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Late Holocene soil evolution and treeline fluctuations in the Northern Apennines

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ABSTRACT

The aim of this study is the reconstruction of Late Holocene soil evolution and environmental changes at the treeline of Northern Apennines (Italy) through field observation, pedoanthracological analysis, soil micromorphology and dendrochronology. Nine soil profiles across the present treeline (c. 1750 m) between 1700 and 2000 m were described. Physical and chemical analyses, and pedoanthracological and micromorphological observations were carried out. Tree ring analysis was also performed to outline recent disturbance events.

All soils consisted of two superimposed units. The lowermost unit consisted of a well developed B horizon resulting from intense brunification process, frequently overtopped by a dark Ab horizon. The superficial unit was up to 1 m thick, consisting of colluvium deposits with poorly developed pedogenesis.

Below the present treeline, charcoals were observed in the B horizon of the buried soils: *Abies* and *Fagus* dominated the anthracological assemblages. *Abies* charcoals were AMS dated to 790–670 cal BP. Above the treeline, a charcoal assemblage dominated by *Abies* and *Laburnum* was found in the buried B horizon. A *Laburnum* charcoal sample was dated to 3920–3700 cal BP. In the Ab horizon another assemblage dominated by *Abies, Laburnum* and *Vaccinium* with abundant insect remains was observed, dated to late Middle Ages.

Soil data suggest a recent phase of marked slope instability. Tree ring analysis indicated that this phase occurred at least during the 18th and early 19th century.

These analyses, together with previous archaeological evidence, indicate the occurrence of forests well above the present treeline in the Early-Mid Holocene. The lowering of the treeline probably started during Late Holocene, but woody vegetation (open forest or treed heathland) occurred at high altitude until recent times. The colluvial episodes and the burial of paleosols probably took place through successive events during modern times. The dominance or co-dominance of fir at the treeline lasted until historical times. The multi-proxy approach allowed previous archaeological data to be put in a wider context, to give better spatial and temporal extent to treeline fluctuations, and to achieve high resolution for the analysis of the most recent time span.

1. Introduction

The position of the treeline (the uppermost or northernmost limit of tree growth form) represents a well-known climatic boundary and, at the same time, is strongly influenced by human activities. Its fluctuations have thus been considered a powerful indicator of past and present environmental changes and have a major influence on processes at landscape scale, including soil evolution, slope stability, ecosystem functioning, fire history and land use (Becker et al., 2007; Holtmeier and Broll, 2007). Climatic fluctuations and anthropic activity during Late Holocene represent a critical case study: progressive forest clearing and treeline lowering resulted in generalized slope instability, indicated in Europe by frequent slope movements and colluvial deposits. The causes can be identified both in the impact of increasing human activities and in the effect of the climatic deterioration after the Holocene optimum (e.g. Marchetti, 2002; Lang, 2003; Eppes et al., 2008). The present warming cycle and the dereliction of traditional pastoral activities in mountain areas have triggered a cycle of treeline elevation, with some significant exceptions and many uncertainties about the role of climate and of other driving forces (Holtmeier and Broll, 2007; Harsch et al., 2009).

The study of treeline fluctuations has been addressed by many palaeoecological studies, mainly using pollen analysis (Tinner and

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Theurillat, 2003; Vescovi et al., 2010a), analysis of plant and insect macrofossils (Nicolussi et al., 2005; Birks and Bjune, 2010) and pedoanthracological analysis (e.g. Carcaillet and Brun, 2000; Ali et al., 2005; Talon, 2010) which gave important information at different spatial and temporal scales.

The complexity of the involved phenomena requires a multi-proxy approach (Tinner et al., 1996; Gobet et al., 2003; Ponel et al., 2011), considering both biotic and abiotic data, particularly when pollen or macrofossils are scarce or not available. Soils may represent a powerful archive of such data, as they can retain traces of the influence of parent material, climate, sedimentological events, vegetation cover, and land use. Paleosols have been used as indicators of past ecological conditions, and soil micromorphology has found wide use in archaeological studies (e.g. Sageidet, 2009; Goldberg and Berna, 2010) and paleopedological research (Kemp, 1998), but detailed soil evidence, particularly micromorphology, have seldom been integrated with those obtained from other proxies in paleoecological studies (e.g. Delhon et al., 2009; Bal et al., 2010).

This paper presents a paleoenvironmental study at the treeline of a mountain area in the Northern Apennines (Italy) through the integrated analysis of present and buried soils, soil micromorphology, pedoanthracological and dendrochronological analyses. The interest of the area lies in the occurrence of complex soil sequences (Panizza et al., 1982) and archaeological and associated pollen records (Panizza et al., 1982; Cremaschi et al., 1984). These data were mainly collected in archaeological contexts, and the area still lacks an historical reconstruction of ecological processes, particularly concerning recent (Late Holocene) time span. A further interest of the area lies in the static treeline behavior which contrasts with the global trend of treeline advancing and with the general pattern of treeline temperature (Körner and Paulsen, 2004). The aims of the research can be summarized as follows.

1) To outline the phases and the processes of soil development across the treeline in the study area;
2) to evaluate the role of soil data in providing information about past environmental conditions complementarily with those coming from other proxies;
3) to outline environmental history and treeline fluctuations with particular focus on Late Holocene, and their relationships with slope instability, climatic phases and human activities.

2. Materials and methods

2.1. Study area

The investigated area is located on the northern slope of Mt. Cusna (2120 m a.s.l., 44°18′N–10°23′E), the second highest peak of the Tuscan-Emilian Apennines (Northern Italy) (Fig. 1). The climate is sub-Mediterranean with abundant and well distributed precipitation (2000 mm y^{-1}), with a summer minimum. Mean annual temperatures range from 8.8 °C (Ligonchio, 928 ma.s.l., 44°31′N–10°35′E) to 2.2 °C (Mt Cimone, 2165 m a.s.l., 44°21′N–10°70′E; observation period for both stations 1961–1990).

The bedrock consists mainly of turbiditic sandstones and marlstones with intercalated sequences of claystones and limestones (Panizza et al., 1982; Bortolotti, 1992). Mt. Cusna was strongly glaciated during the last glacial maximum (Losacco, 1949). At present, the most important geomorphological processes consist of mass movements, action of diffuse and channeled waters, and anthropic processes (Panizza et al., 1982).

The present vegetation is characterized by deciduous forest dominated by beech (*Fagus sylvatica*), with very sparse *Abies alba*, up to ~1750 m a.s.l. The areas above the treeline host *Vaccinium*-dominated heathland and herbaceous vegetation (Tomaselli, 1997). The average temperature of the growing season (May–September) at the treeline, calculated from the above-mentioned weather stations, is ~10.2 °C, substantially higher than the values registered at the treeline worldwide (~7 °C; Körner and Paulsen, 2004). In the study area, such values are reached well above 2100 m (Mt. Cimone: 7.8 °C) similar to what is observed at other Mediterranean *Fagus* and southern hemisphere *Nothofagus* treelines (Körner and Paulsen, 2004).

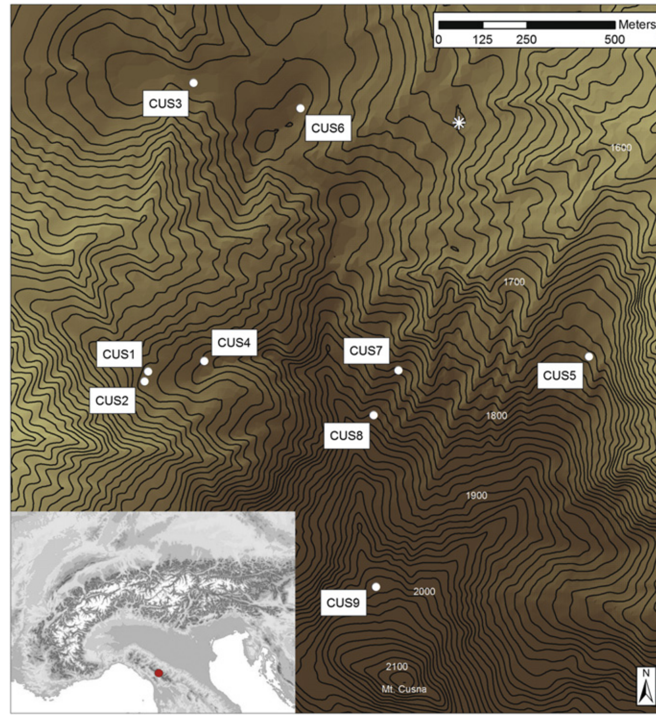

Fig. 1. Study area and location of the investigated profiles. Asterisk indicates the archaeological site of Monte Bagioletto (Cremaschi et al., 1984).

