and *Pinus cembra* type. Starting from 1,300 years cal BP a sharp decrease of *Alnus viridis* PAR values and increase of total P occur till 300 years cal BP. Pollen-inferred annual precipitation show a sharp increase from 7,200 years cal BP with short phases of precipitation decrease during the Early Bronze Age and Roman Period (Fig. 3).

pollen trap	*Alnus viridis* PAR (pollen grains cm^{-2} yr^{-1})
TL12	353
TL10 lt	409
TL10	101
TL9	227
TL13	277
TL14	722
TL8	120
TL15	724
TL7	173
TL6	70
TL5	3191
TL4	173
TL3/4	363
TL3	302
TL2	2441
TL1/2	132
TL1	116

Tab. 1 - Modern *Alnus viridis* PAR values based on pollen monitoring data in the Upper Brembana Valley, representing the period 2016-2017. The location of the Upper Brembana Valley training set is shown in Fig. 1.

4. DISCUSSION AND CONCLUSION

The observed *Alnus viridis* response offset between the paired sites considered is related to variations in local climates (from oceanic external chains to continental inner districts). *Alnus viridis* vegetation needs continuous water supply during the growing season, enhanced by high annual snowfall rate and good soil water balance. Accordingly, in Alpine oceanic climates, the ecological response of the species expands downstream especially along avalanche corridors but also on northern slopes, due to a general increase in soil moisture. This results in a displacement of its optima towards higher temperature and precipitation (Fig. 2c, f, Upper Brembana Valley training set), thus reducing the overall TJuly signal of alder pollen abundance in oceanic climates (Fig. 2f).

Palaeoecological and sedimentary data from Armentarga peat bog show an increase of snowmelt runoff from ca. 7,000 to 5,000 years cal BP (*Alnus viridis* PAR values relative to respective %, lithic fragments concentration and silicoclastic + oxides contents) and decrease of temperature. This humid phase is confirmed by a sharp increase in pollen-inferred annual precipitation since 7200 years cal BP (Fig. 3).

Alnus viridis PAR values show significant peaks from 6,000 to 1,300 years cal BP, comparable or above the modern absolute PAR values obtained in the mountain alder scrub (pollen traps TL 15 and TL14), thus arguing for phases of alder timberline rises. Starting from 1300 years cal BP, the record of *Alnus viridis* PAR values is negatively correlated to an increase of total phosphorus, suggesting that the long since well-established alder subalpine belt was affected by high human impact since the Early Middle Ages.

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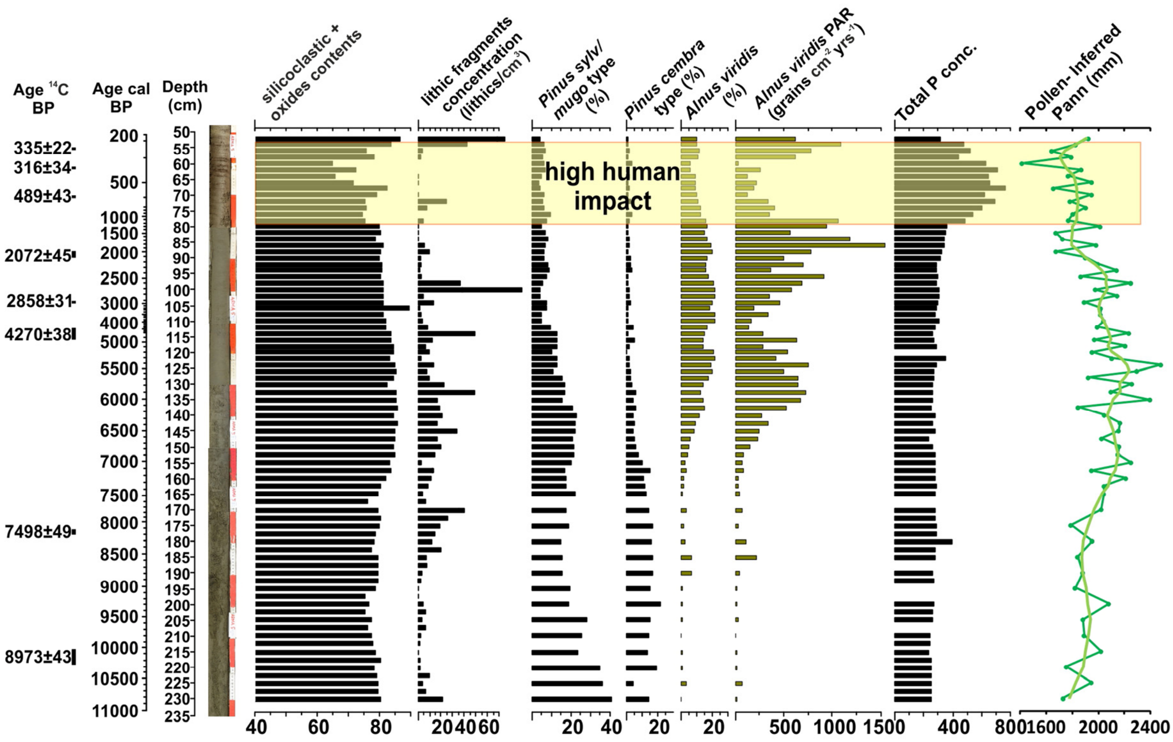

Fig. 3 - Fossil *Alnus viridis* PAR data and pollen inferred annual precipitation from Armentarga fossil record compared with other palaeoecological and geochemical data.

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