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Charcoal fragments of Alpine soils as an indicator of landscape evolution during the Holocene in Val di Sole (Trentino, Italy)

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Abstract: Subalpine and Alpine soils in Val di Sole (Trentino, Italy) have been investigated in order to reconstruct vegetation changes and human impact during the Holocene period. Archaeological findings have demonstrated that Alpine sites have been populated since pre-historical times. Humans have had a great impact on the natural landscape evolution. One of the most-used tools has been fire. The use of fire has enabled the landscape to be cleared to provide new pastures for grazing and also to allow it to be used for agricultural purposes. The ^{14}C dating of charcoal fragments found in subalpine and Alpine soils provide information about the type of vegetation, fires, human impact and soil formation throughout the Holocene. The degree of podzolisation indicates weathering effects and provides information about the stability of the surfaces. According to our results, a quick forest expansion establishment phase must have occurred shortly after the Lateglacial around 10 500 cal. BP. *Pinus sylvestris*, *Pinus mugo* as well as *Larix decidua* established in the investigation area in that period. *Picea abies* had not yet migrated into this region at the transition to the Boreal (around 9000 cal. BP). The vegetation of the investigated area has not substantially changed during the last 10 000 years. *Pinus mugo* was more widespread in some areas during the Older Atlanticum, and the treeline was about 150 m higher at the end of the Younger Dryas than today. Some other sites were most probably used as pasture during the Bronze Age and later abandoned, leading to a natural reforestation. In the investigated area 13 fire events in the past 10 700 years have been recognised, and seven of them can reasonably be attributed to human origin.

Key words: Alps, charcoal, soils, Holocene, anthracology, ^{14}C.

Introduction

The Alpine landscape has been shaped by the movements of the glaciers during the period of ice retreat at the end of the last glacial maximum (LGM, *c*. 24 000–21 000 cal. BP; Kelly *et al*., 2004). The oscillations of the climatic conditions during the Lateglacial have influenced the species composition of the vegetation. After the first retreat of the glaciers, during the Oldest Dryas chronozone (Maisch *et al*., 1999), the Alps were characterised by tundra and steppe species such as *Dryas octopetala* L.*, Ephedra* L.*, Artemisia* L., Poaceae R.Br. and Chenopodiacae Vent. (Burga and Perret, 1998). The subsequent periods of warm and cold phases have caused vegetation changes and seen the progressive establishment of species that are nowadays very typical of the Alpine environment such as *Larix decidua* L., *Pinus cembra* L., *Juniperus* sp. L. and *Picea abies* L. (Wick, 1989; Burga and Perret, 1998). Past environments and climate have been reconstructed by many authors through the identification and dating of sedimentary pollen deposited in peat bogs or in Alpine lakes (ie, Kral, 1971; Wegmüller, 1977; Pini, 2002; Gobet *et al*., 2004; Filippi *et al*., 2005; Finsinger *et al*., 2007; Favaretto *et al*., 2008; Jimenez-Moreno *et al*., 2008). The assemblages of pollen grains are directly related to regional and local vegetation. The success of pollen in determining past climatic conditions is strongly dependent on high-quality modern calibration data for establishing the relationship between vegetation, pollen assemblages and climatic parameters (Birks, 2004).

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Another powerful tool used to reconstruct past environments and climate is the extraction, identification and radiocarbon dating of macrofossil charcoal fragments buried in Alpine soils. All forest ecosystems have the potential to burn as a result of climate- or human-induced fires (Figueiral and Mossbrugger, 2000). Macrofossil charcoal is organic plant material (fragments > 2 mm diameter), that is a C-enriched, N-depleted pyrogenic substance having a highly aromatic structure, preserved in the fossil record through the process of incomplete burning and charcoalification (Schweingruber, 1978, 1990; DeLuca and Aplet, 2008). Charcoal fragments > 2 mm usually remain on the fire site or in the immediate vicinity (Lynch *et al.*, 2004). Charcoal fragments are particularly useful for the identification of fossil wood because the level of preservation is often good enough to examine the transversal, longitudinal and tangential sections of the wood and thus, using this knowledge of the wood structure of the charcoal, to establish the identity of the tree from which it came to the genus (and in some cases to the species) level. The presence of carbonised fragments of wood is clear evidence of the occurrence of a fire, and of the capability of the environment to supply the necessary conditions for the growth of trees belonging to a certain botanical species. Those include an ice-free and in most places permafrost-free terrain, a soil able to support woody vegetation, and extremes of climate that do not exceed the physiological capabilities of the tree taxa (Willis and van Andel, 2004). Moreover, charcoal is often suggested as the most reliable material for radiocarbon dating from archaeological sites (Damblon and Haesaerts, 1997). Charcoal fragments are biologically inert and physically stable within the environment (Pessenda *et al.*, 2001). Furthermore, soil charcoal dating gives a time proxy for soil pedogenesis (Carcaillet, 2001) and can be used to estimate soil age. Charcoal fragments have been widely used especially in studies about treeline shifting, soil pedogenesis, fire regimes, changes in vegetation and carbon storage (eg, Berli *et al.*, 1994; Cherubini *et al.*, 1995; Carcaillet and Brun 2000; Carcaillet, 2001; Carnelli *et al.*, 2004a; Ali *et al.*, 2005; Hajdas *et al.*, 2007; Bélanger and Pinno, 2008; DeLuca and Aplet, 2008). Charcoal identification and dating is a powerful tool to reconstruct past human impact on Alpine territories. Although natural fire regimes appear to be climate-dependent, human activity at the forest- and treeline in the Alps has been occurring for thousands of years (Whelan, 1995; Carcaillet, 1998; Carcaillet *et al.*, 2007). If fire patterns are synchronous at regional scales, then they should be reasonably ascribed to climatic trends: but, if they are not synchronous at regional scales, then fire regimes might be more dependent on local processes such as human disturbance (Clark and Royal, 1995). Charcoal fragments allow the reconstruction of Quaternary landscapes and environments and the identification of natural or human disturbance on vegetation (Figueiral and Mosbrugger, 2000). According to the geomorphological studies of Baroni and Carton (1990), Filippi *et al.* (2007) and Favilli *et al.* (2009), the formation of the present landscape can be dated back between 18 000 and 11 000 yr cal. BP. Studies of human remains (teeth and bones) have dated the first modern-humans settlements in the Trentino region back to 14 000 years ago (Di Benedetto *et al.*, 2000). Archaeological studies have demonstrated the continuous presence of complex human societies in these valleys from the Mesolithic period (*c.* 8000–4500 cal. BP) until modern history (eg, Cucina *et al.*, 1999; Schmidl *et al.*, 2005; Valsecchi *et al.*, 2006).

This study focuses on the identification and dating of charcoal fragments extracted from nine Alpine and sub-Alpine soils. The obtained ages have been compared with archaeological studies done in nearby Alpine valleys to derive a continuum of the human activities in the sub-Alpine and Alpine territories of Trentino (Italy). An additional aim of this research was to relate the age of the charcoal fragments to soil development (see also Zech *et al.*, 2003). This work will also show the importance of Alpine soils as natural archives of past events and climatic shifting.

Materials and methods

Study area and investigation sites

The investigated sites are located in Val di Pejo and Val di Rabbi, two lateral valleys of Val di Sole, Trentino, in the southern Alpine belt of northern Italy (Figure 1). The climate of the valleys ranges from temperate to alpine (above the treeline). Mean annual temperature ranges from 8.2°C (valley floor–800 m a.s.l.) to around 0°C (at 2400 m a.s.l.) and mean annual precipitation approximately from 800 to 1300 mm (Servizio Idrografico, 1959). The treeline is *c.* 2100 m a.s.l. and the forests are dominated by the conifers *Larix decidua* L. and *Picea abies* L. (Pedrotti *et al.*, 1974). Areas above 2300 m are covered with rocks, boulders and short-grass meadows dominated by *Carex curvula* L. and *Nardus stricta* L. The siliceous parent material (paragneiss and micaschists) and the coverage by quaternary deposits are similar in both valleys (Table 1). We investigated nine soil profiles developed in the sub-Alpine and Alpine zone on different morphological aspects with respect to their evolution. Furthermore, charcoal fragments extracted from each soil profile were identified and radiocarbon dated. The investigated soils (Table 1 and Figure 1) were between 1521 m a.s.l. and 2222 m a.s.l., and therefore, in the sub-Alpine and in the Alpine zone (Egli *et al.*, 2008) above the treeline. The whole landscape near the investigation area was strongly influenced by glaciers and later by human activities.