Entisols, Spodosols and Inceptisols (Soil Survey Staff, 2006) can be observed up to 1900 m. In the uppermost area, weakly developed humiferous and desaturated soils occur (Filippi and Sbarbati, 1994). Colluvium-buried paleosols characterize an ancient surface, the Mt. Cusna paleosurface, extensively glaciated during the glacial maxima, subjected to soil evolution and finally buried during the Holocene (Bernini et al., 1978; Panizza et al., 1982). The area was settled between Early and Mid-Holocene by Mesolithic hunters (Monte Bagioletto site, 1.6 kilometers from the summit of Mt. Cusna; Fig. 1). Occasional occupation during Late Holocene to Roman Age has been also recorded (Biagi et al., 1980; Panizza et al., 1982; Cremaschi et al., 1984).

2.2. Soil sampling

Nine soil profiles (CUS1-CUS9) were described and sampled across the present treeline, between 1700 and 2000 m (Fig. 1 and Table 1). Their coordinates were recorded on a GPS receiver (Garmin GPSMap 60cx) with accuracy between 2 and 10 m. Between 0.5 to 2 kg of material were sampled from each soil horizon for laboratory analyses (Cremaschi and Rodolfi, 1991; McRae, 1991).

Sampling for pedoanthracological analysis (from 1 to 4 kg) was performed for each horizon where the occurrence of charcoals could be observed on the field. At site CUS1, a supplementary sample (CUS1b) was taken from an anomalous concentration of charcoal fragments ~1 m apart from the main profile. Insect remains (exoskeleton fragments) could be locally observed and were sampled separately. For a more complete survey of their occurrence, both charcoals and insect fragments were also

Table 1
Main features of the investigated soil profiles.

Soil profile	Elevation (ma.s.l.)	Aspect (°N)	Slope (°)	Parent material	Vegetation	Coordinates
CUS1	1723	297	10	Claystones	Natural forest	44° 17′ 45.25″ N–10° 22′ 57.42″ E
CUS2	1723	287	10	Claystones	Natural forest	44° 17′ 44.34″ N–10° 22′ 56.94″ E
CUS3	1745	–	0	Claystones	Grassland and shrubs	44° 18′ 11.63″ N–10° 23′ 3.84″ E
CUS4	1752	290	22	Claystones	Grassland	44° 17′ 46.11″ N–10° 23′ 4.61″ E
CUS5	1754	12	17	Claystones	Grassland and shrubs	44° 17′ 45.94″ N–10° 23′ 53.82″ E
CUS6	1765	128	6	Claystones	Grassland and shrubs	44° 18′ 9.14″ N–10° 23′ 17.47″ E
CUS7	1804	10	29	Claystones	Grassland and shrubs	44° 17′ 44.98″ N–10° 23′ 29.40″ E
CUS8	1860	19	18	Marlstones	Grassland and shrubs	44° 17′ 40.90″ N–10° 23′ 26.15″ E
CUS9	2006	345	11	Sandstones	Grassland	44° 17′ 25.16″ N–10° 23′ 26.08″ E

searched for and extracted during laboratory analyses of all soil samples. Twenty-one undisturbed samples were collected using Kubiëna boxes (Kubiëna, 1953) from selected soil horizons to obtain thin sections for micromorphological analysis.

2.3. Soil analysis and micromorphological observation

Each soil sample was subjected to routine laboratory analysis, to determine particle size distribution, pH (in 1:2.5 soil:water) and organic matter content (Walkley-Black method) (Ministero per le PoliticheAgricole, 1997). In order to discriminate soil horizons and to outline the main gradient within the different parameters, principal component analysis (PCA) was applied using selected profile attributes (grain size distribution, pH, organic C, color). Hue, chroma and value parameters obtained through Munsell notation were considered separately; the notation for hue was transformed into a continuous scale with greater numerical values as the soil becomes more yellow, with 10R corresponding to zero YR (Munsell Color, 1994). Data were log-transformed, except for grain size percentage values where arcsin-root transformation was applied. Soil thin sections were prepared on covered glass slides from undisturbed samples through impregnation with an epoxy resin and observed at the petrographic microscope at 20–400×, described according to Stoops (2003) and interpreted according to Stoops et al. (2010).

2.4. Extraction and identification of charcoals and insect remains

Samples were air-dried before sieving to determine dry weight; afterwards, they were left in water for 24 h to disrupt soil aggregates. The remaining aggregates were easily destroyed mechanically, and no deflocculant was used. The material was wet-sieved, using sieves of 2.50 and 1.25 mm; a 500 μm sieve was used to separate insect remains. Charcoal and insect fragments were separated by hand-picking under a low power binocular microscope (5–40×).

Charcoals larger than 1.25 mm were weighed, measured and identified. Charcoal fragments were manually broken to observe anatomical characteristics in transversal, tangential and radial sections (Ali et al., 2005). An episcopic microscope was used under magnifications between 100 and 1000×. Identification of charcoal fragments was performed using reference collections and atlases of wood anatomy (Jacquiot, 1955; Greguss, 1959; Jacquiot et al., 1973; Schweingruber, 1990). Fifty charcoal fragments were identified per soil sample, where available; otherwise, all the available fragments were identified.

Insect remains were grouped by taxon at order or family level and sent to specialists for identification at species level and for ecological interpretation.

2.5. Charcoal quantification

Charcoal concentration, or specific anthracomass (SA) was calculated as mg of charcoal kg^{-1} of dry soil (ppm), considering only fragments ≥ 1.25 mm (Touflan et al., 2010). According to Talon (2010), SA was calculated for the whole soil horizon (SAL) and for each taxon within the horizon (SAT). Approximate volume was determined on the identified fragments measuring and multiplying the three dimension of each fragment. The amount of the different taxa was expressed as a percentage of the number and of the volume of the identified charcoal fragments.

2.6. Radiocarbon dates

Radiocarbon dates were performed in order to obtain a temporal reference for some key stratigraphic and ecological topics: the boundary between the two main units (2Ab horizon), the charcoal assemblage of the underlying well developed soils, which has been determined only in archaeological context, and the dominance of *Abies alba* in presently beech-dominated woodlands. Two charcoal fragments (*Abies alba* from CUS1 and *Laburnum* sp. from CUS6) and one sample of insects (consisting of mixed species) were AMS 14C dated (Beta Analytic Inc., Florida USA). Standard laboratory pretreatment (acid or acid-alkali-acid washing) were applied, which proved to yield accurate dating for insect samples (Tripp et al., 2004).

2.7. Dendrochronological sampling and analysis

Tree ring analysis was performed to provide detailed information about the disturbance events which affected the areas at or below the treeline during the last centuries. Forty-three beech trees (24 from site CUS1, 5 from CUS2 and 14 from the slope below the two profiles) were mapped, described and cored with an increment borer, as close as possible to ground level; some tree stems were partially submerged by slope deposits and were cored both at present ground level and at the root collar. Whenever trees showed evidences of disturbed growth, coring was performed throughout the whole diameter in the direction of the maximum growth anomaly (e.g., stem bending).

Cores were mounted, air dried, sanded and observed with a stereomicroscope. All the sampled trees except one were alive. Cores were visually cross-dated through the occurrence of exceptionally narrow or, less frequently, large rings. For each core, every sign of possible disturbance was recorded, in particular the occurrence of reaction wood, i.e. xylem with anomalous cell wall appearance (Schweingruber, 1996; the specific appearance of reaction wood for *Fagus sylvatica* has been described by Heinrich and Gärtner, 2008). Also recorded were the occurrence of anomalous resin concentration and scars due to mechanical damage and fire. Frequency data were arranged into 5-years age classes.

3. Results

3.1. Soil profiles

Soil depth ranged from 75 cm to more than 2 m (Fig. 2). All the investigated profiles consisted of two superimposed units (Fig. 3) enhanced by discontinuities in grain size distribution, pH values and by a marked increase of organic carbon content (up to 110.5 g kg^{-1}) with the inception of the lowermost sequence

Fig. 2. Sketches of the investigated soil profiles.

(Appendix 1). In some cases, more than one soil sequence could be identified within each unit (Appendix 1). The superficial unit was up to 110 cm thick. Within this unit, organic carbon decreased regularly along the profile (Appendix 1). The lowermost unit consisted of well developed B horizons, often with illuvial clay features (Bt) (Appendix 1). Three profiles (CUS3, CUS6 and CUS9) showed a dark horizon (2Ab) at the top of the lowermost unit (Fig. 3).

PCA axes 1 and 2 explained 62.3% and 12.5% of variance, respectively. Axis 1 was correlated with organic carbon content; axis 2 individuated a gradient of color parameters, grain size distribution

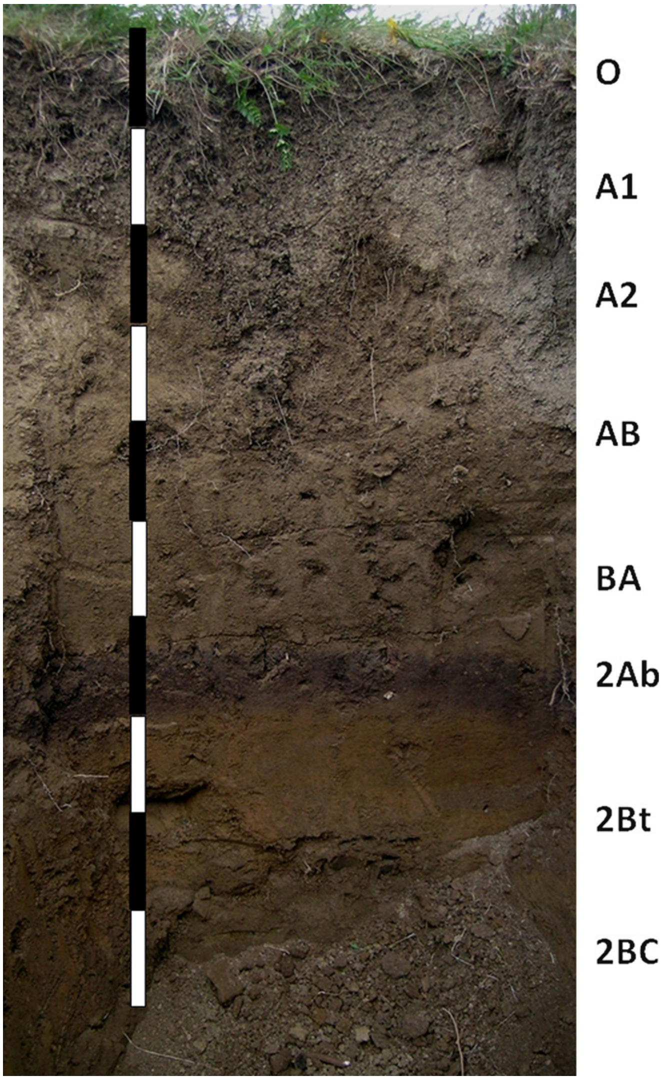

Fig. 3. Typical bisequence (profile CUS6, 1765 m a.s.l.).

and pH. The uppermost horizons of the buried sequence (2Ab and two horizons described as 2Bw) were placed amongst the A horizons in the positive field of axis 1 coordinates, while positive axis 2 scores characterize the buried B horizons (Fig. 4).

3.2. Micromorphology

Thin sections from the uppermost unit showed a weak pedogenesis, with granular aggregation typical of A horizon. Only in the CUS1 profile, located below the treeline, was a weakly developed subangular blocky microstructure observed in the 2Bw horizon, but without evidences of clay illuviation (Appendix 2, Fig. 5). The uppermost unit showed some typical features of colluvial deposits (Fig. 5a), including a weak-moderate sorting of the soil material with frequent coarse rock fragments and some fragments of clay coatings (i.e. papulas sensu Brewer, 1976), and some rounded aggregates of material derived from pre-existing soil (i.e. pedorelicts sensu Brewer, 1976).

The lowermost unit showed a higher degree of development, with stronger pedogenesis in the deepest horizons. The 2Ab horizons were well characterized in thin section, with the absolute dominance of granular aggregate of very well-sorted material and the almost complete absence of mineral grains and nodules (Fig. 5b). In these horizons some planar linear voids could be observed, probably due to frost action (Van Vliet-Lanoë, 2010). In the largest vertical linear voids some clay-rich pedorelicts occurred.

In the deepest horizons, a well-expressed angular-subangular blocky aggregation could be observed with frequent clay coatings in Bt horizons, sometimes well-expressed (Fig. 5c,d). Evidence of argilloturbation and hydromorphy was superimposed on brunification in soils developed on clay- and marlstones with well-expressed Bt horizons. Brunification was less expressed in soil developed on sandstones (CUS9).

3.3. Anthracological analysis

Charcoals fragments were found in four soil profiles: one level from profile CUS1 (horizon 3Bw1, CUS1b) and from profile CUS2 (horizon 2B) and two levels from profile CUS6 (horizons 2Ab and 2Bw, respectively). A total of 420 fragments were identified (Table 2).

The highest SAL was observed in the lowermost profiles: CUS1 (1888 mg kg^{-1}), CUS1b (4829 mg kg^{-1}) and CUS2 (4340 mg kg^{-1}). SAL values observed in profile CUS6 were much lower (2Bw: 384 mg kg^{-1}; 2Ab: 519 mg kg^{-1}) (Table 3).

Below the present treeline, *Abies alba* dominated the anthracological assemblage from CUS1 and CUS1b; hardwood (*Vaccinium* and non-identified hardwood) represented a minor fraction (Table 3). Together with the charcoals, more than 20 charred needle fragments of *Abies alba* and a charred seed of *Rubusi daeus* were also found in CUS1b. In CUS2, *Fagus sylvatica* represented the most abundant species, although *Abies* was still very abundant (Table 3). The high SAT of indeterminable conifer wood was due to the partial vitrification of the wood.

Above the present treeline (site CUS6) two different charcoal assemblages were observed. In the 2Ab horizon, the dominant species were *Laburnum* sp., *Abies alba* and *Vaccinium* sp. In the underlying 2Bw horizon, *Vaccinium* was completely absent, and the assemblage was dominated by *Laburnum* and *Abies* (Table 3).

3.4. Insect remains

Charred insect remains were found in the 2Ab horizon of profile CUS6 at 70 cm depth. The identified taxa were *Curculionidae*, *Aphodidae* and *Chrysomelidae* (*Coleoptera*) and *Formicidae* (*Hymenoptera*) (Table 4). The most abundant species were *Otiorhynchus frescati* (*Curculionidae*) and *Aphodius* sp. (*Aphodidae*) (at least 12 individuals estimated), followed by *Pseudomeira parvula* (*Curculionidae*) (at least 11 individuals) and *Barynotus obscurus* (*Curculionidae*) (at least 5 individuals). All these taxa are epigean: only *Aphodius* species are able to dig for few centimeters in dung or soft soil (Hurka, 2005; Abbazzi and Maggini, 2009).

3.5. Radiocarbon dates

All the analyzed samples dated to Late Holocene. *Abies alba* charcoals from the 3Bw1horizon of profile CUS1 were dated to 790–670 cal BP. At site CUS6, a *Laburnum* charcoal sample from the 2Bt horizon was assigned to 3920–3700 cal BP, while insect remains from 2Ab horizon were dated to the late Middle Ages (640–590/570–530 cal BP). (Table 5).