Soils were classified as *Entic Podzol* between 1500 and 1600 m a.s.l., *Cambic Umbrisol* between 1600 and 1800 m a.s.l., *Haplic Cambisol* and *Entic Podzol* between 1800 and 2200 m a.s.l. according to the WRB (IUSS Working Group, 2007). According to the Soil Taxonomy (Soil Survey Staff, 2006), the soil moisture regime is udic (humid conditions, <90 days/year with a dry soil) at all sites. Maximum precipitation occurs during the summer months.

Sampling

The sampling strategy was based first on the opening of the soil profiles and on the subsequent soil description. Undisturbed soil samples were collected from excavated pits starting from the BC horizon upward to avoid contamination of the soil material. A total of 2 to 4 kg of soil material were collected per soil horizon at the nine soil pits (Hitz *et al.*, 2002). Large charcoal fragments were separated from the soil matrix directly on the field.

Soil chemistry and physics

The samples were air-dried, large aggregates were gently broken by hand and sieved to < 2 mm. Total C and N contents of the soil were measured with a C/H/N analyser (Elementar Vario EL, elementar Analysensysteme GmbH) using oven-dried and ball-milled fine earth. Soil pH (in 0.01 M $CaCl_2$) was determined using air-dried samples of fine earth having a soil solution ratio of 1:2.5. The oxalate-extractable (Fe_o, Al_o) fraction was extracted according to McKeague *et al.* (1971) and analysed by AAS (Atomic Absorption Spectrometry – AAnalyst 700, Perkin Elmer, USA). The carbon and the charcoal stock in each soil profile were calculated according to the amount of organic carbon and of charcoal fragments, the density and the thickness of the soil horizons.

Charcoal identification and analysis

Macrocharcoal fragments having a diameter larger than 2 mm were extracted from the soil matrix by hand, strained through a sieve and dried at 40°C. The individual fragments were analysed

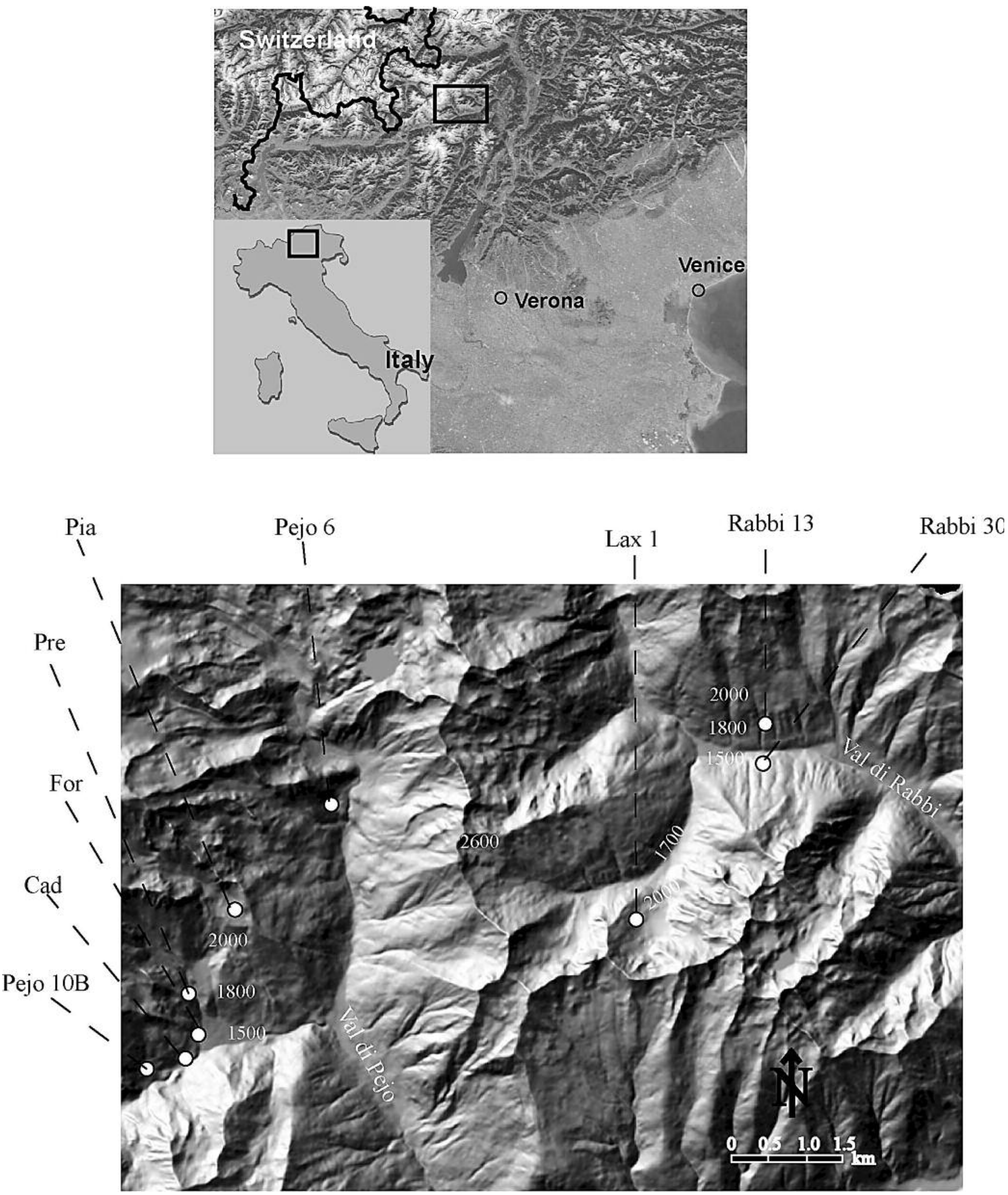

Figure 1 Location of the investigation site

microscopically and separated into coniferous and broadleaved tree species (Schoch, 1986) with a stereomicroscope (magnification 6.4–40×, Wild M3Z Leica, Germany). The charcoal fragments from the coniferous trees were divided further at the genus level using a reflected-light microscope (objective 5×, 10× and 20×, Olympus BX 51, Japan). The observations were compared with a histological wood-anatomical atlas, using an identification key (Schweingruber, 1990).

Radiocarbon dating

The CO_2 of the combusted samples was catalytically reduced over cobalt powder at 550°C to elemental carbon (graphite). After the reduction, this mixture was pressed into a target and carbon ratios were measured by Accelerator Mass Spectrometry (AMS) using the tandem accelerator of the Institute of Particle Physics at the Swiss Federal Institute of Technology Zurich (ETHZ). The calendar ages were obtained using the OxCal 4.0.5 calibration program

Table 1 Characteristics of the study site

Soil profile	Elevation (m a.s.l.)	Aspect (°N)	Slope (%)	Parent material	Vegetation	Land use	WRB (IUSS WRB, 2007)
Cad	1521	275	18	Micaschists	*Larix decidua / Picea abies*	Natural forest	Entic Podzol
Rabbi 30	1600	25	43	Paragneiss	*Larix decidua / Picea abies*	Natural forest	Entic Podzol . (Endoskeletic)
For	1621	350	12	Micaschists	*Larix decidua / Picea abies*	Natural Forest	Cambic Umbrisol
Pejo 6	1630	120	70	Micaschists	*Larix decidua / Picea abies*	Natural forest	Cambic Umbrisol
Pejo 10B	1810	130	70	Micaschists	*Larix decidua / Picea abies*	Natural forest	Haplic Cambisol (Dystric)
Pre	1818	305	5	Micaschists	*Larix decidua*	Natural Forest	Entic Podzol
Rabbi 13	1860	185	65	Micaschists	*Picea abies / Larix decidua*	Natural forest	Haplic Cambisol (Dystric)
Lax 1	2083	240	32	Paragneiss	*Larix decidua / Picea abies*	Natural forest	Entic Podzol
Pia	2222	350	21	Micaschists	*Rhododendro – vaccinietum extrasilvaticum*	Natural grassland and shrubs	Haplic Cambisol (Dystric)

(Bronk Ramsey, 1995, 2001) based on the IntCal 04 calibration curve (Reimer *et al*., 2004). Calibrated ages are given in the 2 σ range (minimum and maximum value).