3.6. Dendrochronology

At site CUS1, trees reached ages >300 years. The oldest trees were often tilted, completely upturned or creeping, while youngest individuals grew generally upright up to the treeline (Fig. 6). Tree ring analysis revealed a marked occurrence of disturbance indicators (reaction wood, resin and scars) in the mid-late 18th century (from AD 1735 to 1780 at site CUS1 and from 1755 to 1790 in the underlying

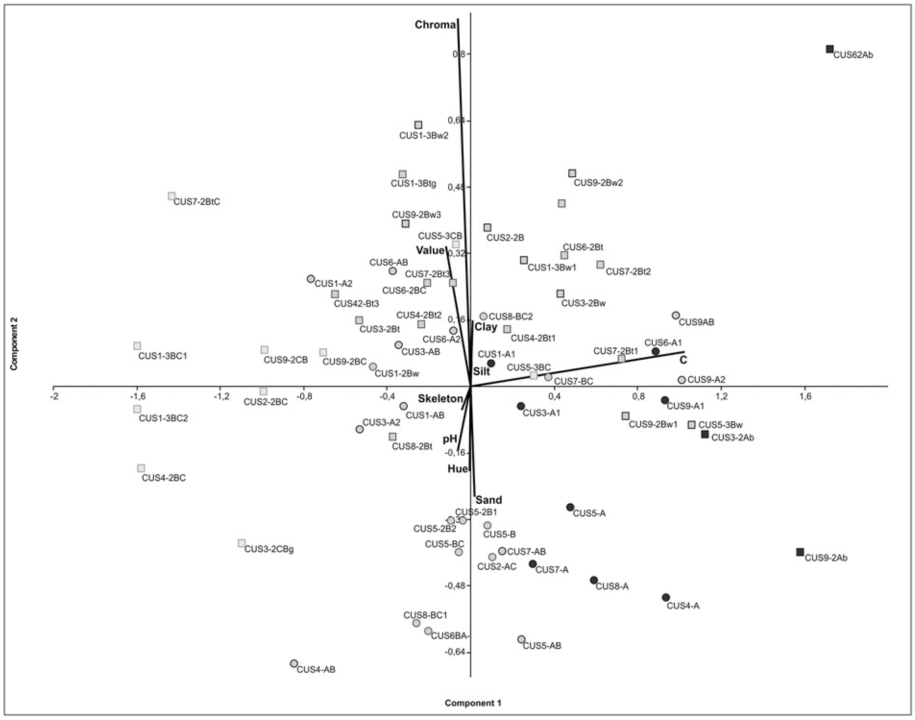

Fig. 4. PCA biplot based on the selected horizon parameters. PCA axis 1 (62.3% of variance) and axis 2 (12.5%) are displayed. Circles refer to horizons from the superficial units, squares to those from the buried one.

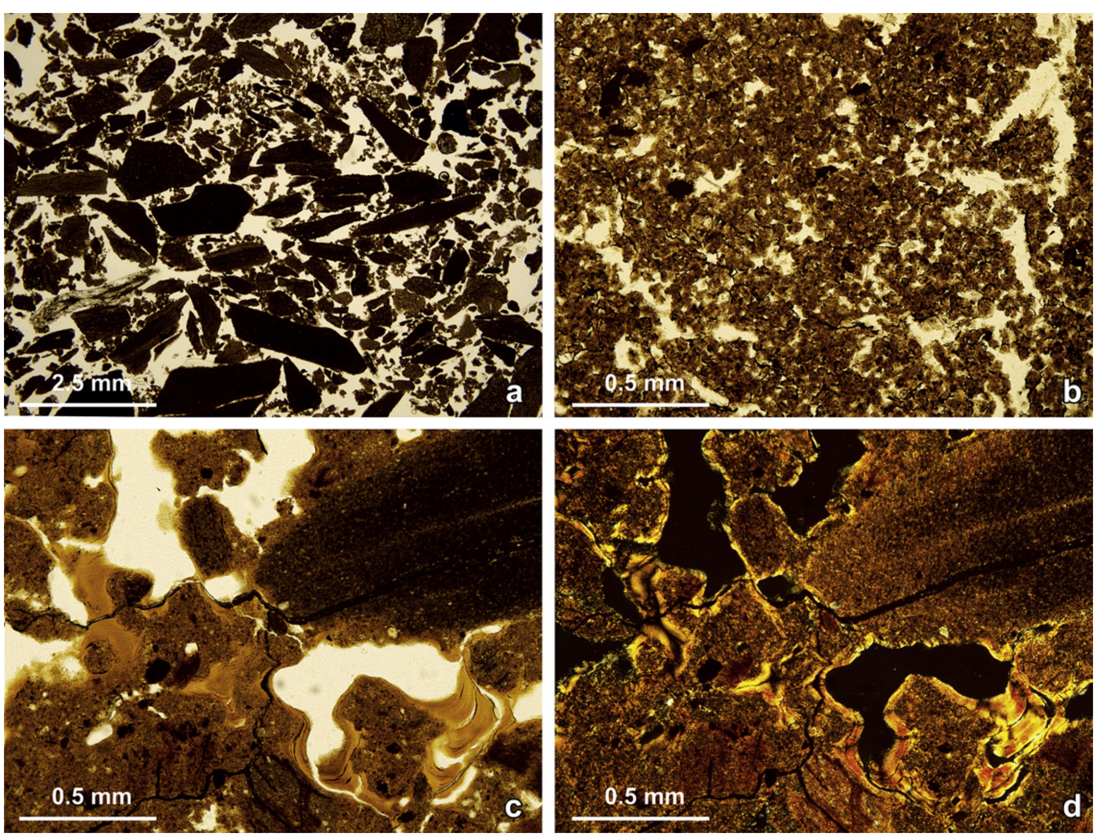

Fig. 5. Photomicrographs of some micromorphological features from soils and paleosols. a) Dominant coarse rock fragments in A horizon of superficial soil unit (CUS4 – 20×, PPL). b) Typical granular microstructure in 2Ab horizon (CUS6 – 100×, PPL). c) Microlaminated limpid clay coatings in 3Btg horizon (CUS1 – 100×, PPL). d) Same field as previous in XPL.

Table 2
Number (upper table) and volume (mm^3) (lower table) of identified charcoal fragments per taxon for each horizon.

Taxa	CUS1		CUS1b		CUS2		CUS6-2Ab		CUS6-2Bw		SUM	%
	2.5 mm	1.25 mm	2.5 mm	1.25 mm	2.5 mm	1.25 mm	2.5 mm	1.25 mm	2.5 mm	1.25 mm		
Abies alba	43	39	33	22	25	25	3	5	3	11	209	50
Laburnum sp.	–	–	–	–	–	–	6	17	6	28	57	14
Fagus sylvatica	–	–	–	–	21	18	–	–	–	–	39	9
Vaccinium sp.	–	–	1	3	–	–	–	24	–	–	28	7
Conifer	5	8	16	23	4	7	–	1	–	4	68	16
Hardwood	2	3	–	2	–	–	–	2	–	7	16	4
Vitrified	–	–	–	–	–	–	2	1	–	–	3	1
TOT	50	50	50	50	50	50	11	50	9	50	420	
Abies alba	3017	81	6309	84	1511	37	207	29	196	28	11240	67
Laburnum sp.	–	–	–	–	–	–	284	40	412	59	696	4
Fagus sylvatica	–	–	–	–	2294	56	–	–	–	–	2294	14
Vaccinium sp.	–	–	124	2	–	–	151	21	–	–	275	2
Conifer	627	17	1045	14	298	7	4	1	29	4	2003	12
Hardwood	72	2	32	0	–	–	8	1	57	8	169	1
Vitrified	–	–	–	–	–	–	62	9	–	–	62	<1
TOT	3716		7510		4103		716		694		16739	

slope) (Fig. 7). A second, less marked occurrence of scars and reaction wood could be observed in the early 19th century (c. 1815–1835) and a third in the late 19th century, peaking in the 1870s. Sporadic disturbance was also recorded in the 1960s and 1970s, particularly at CUS1. Small trees rooted above the horizon 2Bw of profile CUS1 were partially buried by a 35–40 cm thick colluvium layer (Fig. 6). Sampling at the root collar indicated that their establishment took place in the late 19th- early 20th century (minimum establishment date 1900, 1920, 1879, respectively; a dead tree which could not be cross-dated was at least 115 years old). The oldest tree ring sampled above the colluvium (i.e. at the present ground level) dated to 1960 and 1990. Trees rooted above the colluviums, although similar in dimension, were substantially younger (minimum establishment date 1976, 1977, 1961, respectively).

4. Discussion

4.1. Soil evolution

The data indicated the occurrence of a phase with strong pedogenesis which occurred at least up to 2000 m a.s.l. This phase affected only the lowermost unit of the profiles and led to the establishment of well-developed soils with clay illuviation along the profile indicating an intense brunification process (Duchaufour, 1994). The similarity of the horizons overtopping the lowermost unit (2Ab and, in some cases, 2Bw) with the superficial ones (A) confirmed the discontinuity between the two units and thus the occurrence of at least two phases subjected to different pedogenetic processes. The buried paleosurface described by previous authors in archaeological context (Bernini et al., 1978; Panizza et al., 1982) was thus confirmed and extended at much higher altitude, well above the present treeline.

The occurrence of a thick colluvium layer acting as parent material of the superficial unit is one of the most striking features of the profiles. This layer seems to result from successive events at least in some sites, as in profile CUS5, where distinct phases are separated by two stone lines, or profile CUS1, where a tree root collar, already positioned over a colluvium, is buried under further 35–40 cm of material. Pedorelicts moved along the slope with the colluvium. Given their microstructure and their clay abundance, similar to the buried B horizons, they were eroded from these soils and transported along the slope, falling into the open frost cracks (Van Vliet-Lanoë, 2010). Data suggest the deposition of large quantity of material in a relatively short period: the ancient A horizon with insect remains dating to 570 BP is buried under 70 cm of colluvium (site CUS6) and *Abies* charcoals from c. 700 BP lie under 50 cm (site CUS1).

Table 3
Charcoal concentration (mg kg^{-1}) calculated for the whole soil horizon (SAL) and for each taxon within the horizon (SAT).

Profile	CUS1	CUS1b	CUS2	CUS6	CUS6
Horizon	2Bw1	2Bw1	2Bw	2Ab	2Bw
Depth (cm)	60	60	30	70	80
SAL	1888	4829	4340	519	384
Abies alba	1532.85	4056.76	1598.43	149.94	108.45
Laburnum sp.	–	–	–	205.71	227.97
Fagus sylvatica	–	–	2426.74	–	–
Vaccinium sp.	–	79.73	–	109.38	–
Conifer	318.56	671.95	315.24	2.90	16.05
Hardwood	36.58	20.58	–	5.79	31.54
Vitrified	–	–	–	44.91	–

4.2. Environmental history

The B horizons of the lowermost unit share their stratigraphic position and their main characteristics (strong pedogenesis with clay illuviation) with those of the buried soil of the nearby archaeological site of Monte Bagioletto (~400 m E of the nearest profile) (Cremaschi et al., 1984). This unit is associated with archaeological findings resulting from human frequentation between Early and Mid-Holocene (Biagi et al., 1980; Cremaschi et al., 1984). The high degree of soil evolution indicates the occurrence of forest vegetation together with long-time slope stability. The data spatially extend this phase at least up to 2000 m, thus providing indirect evidence of its connection with a climatically favorable period.

The disappearing of the forest cover at highest altitude has been linked to the end of the climatic optimum (Cremaschi et al., 1984). However, analysis indicates the occurrence of woody species (*Abies alba* and *Laburnum*) at relatively high altitude (1765 m) after 4000 cal. BP. This may be supported by palynological data from Monte Bagioletto (Panizza et al., 1982) which showed the persistence of pollen of woody species (*Abies* and *Alnus*) at the bottom of the uppermost unit. This suggests a gradual opening of tree cover rather than its abrupt disappearance, but the temporal and spatial extent of this phase remains largely speculative.

The lowering of the forest limit to the present altitude probably took place at the beginning of Late Holocene when open forests (charcoal assemblage of the 2Bw horizon) were replaced by treed heathlands which gave origin to the 2Ab horizon. This replacement is indicated also in the pollen record of Monte Bagiolettoby high

Table 4
Insect macroremains and ecological traits of the observed species. Information about ecology comes from Osella (1988), Hurka (2005), Abbazzi and Maggini (2009).

Order	Family	Species	Head capsule	Pronotum	Leg segment	Elytra	Abdomen	Ecology
Coleoptera	*Aphodidae*	*Aphodius* sp.				24		Coprophagous species, linked to sheep and cattle pasture
Coleoptera	*Chrysomelidae*			1				Phytophagous and floricole species associated with shrub vegetation
Coleoptera	*Curculionidae*	*Barynotus liguricus* (Solari, 1943)	2	1	2		1	Poliphytophagous and mesophilous species, occurs from coastal environments to the limit of beech and conifer woods
Coleoptera	*Curculionidae*	*Barynotus obscurus* (Fabricius, 1775)	6	5		14 + 1 pair		Apterous species linked to secondary subalpine grasslands (*Nardetum alpigenum*), heavily grazed environments and trampled heatlands
Coleoptera	*Curculionidae*	*Otiorhynchus frescati* (Boheman, 1843)	12	6				Poliphytophagous and mesophilous species, linked to soil surface and soil fissures, occurs from coastal environments to the limit of deciduous forests
Coleoptera	*Curculionidae*	*Otiorhynchus griseopunctatus falteronae* (Pesarini, 1968)	1					Poliphytophagous and mesophilous species, linked to soil surface and woody vegetation, occurs from the upper limit of oak woods to the upper limit of beech or conifer woods
Coleoptera	*Curculionidae*	*Otiorhynchus* sp.	1		26			
Coleoptera	*Curculionidae*	*Pseudomeira parvula* (Seidlitz, 1866)					11 pairs	Poliphytophagous and termophilous species, occurs from coastal environments to the limit of oak woods
Hymenoptera	*Formicidae*	*Lasius* gr. *umbratus/flavus*	1					Lapidicolous species of open and humid environments or of deciduous forest edge
Hymenoptera	*Formicidae*							

values of *Vaccinium* (Panizza et al., 1982) and is coherent with regional pollen record, indicating strong deforestation due to human impact at the beginning of Late Holocene (Lowe et al., 1994; Vescovi et al., 2010b). Treed heathlands lasted until modern times. Insect assemblages confirmed the occurrence of open, grazed vegetation interspersed with shrubs and sparse trees, while at lower altitudes *Abies alba* dominated the forest vegetation. The ultimate disappearing of woody species above the present treeline occurred during modern times (from c. AD 1500 onwards).

More or less at the same time, below the treeline *Abies* was replaced as dominant species by *Fagus*. Charcoal assemblages dominated by fir date back to AD 1200, while still-living beech were established in the early 17th century. The decline of *Abies* and its replacement by *Fagus* occurred during the Mid-Late Holocene in the whole Northern Apennines (Watson, 1996; Vescovi et al., 2010a, 2010b) and on the Alpine chain (Gobet et al., 2000; Carcaillet and Muller, 2005), and are mainly regarded as a consequence of human-induced disturbance. According to the data, *Abies* seems to have kept a prominent role until very recent times, at least at local scale. This contrast with the pollen record from Monte Bagioletto, where the *Abies* maximum was observed within the buried B horizon, followed by a sharp decline (Panizza et al., 1982). However, the species is still present, although very scattered, in the study area and in the whole Apennine chain, where is locally abundant.

Diffuse slope instability occurred until the late 19th century and, with minor events, throughout the 20th century. The old soils were superficially eroded and buried. Locally, their superficial horizons were preserved below the colluvium layer. Below the treeline, trees were variously affected by such events. The timing of the instability phases resulting from the combination of soil, charcoal and tree ring evidence agrees with the general framework outlined by Panizza et al. (1982) and Cremaschi et al. (1984) from archaeological and historical evidence: increasing slope dynamicity during Late Holocene and onset of marked erosion from the 12th–13th century AD. Bertolini et al. (2004) reported high landslide activity in Northern Apennines at the Mid - Late Holocene boundary, and from the 16th century to present. Pollen data indicate the increase of human disturbance in the last 1000 years (Vescovi et al., 2010b), but this study's data, particularly those from tree rings, achieved greater resolution for the most recent events.

Afterwards, treeless vegetation was established on the newly exposed surface above the treeline, giving origin to the present poorly developed soils. Below the treeline, the forest was able to regenerate.

4.3. Treeline dynamics

At present, the abrupt treeline dominated by *Fagus sylvatica* is static, with no establishment of new individuals above the current limit. Analysis did not show any past occurrence of *Fagus* above the present treeline, suggesting long-term stability of the uppermost limit of beech forest. Furthermore, the overall charcoal abundance showed a marked decline in correspondence of the present treeline (Table 3), indicating that at least within the time span outlined by the radiocarbon dates (Late Holocene), no dense forest covered the slopes of Mt. Cusna above this limit. However, the degree of evolution of the buried soils suggests the previous occurrence of a stable, long lasting forest cover up to 2000 m, which left no traces within the charcoal

Table 5
Radiocarbon dates.