Results

Physical characteristics and chemical composition of the soils

The investigated soils developed on paragneiss or micaschists containing morainic till (Table 1). The proportion of rock fragments increases with soil depth (Table 2), showing typical values for Alpine soils developed on a morainic sediment (Egli *et al*., 2001). All investigated soils have a loamy to loamy-sand texture. Because of the acidic characteristics of the parent material, the soils show pronounced acidification (Table 2). Total C corresponds to organic C because of the absence of any carbonates in the soil. The C stock is higher in the N-exposed soils located below 1800 m a.s.l. (Table 2).

The soils (‘Cad’, ‘Rabbi 30’, ‘Pre’, ‘Rabbi 13’ and ‘Lax 1’) showed a pronounced podzolisation, as shown by the clear increase in the oxalate-extractable iron and aluminium contents measured in all spodic horizons (Figure 2 and Table 2). Chemical criteria for spodic material require that oxalate-extractable Al_o + 0.5 Fe_o is ≥ 0.5% and at least two times greater than in the overlying albic horizon (Soil Survey Staff, 2006; Briggs *et al.,* 2006). In our studied soils, the average Al_o + 0.5 Fe_o value in the Bs (or Bs1 or Bs2) horizon is 0.94 (%wt) and 0.47 (%wt) in the AE (or BE) horizon.

The soils ‘For’ and ‘Pejo 6’ developed at 1600 m a.s.l. and on the same parent material. The soil ‘For’ developed on a north-facing slope most probably near a former charcoal pile in a coniferous forest. This soil is only 50 cm deep and correspondingly weakly developed. The first 25 cm contained large charcoal fragments. Therefore, the level of charcoal preservation is very good and the topsoil is extremely rich in organic carbon, which decreases substantially in the subsoil (Table 2). The stock of C is mostly due to the big charcoal accumulation as a charcoal pile. The chemical evolution indicates an initial downward movement of Fe and Al (Figure 2). The Al_o + 0.5 Fe_o value in the Bs horizon is 0.78% which is consistent with an on-going podzolisation (Table 2) (Soil Survey Staff, 2006; Briggs *et al*., 2006). The soil ‘Pejo 6’ developed on a south-facing slope and shows a more pronounced development of horizons. Fe and Al migrated and accumulated in the BA horizon. The AE and BA horizon had a dark brownish-black colour. The horizons differed in the soil skeleton, the organic matter content and in the pH. The two subsoil horizons (Bs and BC) were very similar. Both present a brown colour (7.5YR 4/4 and 10YR 4/4) and a higher pH. The organic matter content decreases clearly in the subsoil. ‘Pejo 10B’ developed on a south-facing slope under a coniferous forest and had a layer at around 75 cm depth that was particularly enriched with charcoal fragments. This enrichment is also indicated by the higher amount of organic C in the BC horizon (Table 2). The oxalate-extractable Fe and Al shows an increase with depth throughout the profile owing to the continuous differentiation of the horizons. In the soil profile ‘Pia’, an initial migration of iron and aluminium can also be measured.

Charcoal identification and age

Charcoal fragments occurred in all investigated soils. We dated 23 charcoal fragments extracted from different soil profiles. The ratios of the weight of the macrocharcoal fragments to the total weight of the sampled soil material can themselves give an indication of the age of the charcoal. Coarse charcoal particles derive from deadwood and downed wood, stumps or dead roots. Microcharcoal is related to fine plant material (eg, grass) or to the physical breakdown of macrocharcoal (DeLuca and Aplet, 2008). The presence of young and well-preserved carbonised wood in the soil horizons can be indicated by a charcoal/soil weight ratio > 0.4 (Table 3). A better preservation of carbonised young wood implies a modern age of the fragments. Over time, a part of the macrocharcoal can decay or is physically reduced in size. A positive and significant correlation between the percentage of macrocharcoal and the ^{14}C age was also found (Figure 3).

The age of the charcoal fragments spans more than 10 000 years, between 1799–1894 cal. AD and 8844–8429 cal. BC (10 378–10 793 cal. BP) (Table 3). The oldest charcoal fragments were found in the deepest soil horizons, in accordance with the assumption of the stratification of wood charcoal in soil (Berli *et al*., 1994; Carcaillet, 2001) (Figure 4). Since the soils are acidic and have, if any, only a weak (endogeic) earthworm activity, bioturbation has been negligible. Old charcoal could move downward in the profile due to trapping in the plant-root network.

Table 2 Chemical and physical characteristics of the investigated soils

Site	Soil horizon	Depth (cm)	Munsell colour (moist)	Skeleton[a] (weight %)	pH ($CaCl_2$)	Org. C (g/kg)	Total N (g/kg)	C/N	Al_o (g/kg)	Fe_o (g/kg)	Al_o+ 0.5 Fe_o (%)	C Stock (t/ha)	Charcoal (t/ha)
Cad													
	O	0–12	7.5YR 3/3	11	4.2	161.9	10.4	15	–	–	–	98.2	0.35
	AE	12–20	7.5YR 3/4	18	4.0	55.5	3.5	15	1.41	4.85	0.38	21.4	4.27
	BA	20–35	7.5YR 4/6	17	4.1	30.4	1.7	18	4.27	7.68	0.81	36.1	3.45
	Bs1	35–45	10YR 4/6	21	4.2	16.5	0.9	17	2.26	2.63	0.36	14.3	0.31
	Bs2	45–70	7.5YR 5/6	29	4.3	17.2	0.9	19	1.24	2.46	0.24	34.3	0.45
Rabbi 30												∑: 204.3	∑: 8.83
	AE	18–25	10YR 1.7/1	30	3.0	103.5	5.0	21	3.66	3.36	0.53	228.2	-
	Bs1	25–50	7.5YR 4/3	50	3.4	59.0	2.6	23	5.21	10.52	1.05	56.1	-
	Bs2	50–60	5YR 3/3	60	3.7	87.3	3.9	22	10.35	18.22	1.95	37.0	-
	BC	60–90	10YR 4/6	70	3.9	63.1	2.2	29	10.1	15.61	1.79	90.9	-
For												∑: 412.2	
	OE	0–25	10YR 1.7/1	20	3.9	137.6	4.1	34	3.02	5.06	0.55	221.0	239.10
	Bs	25–50	7.5YR 4/6	32	4.2	25.7	1.2	21	4.37	6.85	0.78	47.4	8.37
Pejo 6												∑: 268.5	∑: 247.47
	AE	0–10	7.5YR 3/2	10	3.8	115.1	6.2	19	2.02	5.41	0.47	109.8	–
	BA	10–35	7.5YR 3/2	15	4.0	36.3	13.3	3	3.90	7.37	0.76	58.6	–
	Bs	35–58	7.5YR 4/4	15	4.6	12.4	1.2	10	3.62	4.83	0.61	17.2	–
	BC	58–85	10YR 4/4	35	4.7	7.6	0.6	11	1.62	4.45	0.38	22.0	–
Pejo 10B												∑: 207.7	
	A	4–10	7.5YR 3/2	10	3.9	46.8	2.4	19	2.37	6.17	0.55	19.8	–
	Bs1	10–50	7.5YR 4/3	30	4.0	14.6	0.6	24	2.71	6.53	0.59	49.9	–
	Bs2	50–70	5YR 3/2	50	4.3	16.1	0.6	27	3.09	7.62	0.69	18.8	–
	BC	70–80	10YR 4/4	60	4.3	72.3	2.0	36	7.06	10.77	1.24	36.7	–
Pre												∑: 125.2	
	A	0–3	10YR 3/2	20	3.9	62.4	3.6	17	1.61	5.11	0.42	8.4	0.01
	AE	3–12	10YR 4/4	45	4.1	30.7	1.8	17	1.83	5.46	0.46	14.5	0.44
	Bs	12–45	10YR 5/4	47	4.7	17.8	1.2	17	6.98	9.15	1.15	38.9	0.05
	BC	45–60	10YR 4/6	38	4.8	7.5	0.5	14	3.20	4.31	0.23	8.7	0.97
Rabbi 13												∑: 70.6	∑: 1.47
	AB	3–10	10YR 4/4	10	4.2	24.4	0.6	40	2.15	4.66	0.45	21.7	–
	Bs1	10–37	7.5YR 4/6	15	4.3	20.2	0.8	25	2.68	4.44	0.49	51.9	–
	Bs2	37–55	7.5YR 4/6	25	4.9	10.3	0.7	15	4.47	4.88	0.69	18.1	–
	BC	55–100	2.5YR 5/4	45	5.0	4.3	0.4	11	2.08	1.05	0.26	15.2	–
Lax 1												∑: 107.0	
	AE	5–11	10YR 4/3	7	3.5	56.9	2.7	21	2.18	7.13	0.57	–	–
	Bs1	11–26	5YR 4/6	16	3.8	35.3	1.7	21	6.42	20.19	1.65	–	–
	Bs2	26–50	7.5YR 4/6	47	4.3	22.8	1.1	21	6.35	10.08	1.14	–	–
Pia													
	AE1	0–8	7.5YR 3/2	19	4.6	75.8	4.4	17	–	–	–	24.6	0.12
	AE2	8–11	7.5YR 4/3	19	4.4	52.4	3.3	16	1.49	5.04	0.41	8.3	0.05
	BE	11–25	7.5YR 4/4	12	4.3	14.4	0.9	15	1.38	5.05	0.39	14.9	0.50
	Bs1	25–55	7.5YR 4/6	26	4.5	8.7	0.6	14	1.87	5.46	0.46	22.0	0.39
	Bs2	55–80	10YR 4/6	29	4.7	7.1	0.5	15	1.66	4.48	0.39	16.1	0.27
												∑: 85.9	∑: 1.33

[a] Skeleton = material > 2 mm.

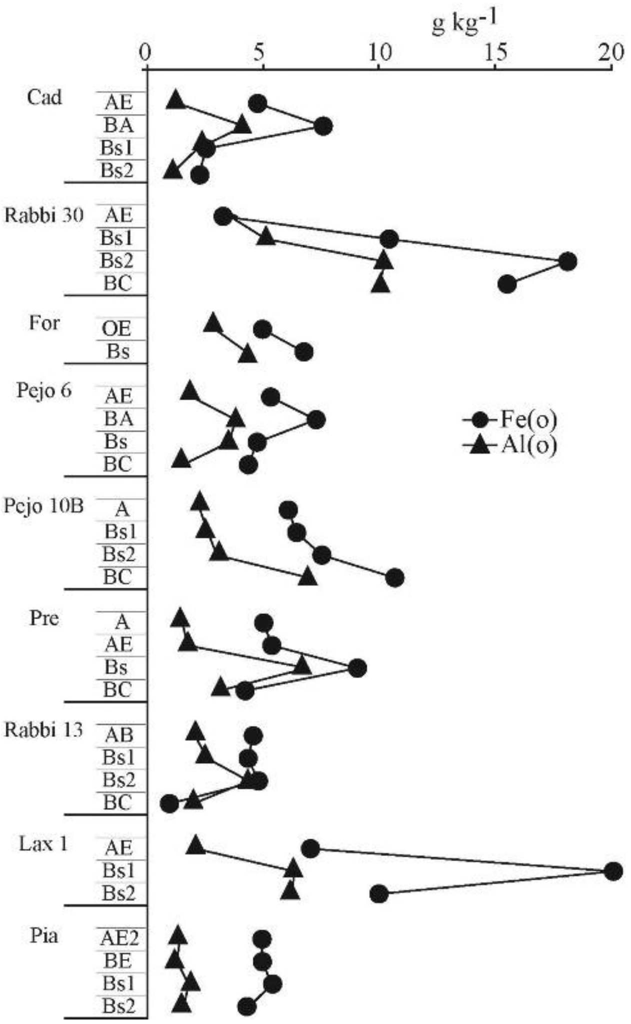

Figure 2 Migration of Fe and Al (dithionite extraction) in the investigated soil profiles

In general, vegetation did not dramatically change during the last 10 000 years. The charcoal fragments mostly belong to *L. decidua, P. abies, Clematis* spp. and Ericaceae – trees and bushes which also dominate the present-day forest (Table 3). The differentiation was not possible between *Picea* and *Larix* species based on the wood anatomy (Schweingruber, 1978). Some fluctuations can, however, be observed in the charcoal composition within the individual soil profiles (Figure 5).

The charcoal fragments of the profile 'Cad' (1521 m a.s.l.) in the Bs1 horizon were identified as *Clematis* sp.; most probably it belongs to the Alpine variety of this plant, in the family Ranunculacae (*Clematis alpina* (L.) Mill.). This plant is typical of a sub-Alpine forest in the sub-association *Rhododendro-Vaccinietum cembretosum* in the mesophylous *Pinus cembra* forests on the cooler aspects (Motta and Nola, 2001).

Other charcoal fragments in the Bs2 horizon of 'Cad' and in the Bs1 of 'Pejo 10B' belong to the Ericaceae family, which also includes species such as *Rhododendron, Vaccinium* and *Calluna*, which are common in the sub-Alpine forest (Carnelli *et al*., 2004b).

The vegetation currently present at the site 'For' (1621 m a.s.l.) is a *P. abies/L. decidua* forest. The charcoal fragments in the soil indicate that a vegetation change took place in the past. Charcoals of *L. decidua*, *P. abies*, *Alnus* sp. and *Betula* sp. were found in the soil profile. About half of the charcoals derive from coniferous and the other half from deciduous trees, which are now absent from the site.

The site 'Pre' (1818 m a.s.l.) shows a change from a *Pinus sylvestris or Pinus mugo* dominated forest (beginning of the Preboreal) to a *Picea* or *Larix* forest. The oldest charcoal fragments of the 'Pia' soil profile (2222 m a.s.l.) also evidenced a change from a *Pinus sylvestris or Pinus mugo* dominated forest to a *Picea/Larix* forest and an early-Holocene coniferous forest above the present-day treeline.

According to the radiocarbon age of the charcoal fragments, several fire phases can be recognised. The sites located at low altitudes (1500–1700 m a.s.l.) showed a predominance of charcoal fragments in the period 1399–1894 cal. AD, that can be attributed to the Middle Ages and Modern history. Some fragments refer to the Bronze Age (1450–825 cal. BC) and to the Roman Time period (119–253 cal. AD) (Table 3).

In the altitudinal range 1800–2000 m a.s.l., we detected a higher number of older charcoal fragments with a peak in the Bronze Age (*c*. 2300–600 cal. BC, Schmidl *et al*., 2005). Only few recent charcoal fragments (Modern history) were found in the top horizons.

The soils located > 2000 m a.s.l. showed some very old charcoal fragments (around 10 000 years) in the subsoil, with only a few fragments in the Bronze Age or Middle Ages. No fragments of the Modern history period were found.

In the investigated area and sites, no charcoal fragments were found having an age between 8200 and 3300 cal. BC. A fire synchronicity could be observed for the periods around 8500 cal. BC (10 500 cal. BP), 1400–1800 cal. BC (3350–3750 cal. BP), ~1420 cal. AD (600–1000 cal. BP) (Figure 6). The other fires referred to isolated dates and are probably human-induced.