Sample	Altitude (m a.s.l.)	Depth (cm)	Context	Taxa	Age BP	Cal BP (2 sigma)	Method	Lab number
CUS1_Charcoals	1723	60	Natural	*Abies alba*	810 ± 40 BP	790–670 cal BP	AMS	Beta − 280565
CUS6_Insects	1765	70	Natural	Mixed	570 ± 30 BP	640–590 and 570–530 cal BP	AMS	Beta − 292530
CUS6_Charcoals	1765	80	Natural	*Laburnum* sp.	3540 ± 40 BP	3920–3700 cal BP	AMS	Beta − 257239

Fig. 6. Trees affected by slope instability. a) Beech trees partially buried by a colluvium layer at site CUS1: minimum age at root collar ranges between 90 and 130 years. b) Old upturned beech tree below site CUS1. The tree established before AD 1721 and lost its vertical growth in the late 1770s; the upright growth started in the 1890s.

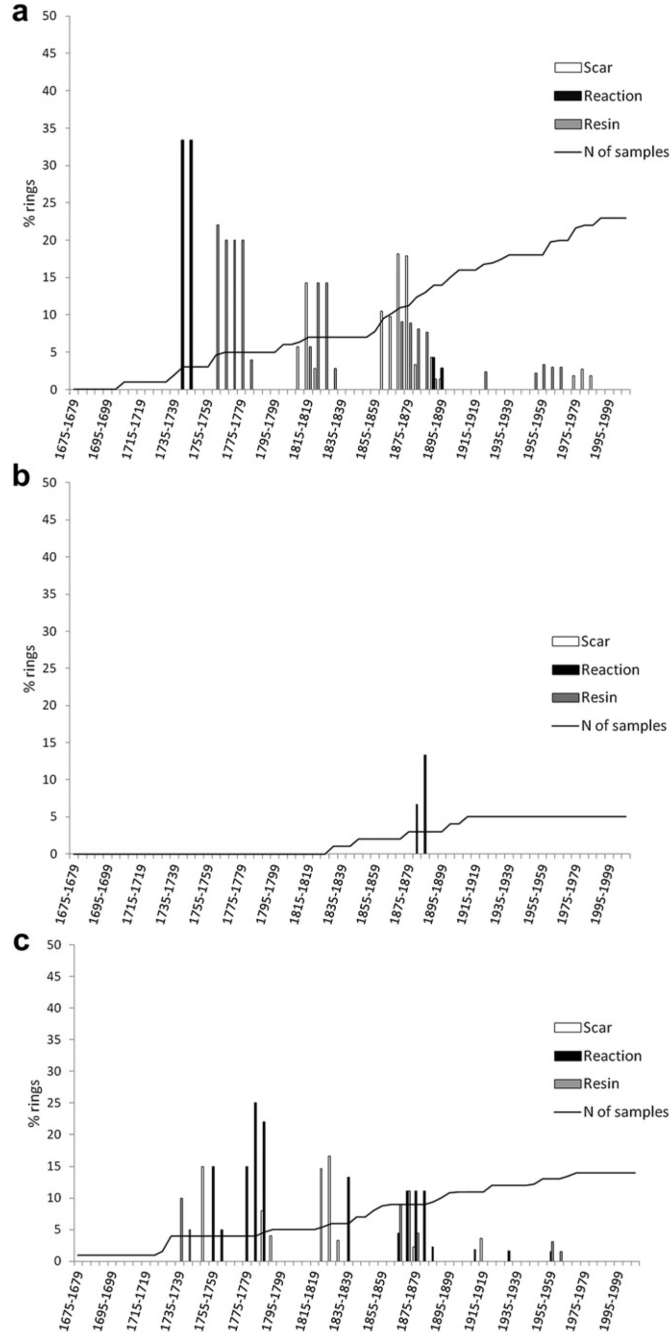

Fig. 7. Frequency of diagnostic tree rings at profiles CUS1 (panel a), CUS2 (b) and underlying slope (c). Reaction wood (Reaction), scars (Scar) and anomalous resin concentration (Resin) are reported. Data are arranged in 5-year intervals. Line indicates the number of samples for each time interval.

assemblages except for the archaeological sites. This forest could have been gradually opened because either of anthropic pressure and/or of climatic cooling. The lack of charcoals could indicate low importance of fire in this phase. However, soil anthracomass may depend on the intensity of the fire rather than on the woody biomass (Carnelli et al., 2004). The absence or the low occurrence of charcoal could thus be due to a low intensity fire regime.

The Holocene treeline fluctuation of c. 300 m outlined by the soil data is comparable with those observed on the Alps by many pedoanthracological studies (Tinner and Theurillat, 2003; Carnelli et al. 2004; Ali et al., 2005; Talon, 2010). However, unlike the Alpine treeline fluctuation, the uppermost position was probably marked by different species composition than that of the present treeline. Charcoal data together with the sporadic occurrence of *Fagus* in the oldest charcoal assemblages found in the archaeological site of Monte Bagioletto (only 5 fragments over 1004 in the lowermost unit, 95 over 879 in the overlying level, interpreted as a recent contamination; Cremaschi et al., 1984) exclude the occurrence of beech at the treeline during the Early-Mid Holocene. The species became abundant only more recently (3790 BP, Cremaschi et al., 1984) coherently with its regional pattern of Holocene distribution (Watson, 1996).

This evidence suggests that *Fagus* treelines never reached altitudes higher than at present, and could give paleoecological support to the hypothesis of Körner and Paulsen (2004) concerning a genus-specific upper boundary for *Fagus*, whose altitudinal distribution ends well below the thermal limits recognized for the treelines worldwide. This could have important implication for the future behavior of the Apennine treeline, even under a climate warming cycle.

5. Conclusions

This study outlined the complex interaction between climate, geomorphological processes, vegetation and man in shaping the environmental history of high altitude ecosystems. The complexity emphasizes the need for a multidisciplinary approach, particularly for areas subject to slope activity and lacking continuous sedimentological and paleobotanical record such as those provided by lake sediments or peat bogs. Soil data (both routine soil analyses and micromorphology) provided the general framework of the processes occurred in the area during the investigated period, thus filling the gaps due to the spatial and temporal discontinuity of the botanical, zoological and archeological records. Moreover, the integrated analysis of tree ring and sedimentological data gave very high resolution for the most recent time span, often overlooked by paleoenvironmental reconstructions.

The environmental history outlined by the data needs further investigations to outline the vegetation responsible for the development of the oldest soils and more AMS dates to obtain a higher temporal resolution. Sedimentological investigations could give further insight into the colluvial events. Historical and archaeological records should be also integrated with the evidence. However, the data indicated that the main events which shaped the high altitude landscape of the Northern Apennines took place throughout the whole Holocene until very recent times.

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Appendix 1. Soil analyses.