Discussion

Fire regimes and human impact

Fire regimes are influenced by the presence of vegetation, favourable climatic conditions and human activities. Several fire events or sequences occurred simultaneously at different sites. This synchronicity may be used as an indication of climate forcing (Carcaillet *et al*., 2007).

We consider the following time periods for a better explanation of the fire events at our sites (Figure 7):

1. early Holocene (8900–8200 cal. BC)
2. Copper, Bronze and early Iron Age (4300–400 BC)
3. late Iron Age, Roman Time and Middle Ages (400 BC–AD1400)
4. Modern history (> AD 1400)

(1) Early Holocene (8900–8200 BC) (Figure 7a)

Some very old charcoal fragments (8900–8200 cal. BC) were found in the soils at the highest elevations (1818–2222 m a.s.l.) and can be attributed to the transition of the Egesen glacier readvance phase to the Preboreal phase (11 600–10 200 cal. BP; Maisch *et al*., 1999; Ivy-Ochs *et al*., 2006, 2008; Favilli *et al*., 2008, 2009). According to pollen studies in nearby lakes (Pini, 2002; Filippi *et al*., 2005), the immigration of *P. sylvestris* and *P. mugo* occurred around 13 000 cal. BP at 700 m a.s.l. and the increase in xerophytes plants suggests the onset of a dry climate after the Younger Dryas. This change in climatic conditions could be responsible for the occurrence of natural fires in this period. Pollen studies indicated that *P. cembra*, *L. decidua* and *Betula pubescens* grew locally at 2200 m a.s.l. around 9300 cal. BP (Wick and Tinner, 1997). The three charcoal fragments extracted from the alpine soils ('Pia', 'Pre' and 'Lax 1') confirmed the early-Holocene establishment of the forest (*L. decidua, P. sylvestris* and *P. mugo*) and evidenced fires *c*. 10 500 years ago in

Table 3 Measured and calibrated radiocarbon ages of charcoal fragments > 2 mm. Calibrated ^{14}C ages are given in the 2 σ range

Site	Soil horizon	Depth (cm)	Identified charcoal fragments	Dated charcoal fragment	Macrocharc g/kg soil	Uncal ^{14}C	Cal ^{14}C BP	Calendar age (years BC/AD) and prehistoric civilization
Cad								
	O	0–12	*Picea/Larix*	–				
	AE	12–20	*L. decidua*[a]	–				
	BA	20–35	*L. decidua*	–				
	Bs1	35–45	*Larix/Picea*	Clematis	0.3	3090 ± 50	3205–3405	1456–1256 BC Bronze Age
	Bs2	45–70	*L. decidua*	*Ericaceae*	0.1	4550 ± 55	5038–5327	3378–3089 BC Copper Age
Rabbi 30								
	AE	18–25	*L. decidua*	*L. decidua*	3.3	495 ± 30	500–551	1399–1450 AD Modern
	Bs1	25–50	*L. decidua*	*L. decidua*	0.3	1830 ± 30	1698–1831	119–253 AD Roman Time
	Bs2	50–60	*L. decidua*	*L. decidua*	0.1	2755 ± 35	2774–2929	825–980 BC Bronze Age
	BC	60–90	–	–				
For								
	OE	0–25	*Alnus* sp.	*L. decidua*	89.3	240 ± 45	260–334	1616–1691 AD Modern
			Betula sp.	*L. decidua*		185 ± 45	124–231	1719–1826 AD Modern
	Bs	25–50	–	–				
Pejo 6								
	AE	0–10	*L. decidua*	*L. decidua*	2.2	130 ± 30	57–152	1799–1894 AD Modern
	BA	10–35	*L. decidua*	*L. decidua*	0.7	150 ± 30	167–233	1718–1734 AD Modern
	Bs	35–58	*L. decidua*	*L. decidua*	0.7	480 ± 30	498–543	1407–1453 AD Modern
	BC	58–85	–	–				
Pejo 10B								
	A	4–10	*Larix/Picea*	*L. decidua*	3.1	375 ± 30	424–505	1446–1527 AD Modern
	Bs1	10–50	*Ericaceae*	*Ericaceae*	0.3	3100 ± 35	3239–3390	1441–1290 BC Bronze Age
	Bs2	50–70	–	–				
	BC	70–80	*Larix/Picea*	*Larix/Picea*	9.7	3460 ± 35	3640–3831	1882–1691 BC Bronze Age
				Larix/Picea		3445 ± 35	3631–3832	1883–1682 BC Bronze Age
Pre								
	A	0–3	–	–				
	AE	3–12	*Picea/Larix*	*Picea/Larix*	0.2	1135 ± 50	937–1174	776–1031 AD Middle Age
	Bs	12–45	–	–				
	BC	45–60	*P. sylvestris*[b]	*P. sylvestris*	0.1	9385 ± 75	10378–10793	8844–8429 BC Early Holocene
Rabbi 13								
	AB	3–10	*L. decidua*	*L. decidua*	0.4	510 ± 30	505–555	1395–1445 AD Modern
	Bs1	10–37	*L. decidua*	*L. decidua*	0.1	1725 ± 30	1557–1708	243–393 AD Roman Time
	Bs2	37–55	–	–				
	BC	55–100	–	–				
Lax 1								
	AE	5–11	*Larix/Picea*	*Larix/Picea*	n.d.	3055 ± 50	3081–3381	1432–1192 BC Bronze Age
	Bs1	11–26	*Larix/Picea*	*Larix/Picea*	n.d.	3065 ± 55	3080–3393	1444–1191 BC Bronze Age
	Bs2	26–50	*Larix/Picea*	*Larix/Picea*	n.d.	9160 ± 70	10212–10509	8560–8263 BC Early Holocene
Pia								
	AE1	0–8	–	–				
	AE2	8–11	–	–				
	BE	11–25	*Pinus/Larix*	*Pinus/Larix*	0.1	1220 ± 50	1054–1277	674–897 AD Middle Age
	Bs1	25–55	–	–				
	Bs2	55–80	*Pinus/Larix*	*P. sylvestris*	0.1	9340 ± 75	10293–10734	8785–8344 BC Early Holocene

– = no charcoal fragments/size < 1 mm

n.d. = Not determined

[a] *L. decidua* = *Larix decidua*

[b] *P. sylvestris* = *Pinus sylvestis*

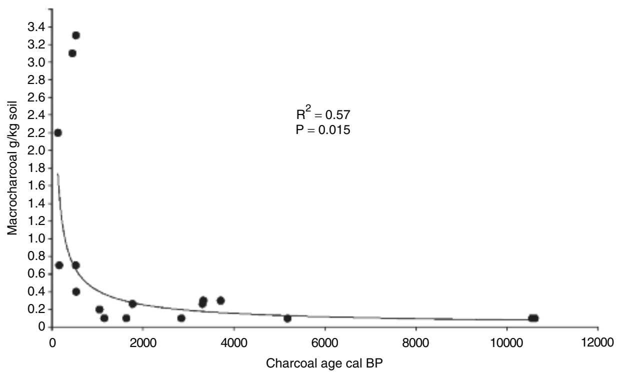

Figure 3 Correlation between the macrocharcoal weight in soil and the calibrated ^{14}C ages of the charcoal fragments

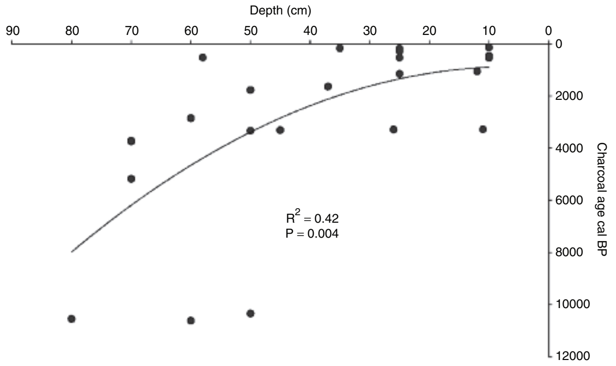

Figure 4 Relationship between the age of the charcoal fragments and soil depth (using second order polynomial regression)

a wider area (Figures 1 and 7a). During the early Holocene, the treeline reached altitudes of around 2200–2300 m a.s.l. (Burga and Perret, 1998; Dalmeri *et al.*, 2007). The climate was generally slightly warmer than today in the period from the Preboreal until the beginning of the Bronze age (Burga and Perret, 1998). *P. sylvestris, P. mugo* and *L. decidua* were present in the mixed coniferous forest (Pini, 2002), which is in accordance with the change in vegetation found at the highest sites (Figure 5). The charcoal fragment extracted from the soil 'Pia' at 2222 m a.s.l. evidenced a downward shifting of the treeline by about 150 m from the early Holocene to the present. Several studies carried out in the French Alps (eg, David, 1993), in Scotland (Pears, 1968) and in Switzerland (Carnelli *et al.*, 2004a), have demonstrated that during the Preboreal and Boreal period (*c.* 9500–7000 cal. BP; Maisch *et al.*, 1999) the treeline was about 200–250 ± 100 m higher than today.

Preconditions for forest fires are the presence of a substantial amount of flammable conifers, a relatively dry climate or periods with drought and thunderstorms (lightning). Such conditions were obviously prevalent at the beginning of the Preboreal. High elevation woodlands have been dominated by relatively flammable conifers since 8000 cal. BP (David, 1995; Carcaillet

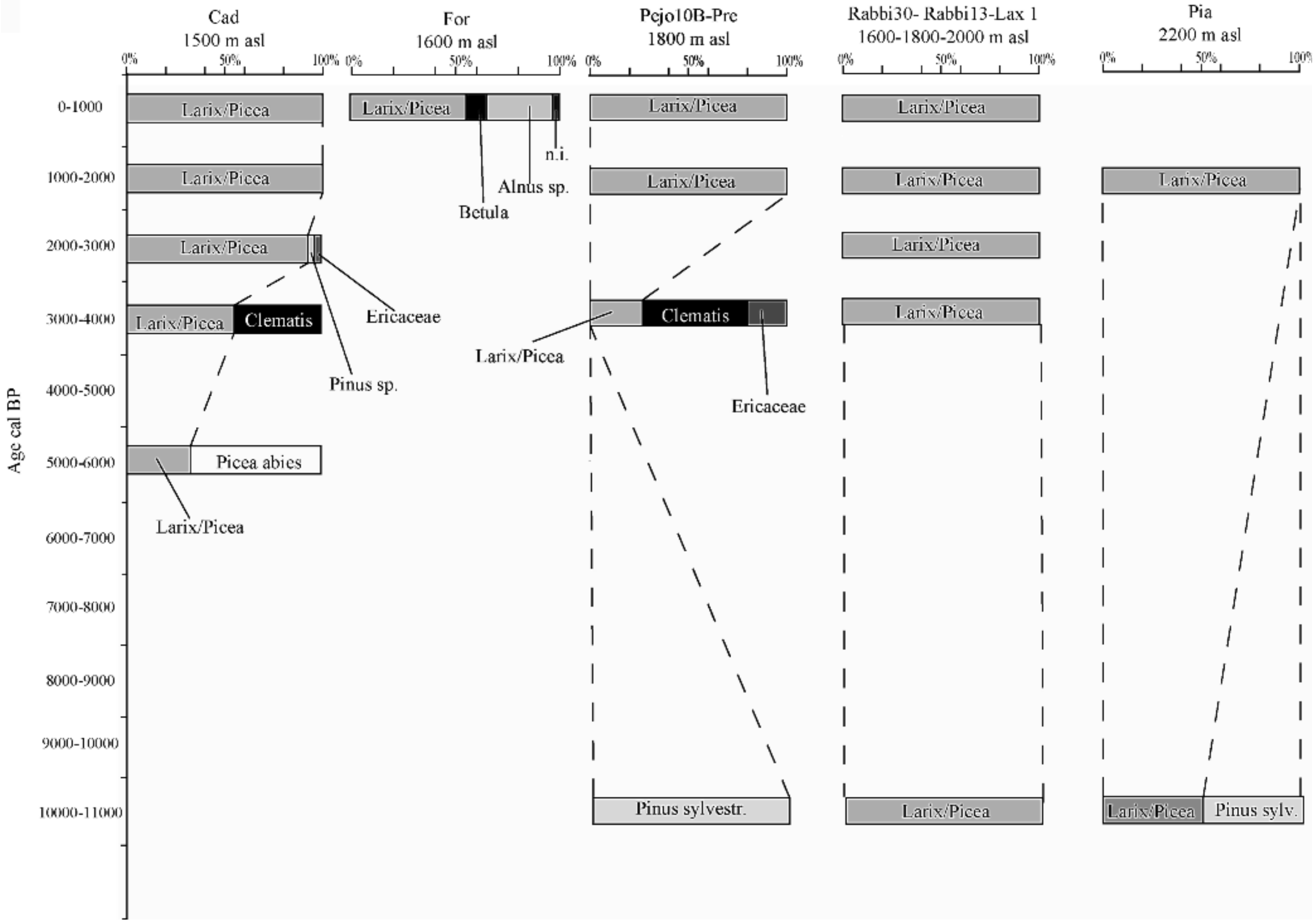

Figure 5 Composition of the vegetation as a function of time derived from charcoal fragments in the soils (up to 107 charcoal fragments per soil horizon were analysed). Some soils having a similar altitude and evolution were unified in one graph. n.i., Not identified

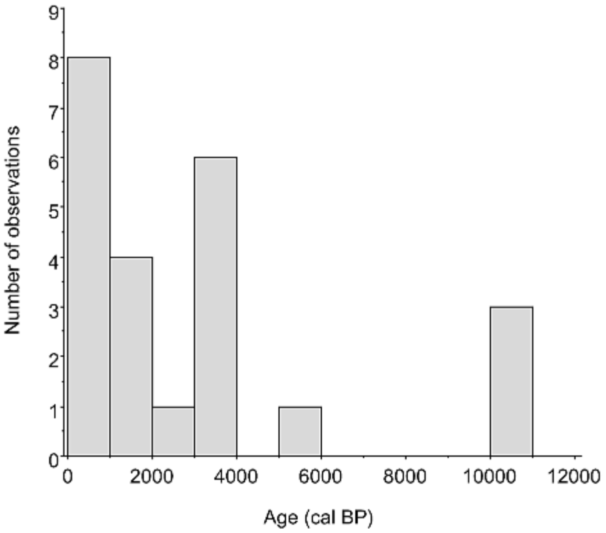

Figure 6 Distribution of the ^{14}C ages (number of observations) over the considered time span

and Thinon, 1996). As no big changes in vegetation have been recognised at our sites, we can assume that the area was dominated by mixed coniferous forests since the early Holocene and that the climate was relatively constant. The distinct warming of the climate after the Boreal chronozone (around 9000 years ago) gave rise to a rapid melting of the glaciers and enabled the Mesolithic human settlements up to the main Alpine range (Bassetti and Angelucci, 2007). At the passage between Boreal and Atlantic (9000–7400 cal. BP) *P. sylvestris* and *P. mugo* started to decline and mixed stands *Larix/Picea* increased their presence (Pini, 2002; Piussi, 1992).