Soil profile	Horizon	Depth (cm)	Munsell color	Skeleton >2 mm (%)	Sand (%)	Silt (%)	Clay (%)	pH (H_2O)	Org. C (g/kg)
CUS1	A1	0–5	10 YR 5/3	2.19	6.85	56.73	34.23	5.8	21.39
	A2	5–14	10 YR 5/4	1.89	4.91	57.88	35.32	5.4	14.05
	AB	14–34	10 YR 5/3	2.10	23.50	46.01	28.39	5.6	14.05
	2Bw	34–50	10 YR 5/3	1.52	4.92	59.09	34.47	5.1	12.04
	3Bw1	50–65	10 YR 4/4	1.12	3.96	52.41	42.52	4.7	24.75
	3Bw2	65–78	10 YR 4/6	0.38	1.99	48.81	48.81	5.0	15.28
	3Btg	78–95	10 YR 4/6	0.98	23.76	40.60	34.66	4.6	14.05
	3BC1	95–117	10 YR 4/4	3.24	10.64	53.22	32.90	4.9	3.82
	3BC2	117 170+	10 YR 4/4	5.37	47.31	26.50	20.82	4.9	3.82
CUS2	AC	0–26	10 YR 4/2	3.00	16.49	52.38	28.13	5.5	20.63
	2B	26–50	7.5 YR 4/4	0.14	2.00	39.94	57.92	4.7	20.63
	2BC	50–75	7.5 YR 4/3	1.11	4.94	53.40	40.54	5.0	6.88
CUS3	O	0–7							
	A1	7–12	7.5 YR 4/3	10.78	29.44	42.83	16.95	4.8	24.09
	A2	12–35	7.5 YR 5/3	6.33	45.90	40.28	7.49	4.8	11.29
	AB	35–50	7.5 YR 4/4	4.69	46.70	36.22	12.39	4.8	13.50
	2Ab	50–53	7.5 YR 2/3	1.24	14.81	54.32	29.63	4.4	53.45
	2Bw	53–65	7.5 YR 4/4	4.43	34.41	40.14	21.03	4.5	29.36
	2Bt	65–85	7.5 YR 4/4	23.49	21.42	33.66	21.42	4.7	11.29
	2CBg	85 100+	7.5 YR 3/3	12.11	58.89	24.61	4.39	4.9	6.02
CUS4	O	0–5							
	A	5–50	7.5 YR 2.5/2	15.37	32.16	38.93	15.23	4.6	44.75
	AB	50–110	10 YR 3/2	6.43	30.88	37.43	25.26	6.5	7.72
	2Bt1	110–140	10 YR 3/4	1.73	8.84	48.15	41.27	5.9	22.37
	2Bt2	140–150	7.5 YR 3/4	1.95	8.82	49.03	40.20	6.0	14.66
	2Bt3	150–180	7.5 YR 4/4	2.13	8.81	48.94	40.13	5.8	10.03
	2BC	180–200+	10 YR 4/3	7.76	13.84	46.12	32.28	5.9	3.86
CUS5	O	0–2							
	A	2–12	10 YR 3/3	3.56	59.79	25.07	11.57	5.3	29.50
	AB	12–20	2.5Y 4/2	3.02	61.10	24.25	11.64	5.3	23.45
	B	20–33	2.5Y 3/3	7.37	50.95	25.01	16.67	5.2	19.67
	BC	33–42	2.5Y 3/3	19.35	55.65	16.94	8.07	5.2	17.40
	2B1	42–55	2.5Y 3/3	5.92	45.16	30.11	18.82	5.2	17.40
	2B2	55–75	2.5Y 3/3	4.80	44.74	32.37	18.09	5.2	16.64
	3Bw	75–85	10 YR 3/3	1.53	27.57	35.45	35.45	4.9	52.96
	3BC	85–102	10 YR 3/4	30.46	23.64	37.55	8.34	4.9	25.72
	3CB	102 110+	10 YR 3/6	55.92	15.87	20.72	7.49	5.1	18.16
CUS6	O	0–3							
	A1	3–12	7.5 YR 4/3	1.25	9.88	79.99	18.76	5.5	46.06
	A2	12–30	10 YR 3/4	1.14	8.90	56.35	33.61	5.0	16.89
	AB	30–45	7.5 YR 4/4	2.09	5.87	56.79	35.25	4.8	13.05
	BA	45–64	10 YR 2/2	2.14	6.85	56.76	34.25	4.6	13.82
	2Ab	64–71	7.5 YR 4/6	1.10	11.87	42.53	44.51	3.9	110.55
	2Bt	71–82	10 YR 4/4	1.24	7.90	43.45	47.40	4.2	29.94
	2BC	82 94+	10 YR 4/4	2.39	5.86	47.83	43.92	4.6	15.35

(*continued on next page*)

(*continued*)

Soil profile	Horizon	Depth (cm)	Munsell color	Skeleton >2 mm (%)	Sand (%)	Silt (%)	Clay (%)	pH (H_2O)	Org. C (g/kg)
CUS7	A	0–21	10 YR 4/2	13.23	16.49	46.86	23.43	6.0	25.33
	AB	21–32	10 YR 4/2	4.88	12.37	53.27	29.49	5.7	21.50
	BC	32–40	10 YR 4/3	4.58	4.77	54.39	36.26	5.4	27.64
	2Bt1	40–45	10 YR 4/3	0.24	5.99	49.88	43.89	5.2	39.15
	2Bt2	45–55	10 YR 4/4	0.70	7.94	47.66	43.69	5.3	36.08
	2Bt3	55–85	10 YR 4/4	2.16	2.94	57.73	37.18	5.4	17.66
	2BtC	85–102	2.5 YR 5/4	4.76	6.67	58.10	30.48	5.4	4.61
	2C	102+							
CUS8	A	0–20	10 YR 3/2	1.81	9.82	56.95	31.42	7.1	32.97
	BC1	20–50	10 YR 3/2	2.87	11.66	69.93	15.54	6.9	13.89
	BC2	50–78	10 YR 4/4	3.19	12.59	57.12	27.11	6.7	20.83
	2Bt	78 120+	10 YR 4/3	4.25	14.36	47.88	33.51	6.7	13.12
CUS9	O	0–4							
	A1	4–8	7.5 YR 4/3	4.96	48.47	32.31	14.26	4.3	47.78
	A2	8–15	7.5 YR 4/3	2.12	38.17	41.11	18.60	4.3	51.46
	AB	15–18	10 YR 4/4	27.39	36.31	23.96	12.34	4.2	52.19
	2Ab	18–22	5 YR 2/2	0.88	30.73	43.61	24.78	4.2	82.33
	2Bw1	22–28	7.5 YR 3/3	2.56	31.18	39.95	26.31	4.4	38.23
	2Bw2	28–38	7.5 YR 4/6	1.11	48.46	46.48	3.96	4.3	31.62
	2Bw3	38–55	10 YR 4/6	13.05	39.13	40.00	7.83	4.7	14.30
	2BC	55–70	10 YR 5/4	27.75	35.40	28.18	8.67	4.9	9.79
	2CB	70 105+	10 YR 6/4	32.61	41.11	19.54	6.74	5.0	7.53

Appendix 2. Micromorphological features of the analyzed thin sections. Fine material: clay and fine silt; l.p.: lower part; u.p.: upper part; abundance: very dominant: >70%; dominant: 50–70%; frequent: 30–50%; common: 15–30; few: 5–15%; very few: <5%.

Sample	CUS1 AB (23–33 cm)	CUS1 2Bw (39–49 cm)	CUS1 3Bw1–3Bw2 (59–69 cm)
Microstructure	Complex, granular/subangular blocky	Complex, granular/subangular blocky	Complex, subangular blocky/channel
Aggregates	Granular	Granular, subangular blocky	Subangular blocky
Porosity	Frequent vughs	Frequent vughs	Very few
c/f limit - c/f ratio	10 μm–50/50	10 μm–20/80	5 μm–25/75
c/f related distribution	Close porphyric	Double-spaced porphyric	Single-spaced porphyric
Mineral fragments	Common subrounded claystones	Few rounded claystones and subrounded sandstones	Frequent rounded claystones
Fine material	Grey-brownish speckled	Yellowish-brown speckled-cloudy	Reddish-brown cloudy
b-Fabric	Stipple speckled, yellowish-grey	Stipple speckled (locally grano-porostriated), yellowish-grey	Stipple speckled and grano-porostriated (locally striated), reddish-brown
Vegetal material	Very few plant residues (roots)	Very few plant residues (roots) and charcoals	Very few plant residues (roots)
Pedofeatures	Very few alteromorphic black-reddish and typic nodules of Fe-Mn; few matrix infillings	Very few alteromorphic black-reddish and typic nodules of Fe-Mn; few matrix infillings	Very few alteromorphic black-reddish and typic nodules of Fe-Mn; very few clay coatings and coalescent excrements
	CUS1 3Btg (85–95 cm)	CUS1 3BC1 (105–115 cm)	CUS1 3BC2 (158–168 cm)
Microstructure	Subangular blocky	Channel	Intergrain micro aggregates
Aggregates	Very dominant subangular blocky	Very dominant subangular blocky	Very few granular
Porosity	Few – very few	Few – very few	Common complex packing voids
c/f limit - c/f ratio	5 μm–15/85	5 μm–25/75	5 μm–80/20
c/f related distribution	Open porphyric	Double-spaced porphyric	Fine close enaulic
Mineral fragments	Few subrounded claystones and sandstones	Few (locally frequent) rounded claystones and subrounded sandstones	Common subangular-rounded claystones
Fine material	Brown (yellowish in the u.p.) speckled-cloudy	Reddish-brown cloudy	Yellowish-brown, cloudy (grey in the upper part)
b-Fabric	Stipple speckled, reddish-brown (locally striated, yellowish-grey in the u.p.)	Stipple speckled, yellowish-grey	Stipple speckled, yellowish-grey (grey in the u.p.)
Vegetal material	Very few plant residues (roots)	Very few plant residues (roots)	Very few plant residues (roots)
Pedofeatures	Very few alteromorphic black-reddish and typic nodules of Fe-Mn; very few clay infillings-crescents, depletion coatings and matrix infillings	Very few alteromorphic black-reddish and typic nodules of Fe-Mn; very few clay infillings-crescents and matrix infillings	Very few typic nodules of Fe-Mn; very few clay coatings; few matrix infillings