(2) Copper, Bronze and early Iron Age (4300–400 BC) (Figure 7b)

The Trentino region was at that time already populated, as documented by the finding of the Alpine ‘iceman’ dated to 5300–5050 cal. BP (Baroni and Orombelli, 1996). The period around 4000 cal. BP is considered to be the beginning of the integration of high-mountain pastures with hunting practices (Marzatico, 2007). A clear evidence of these practices is the presence of *Plantago lanceolata* pollens in Alpine peat bogs (Della Casa, 2001). The first human interference in the investigation area is recorded during the Copper Age, at around 3000 BC. The charcoal fragments extracted from the soil ‘Cad’ at an altitude of 1521 m a.s.l. with an age of 3378–3089 cal. BC could be due to human settlements in the sub-Alpine altitudinal range. Already in the late Neolithic the use of fire to open up new pastures has been documented (eg, Kaufmann and Demetz, 2004). Other studies in nearby Alpine and sub-Alpine sites in Trentino and in Austria reported an increase in agricultural and pastoral practices in valleys during that time (Cucina *et al*., 1999; Schmidl *et al*., 2005). The first clearances were carried out in deciduous forests of the valley bottoms and indicate the location of settlements in the surroundings. The occurrence of birch (*Betula* sp.), hornbeam (*Carpinus betulus*), pine (*Pinus*) and larch (*Larix*) shows an opening-up of the forests for timber, firewood and agricultural use. The beginning of the human activity is indicated by the first occurrence of ribwort plantain (*Plantago lanceolata* type) and juniper (*Juniperus communis*) (Schmidl *et al*., 2005), species common nowadays in the sub-Alpine and Alpine altitudinal range (Carnelli *et al*., 2004b).

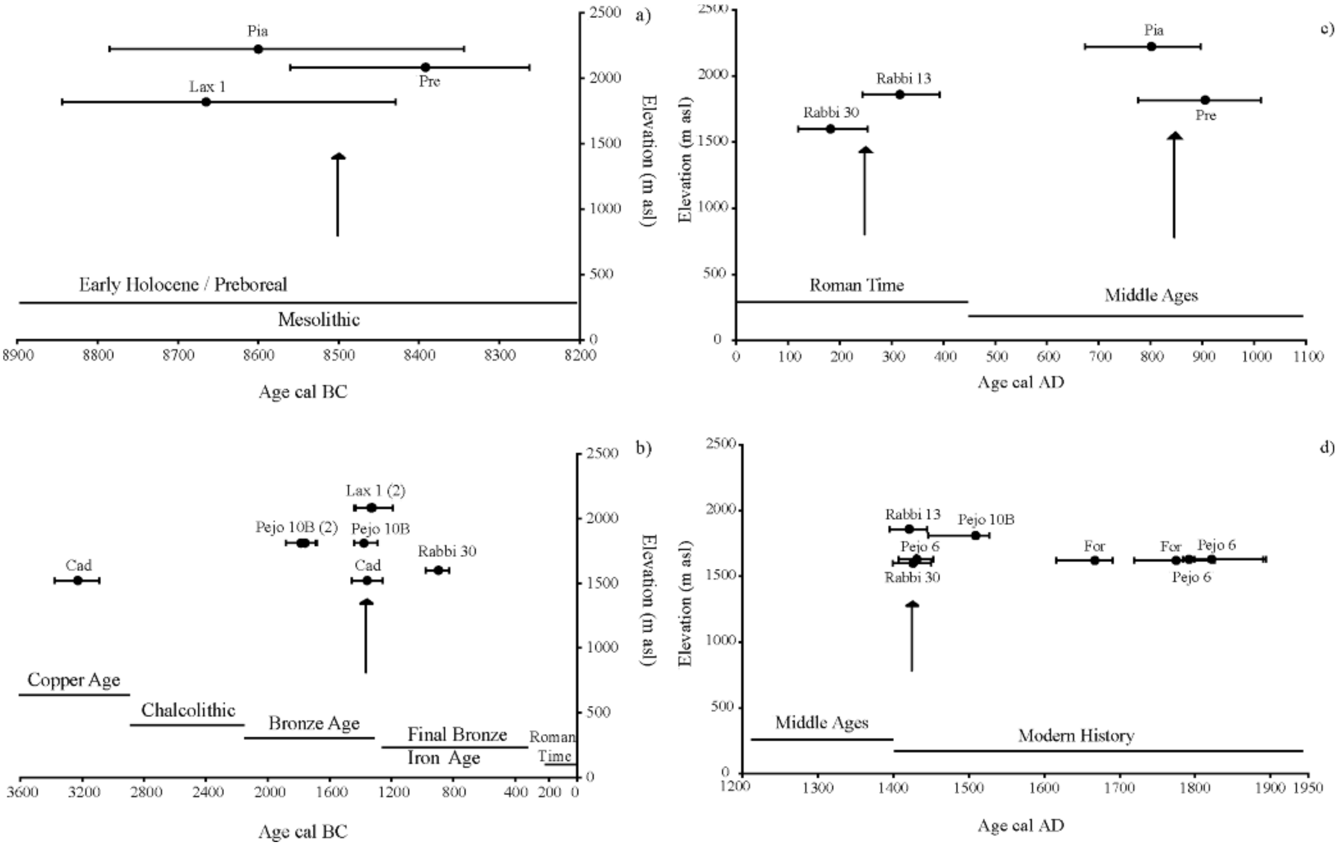

Figure 7 Chronology of fire events: (a) during the Mesolithic period, (b) until the late Iron Age, (c) during Roman time and early Middle Ages, (d) late Middle Ages and Modern history. The 1 σ range of the calibrated ^{14}C ages is given with the median value

In the Copper Age, Alpine passes were intensively used to transport merchandise (eg, painted pottery) to Middle Europe (Pedrotti and Demetz, 1997). Trading along commerce routes had been common since the Neolithic (5000–3200 cal. BC; Moe *et al*., 2007), mainly along the valleys. The fire reported during this period is probably of human origin, but more fragments are needed to confirm this hypothesis. *Larix* meadows (a form of grazed forest still present nowadays) started to spread around 4820 cal. BP, simultaneous with a phase of anthropic cutting of *Picea*. *Larix* pollens of this period represent the highest percentage (Pini, 2002). In the altitudinal range 1500–1800 m a.s.l. *P. abies* trees started to be present in combination with *Pinus* (Burga and Perret, 1998).

The charcoal fragments of 1400–1800 cal. BC (3350–3750 cal. BP; early and middle Bronze Age) correlate well with the climate change that occurred around 3000–3500 BP leading to the Göschener cold-phases (Zoller *et al*., 1966; Burga and Perret, 1998; Maisch *et al*., 1999). The treeline reached an altitude similar to the present (around 2100 m a.s.l.). In addition, human impact has increasingly influenced the treeline since that period (Di Benedetto *et al*., 2000; Schmidl *et al*., 2005). Compared with the Neolithic, later human impact on the landscape became more intense, with more extensive cultivation (Eckmeier *et al*., 2007) and animal husbandry, accompanied by a development towards more complex societies (Castelletti *et al*., 2001). The vegetation pattern of nearby sites in Trentino (Valsecchi *et al*., 2006) suggested that the landscape has been exposed to more intense human impact since about 2000 BC. The human presence in the Bronze Age is supported by several finds of artefacts in Alpine valleys in Austria, Germany and Trentino (Finsinger, 2001; Schmidl *et al*., 2005; Eckmeier *et al*., 2007). In our investigated sites, this period is represented by the charcoal layer found in 'Pejo 10B' at around 75 cm of soil depth and which is mainly composed of charcoal fragments of the Bronze Age and by three fires which occurred in the area between 1800 and 900 cal. BC (Table 3 and Figure 7b). The charcoal fragments dated back 1400 cal. BC demonstrated a synchronicity which could be due to climate forcing, as the soils are located between 1500 and 2100 m a.s.l. and on different sides of the investigated area (Figures 1 and 7b). This event could also be caused anthropogenically, since the human impact activity in that period was high (Brochier *et al*., 1998; Castelletti *et al*., 2001).

Isolated fires occurred between 1800 and 900 cal. BC (Table 3; Figure 7b). During the transition from the middle to the final Bronze Age (1300–800 cal. BC), a shift towards more intense grazing and to increased cereal cultivation was suggested by archaeological evidence and by palaeobotanical records of Pian di Gembro and Lago Lucone near the Garda Lake (Valsecchi *et al*., 2006). Charcoal of local origin and increased values of *Poaceae* and most herbs showed active grazing until about 2000 cal. BP (Moe *et al*., 2007). In that period, *Larix* meadows definitely took the place of former *Pinus* stands (Pini, 2002).

(3) Late Iron Age, Roman time and Middle Ages (400 BC–AD 1400) (Figure 7c)

Only few charcoal fragments were found that could be attributed to the Roman time period and the late Iron Age (*c*. 400 BC–AD 630). This suggests a decrease in the use of fire in land use (Galop *et al*., 2000). Such a reduction can be explained as the result of a more attractive economy in the lowlands and specialisation in viticulture (Riera-Mora and Esteban-Amat, 1994). Similar observations were made for the same period in western Germany and in Scotland (Clark *et al*., 1989; Edwards and Whittington, 2000). One natural fire can be recognised around 250 cal. AD in the eastern part of the investigated area (profiles 'Rabbi 30' and 'Rabbi 13') (Figures 1 and 7c). The synchronicity of the ^{14}C age of their charcoal fragments and their geographical position suggest the occurrence of a natural fire which affected both sides of Val di Rabbi (Figure 1). Around 800 cal. AD another fire was recorded in the western part of the investigated area (soils 'Pia' and 'Pre', Val di Pejo – Figure 1) at an elevation between 1800 and 2200 m a.s.l. In this period of the Middle Ages, an increase in agricultural activities was recorded in several mountainous slopes (eg, Galop, 1998; Galop *et al*., 2000) with the concomitant effect of regional fires. Palynological studies in lakes of Trentino (Filippi *et al*., 2005), Austria (Kral, 1971), France (Wegmüller, 1977) and Switzerland (Gobet *et al*., 2004) support an increase of the human impact in Alpine valleys as shown by the high deforestation rates and by the development of high-elevation pastures during the first period of the Middle Ages (600–1000 cal. AD). According to the possible land use of that time, we hypothesise the fires between 1800 and 2200 m a.s.l. to be caused by human activity such as the opening of new pastures.

(4) Modern history (> AD 1400) (Figure 7d)

According to the ^{14}C ages of the charcoal fragments, the greatest human impact in Modern history was recorded in the elevation range 1500–1800 m a.s.l. (Figure 7d, Table 3). The existence of several iron-smelting sites in Val di Sole (Speranza *et al*., 1996) could explain the need for wood. A synchronous fire was recorded in the western and eastern part of the investigated area at around 1420 cal. AD. Studies from the Pyrenees indicated an extensive human pressure on the landscape during the last centuries (Galop *et al*., 2000). At the end of the nineteenth century, the pastures reached their maximum extent until the latest period of the twentieth century which was characterised by a great increase in forest regeneration and expansion because of the countryside being abandoned and the progressive industrialisation of the region (Filippi *et al*., 2005). The high presence of more recent charcoal fragments suggests an increase in the use of fire for pasture management or for charcoal production (charcoal piles). The soil at the site 'For' is a typical example of this practice in recent centuries. The first 25 cm of this soil were almost entirely composed of charcoal fragments, most of them having a diameter of > 2 cm. The C stock was almost entirely composed by charcoal fragments (Table 2, Figure 8). The dated charcoal fragments of this soil all had a similar age (1700 cal. AD and younger). The western part of the investigated area (Val di Pejo) was probably utilised for relatively intense agro-forestry activities, as demonstrated by the five fires which occurred during the last 500 years (Figure 7d). This valley is still relatively intensively used today.

Soil evolution

The most developed soils in the siliceous Alpine environment are usually podzols, whose degree of evolution can be used to estimate the stability of surfaces (Egli *et al*., 2003; Briggs *et al*., 2006). In the case of undisturbed soil development, the age of the

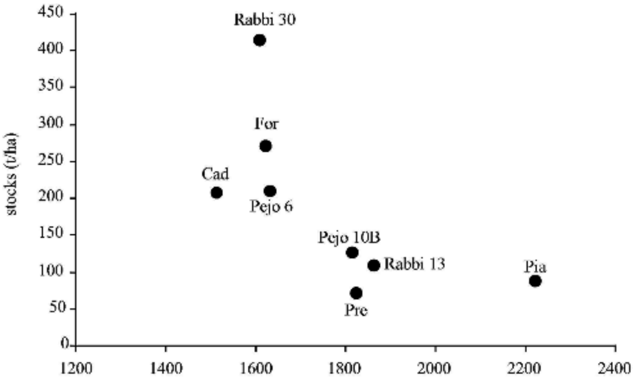

Figure 8 Abundance of organic carbon (kg/m^2) in the soils as a function of the altitude

oldest charcoal fragments can be directly linked to soil age (see Favilli *et al.*, 2008). Charcoal fragment in soils can help to estimate soil age (Carcaillet, 2001). The soils 'Pre', 'Lax 1' and 'Pia' have charcoal fragments that can be related to the beginning of the Holocene (10 200–10 700 cal. BP; Table 3) and consequently can give an indication about the soil formation. According to the ^{14}C age of the charcoal and to the development of the horizons, an undisturbed soil evolution has been taking place during the last 10 000 years on stable surfaces of higher elevation. Such a time span leads to well-developed podzols (Lundström *et al.*, 2000; Sauer *et al.*, 2007). Sites with repeated fire events or a high charcoal content (such as 'For' or 'Cad') may be subjected to soil degradation and erosion: the site 'For' had a relatively shallow soil. It has been shown that post-fire flow erosion rates exceed long-term rates up to a factor of six (Roering and Gerber, 2005). Given the sensitivity of steep hillslopes to post-fire-driven transport, changes in climate and fire frequency may affect soil resources by disturbing the balance between soil transport and production.

In Alpine environments, the stocks of organic C close to the treeline are considerable (> 230 t/ha, up to 400t/ha; Hitz *et al.*, 2002; Tonolli and Salvagni, 2007). The abundance of soil organic carbon (SOC) usually shows a non-linear climate dependent tendency (Egli *et al.*, 2006). Highest amounts of SOC are measured in the sub-Alpine range or near the treeline. In this range, a high amount of flammable wood can be provided and the probability of fires due to lightening is increased (Figure 8).

The measured charcoal stocks in the soils (Cad, Pre and Pia: 1.3–8.8 t/ha, Table 2) correspond approximately to values recorded in the southern Alps (Schlumpf, 2004) where forest fires are frequent. The amount of charcoal measured at the site 'For' was 247.5 t/ha, which makes it almost the sole contributor to the total soil organic carbon. This site definitely must have been affected by a charcoal pile.

Conclusions

We used the age of 23 charcoal fragments extracted from nine sub-Alpine and Alpine soils in Val di Sole to reconstruct the landscape evolution since the beginning of the Holocene and to separate, as far as possible, naturally driven from human-induced processes. We obtained the following findings:

(1) Sub-Alpine and Alpine soils are good archives about past climatic evolution and human impact on landscape evolution.

(2) The signal of the charcoals in the soils agreed well over the last 10 000 years with existing archaeological and botanical proxies (ie, palynological).

(3) Synchronous charcoal fragments at different sites are possible evidence for natural fires which occurred in several parts of the region, mainly induced by climatic conditions (ie, dry periods, lightning).

(4) Isolated fires are probably human-induced but more charcoal fragments of the same age in the same site are needed to support such a hypothesis.

(5) The charcoal chronology shows at least 13 fire events in the last 10 000 years, of which seven or eight are likely to be human-induced.

(6) A quick forest expansion phase must have occurred shortly after the Lateglacial around 10 500 cal. BP. *Pinus sylvestris* and *Pinus mugo*, as well as *Larix decidua,* populated the investigation area in that period. At the transition to the Boreal, *Picea abies* had not yet settled into this region.

(7) *Pinus sylvestris* and *Pinus mugo* were displaced around 4000 cal. BP.

(8) At the beginning of the Holocene the treeline was at a higher altitude compared with the present-day but was heavily influenced by human activities during the centuries.

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