	CUS3 AB-2Ab (45–55 cm)	CUS3 2Bw (55–65 cm)	CUS3 2Bt (68–78 cm)
Microstructure	Primary granular, secondary angular blocky	Complex, granular/subangular blocky	Subangular blocky
Aggregates	Dominant-common granular, dominant angular blocky	Dominant subangular blocky, common granular	Dominant subangular blocky
Porosity	Common complex packing voids	Frequent complex packing voids	Frequent linear planar voids
c/f limit - c/f ratio	5 μm–10/90 (40/60 in the u.p., locally up to 70/30)	5 μm–10/90	10 μm–20/80
c/f related distribution	Open porphyric (fine open enaulic in the u.p.)	Open porphyric	Open porphyric
Mineral fragments	Frequent subrounded claystones	Very few rounded claystones and sandstones	Few rounded claystones
Fine material	Brown speckled (brown-yellowish in the l.p.)	Reddish-brown cloudy	Reddish-brown cloudy
b-Fabric	Stipple speckled, brown-yellowish brown (stipple speckled greyish-dark reddish in the l.p.)	Stipple speckled and grano-porostriated, reddish-brown	Striated and grano-porostriated, reddish-brown
Vegetal material	Very few plant residues (roots) and charcoals	Very few plant residues (roots) and charcoals	Very few charcoals
Pedofeatures	Very few alteromorphic black-reddish and typic nodules of Fe-Mn; very few discontinuous fabric infillings and fabric hypocoatings	Very few alteromorphic black-reddish and typic nodules of Fe-Mn; one clay infilling; frequent matrix infillings	Very few alteromorphic black-reddish and typic nodules of Fe-Mn; very few clay coatings-infillings and fabric hypocoatings; few matrix infillings
	CUS4 A (37–47 cm)	CUS4 2Bt1-2Bt2 (134–144 cm)	CUS4 2Bt3 (152–162 cm)
Microstructure	Intergrain microaggregates	Complex, vughy/channel (channel in the l.p.)	Complex, subangular blocky/channel
Aggregates	Few granular	Very dominant subangular blocky	Very dominant subangular blocky
Porosity	Dominant complex packing voids	Few – very few	Few – very few
c/f limit - c/f ratio	10 μm–75/25	5 μm–25/75 (10/90 in the lower part)	5 μm–15/85
c/f related distribution	Fine close enaulic	Double-spaced porphyric (open porphyric in the l.p.)	Open porphyric
Mineral fragments	Frequent subangular claystones and sandstones	Few rounded claystones	Few subangular-subrounded claystones
Fine material	Brown speckled	Reddish-brown cloudy	Reddish-brown (yellowish-brown in the l.p.) cloudy
b-Fabric	Stipple speckled, dark brown	Stipple speckled and porostriated, reddish-brown (mozaic speckled and grano-porostriated, yellowish-brown in the lower part)	Striated and grano-porostriated, reddish-brown (mozaic speckled and grano-porostriated, yellowish-brown in the lower part)
Vegetal material	Very few plant residues (roots)	Very few partially burned wood fragments	Very few partially burned wood fragments
Pedofeatures	Very few typic nodules of Fe-Mn; one fragmented clay infilling; very few depletion coatings and matrix infillings	Very few alteromorphic black-reddish and typic nodules of Fe-Mn; very few clay coatings-crescents and fabric hypocoatings; few matrix infillings	Very few alteromorphic black-reddish and typic nodules of Fe-Mn; very few clay coatings-crescents and fabric hypocoatings; few matrix infillings
	CUS6 BA (50–60 cm)	CUS6 2Ab (62–72 cm)	CUS6 2Bt-2BC (75–85 cm)
Microstructure	Granular	Granular	Complex, subangular blocky/channel
Aggregates	Dominant granular	Very dominant granular	Dominant blocky, frequent granular
Porosity	Common complex packing voids	Frequent complex packing voids	Few - very few
c/f limit - c/f ratio	10 μm–40/60	5 μm–5/95	5 μm–5/95
c/f related distribution	Fine single-spaced enaulic, locally double-spaced porphyric	Open enaulic	Open porphyric
Mineral fragments	Frequent subrounded claystones	Very few rounded claystones and sandstones	Very few rounded claystones and subangular sandstones
Fine material	Brown opaque	Brown-reddish speckled	Brown-yellowish speckled (yellowish cloudy in the lower part)
b-Fabric	Stipple speckled, locally granostriated, brown-reddish	Stipple speckled, grey	Stipple speckled and grano-porostriated, brown-yellowish brown (stipple speckled, striated-granostriated, yellowish-greyish in the l.p.)
Vegetal material	Very few plant residues (roots)	Very few plant residues (roots) and charcoals	Very few charcoals
Pedofeatures	Very few alteromorphic black-reddish and typic nodules of Fe-Mn; very few fragmented clay infillings and fabric hypocoatings; frequent matrix infillings	Very few alteromorphic black-reddish and typic nodules of Fe-Mn; very few matrix infillings	Very few alteromorphic black-reddish and typic nodules of Fe-Mn; very few typic clay and silt coatings and matrix infillings
	CUS7 2Bt1-2Bt2 (40–50 cm)	CUS7 2Bt3-2BtC (75–85 cm)	CUS8 2Bt (95–105 cm)
Microstructure	Complex, granular/subangular blocky	Subangular blocky in the upper part, channel in the lower part	Channel
Aggregates	Dominant granular, frequent subangular blocky	Very dominant subangular blocky	Very dominant subangular blocky
Porosity	Dominant complex packing voids	Few – very few	Few – very few
c/f limit - c/f ratio	5 μm – 10/90	5 μm–5/95 (30/70 in the upper part)	5 μm–10/90
c/f related distribution	Open porphyric	Open porphyric (double-spaced in the l. p.)	Open porphyric
Mineral fragments	Very few subrounded claystones and sandstones	Common subangular-subrounded sandstones	Very few subrounded claystones and sandstones
Fine material	Reddish-brown speckled-cloudy	Yellowish-brown (greyish in the l.p.) cloudy	Yellowish-brown opaque
b-Fabric	Stipple speckled (locally striated in the l.p.), reddish-grey	Crosstriated and grano-porostriated, yellowish-grey	Striated and grano-porostriated, dark yellowish-grey

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(*continued*)

Vegetal material	Very few plant residues (roots)		
Pedofeatures	Very few alteromorphic black-reddish and typic nodules of Fe-Mn; very few clay infillings; few matrix infillings	Very few alteromorphic black-reddish and typic nodules of Fe-Mn; very few clay infillings and clay crescent; very few fabric hypocoatings; few matrix infillings	Very few alteromorphic black-reddish and typic nodules of Fe-Mn; very few silt-clay coatings, clay coatings and fabric hypocoatings; few matrix infillings
	CUS9 2Ab-2Bw1 (17–27 cm)	CUS9 2Bw2 (27–37 cm)	CUS9 2BC-2CB (65–75 cm)
Microstructure	Primary granular, secondary subangular blocky	Complex, pellicular-intergrain microaggregate	Pellicular (subangular blocky the u.p.)
Aggregates	Dominant granular, locally subangular blocky; secondary subangular blocky	Common crumbs, frequent granular	Very dominant subangular blocky
Porosity	Few – very few	Common complex packing voids	Common complex packing voids
c/f limit - c/f ratio	5 μm–40/60	5 μm–60/40	5 μm–75/25 (25/75 in the u.p.)
c/f related distribution	Fine double-spaced enaulic	Chitonic/fine double-spaced enaulic	Chitonic/gefuric (double-spaced porphyric in the u.p.)
Mineral fragments	Few rounded claystones	Frequent euhedral unaltered quartz grains	Dominant subangular sandstones
Fine material	Yellowish-brown speckled	Grayish-brown stipple speckled	Grayish-brown speckled
b-Fabric	Stipple speckled, brown	Granostriated, grey	Granostriated, grey
Vegetal material	Very few plant residues (roots)		
Pedofeatures	Very few alteromorphic black-reddish and typic nodules of Fe-Mn; very few fabric hypocoatings	Very few alteromorphic black-reddish and typic nodules of Fe-Mn	Very few alteromorphic black-reddish and typic nodules of Fe-Mn

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