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Wildfire history and fire ecology of the Swiss National Park (Central Alps): new evidence from charcoal, pollen and plant macrofossils

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Abstract: Microscopic (> 10 μm) and macroscopic (> 200 μm) charcoal particles were analysed in sediments from two mires in subalpine coniferous forests at *c.* 1800 m a.s.l. in southeastern Switzerland. Pollen and plant macrofossils suggest that since 6000 BC, *Pinus mugo* ssp. *uncinata* (DC) Domin ('upright mountain pine') has mostly been the dominant tree species at one of the study sites (Il Fuorn). In contrast, forests dominated by *Picea abies* (Norway spruce) have formed the vegetation since *c.* 4000 BC around the mire 'Fuldera-Palü Lunga'. Mean fire-return intervals (MFI) varied from 250 to > 600 years, depending on forest type, climate and land use. In mountain-pine forests (Il Fuorn), local fires occurred approximately every 250 years, even before the region was agriculturally used (ie, before 3600 BC). About 2000 years ago, intensified human impact as documented by the pollen record resulted in increased fire activity at Fuldera. Post-fire vegetation dynamics suggest that the mountain-pine stands at Il Fuorn had a moderate fire regime with a mix of surface and crown fires. In alpine ecosystems, the impact of fire is generally overshadowed by other disturbance factors such as windthrow, landslides, fungal decay and by climate changes or human land use. Nevertheless, our results show for the first time that natural wildfires exerted a major control on the subalpine coniferous forest ecosystems of the Swiss National Park and its neighbouring areas, eg, by contributing to maintain *Pinus mugo* ssp. *uncinata* forests throughout the mid and late Holocene.

Key words: Charcoal analysis, macroscopic charcoal, fire history, fire intervals, central Alps, *Pinus mugo* ssp. *uncinata*, mountain pine, Holocene.

Introduction

Although park legislation (Nationalparkgesetz, 1980) protects all natural processes within the borders of the Swiss National Park (SNP), all fires are suppressed at present, regardless of whether they are natural or human induced. Knowledge of fire and its long-term role in this landscape is lacking. In Central Europe, wildfire still receives very little attention in both nature conservation and management, and its potential managerial benefits are generally disregarded, eg, the fact that low-intensity surface fires prevent severe crown fires by burning dead wood and create disturbed areas where pioneer species can sprout. In this regard, knowledge of fire history can help the design of a future management plan for the SNP that allows for certain naturally caused fires (Allgöwer *et al.*, 2003).

The SNP is located in one of the driest regions of the Alps, the Engadine Valley (Canton of Grisons). Only 900 mm of precipitation per year are measured at the meteorological station of Buffalora (1970 m a.s.l.) in the Fuorn Valley by the meteorological service MeteoSwiss. The climatic setting, together with the extensive mountain-pine forests (*Pinus mugo* ssp. *uncinata* (DC) Domin), on the SNP area is one of the most wildfires-susceptible regions in Switzerland. This was shown by the elaboration of area-specific fuel models (Allgöwer *et al.*,

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1998), by statistical evaluation of twentieth-century fires (Langhart *et al.*, 1998) and by fuel investigations (Allgöwer and Gleason, 2001). In fact, both within and close to the SNP some severe, stand-replacing forest fires have even occurred in the past century due both to lightning and human negligence (eg, 1951 at Il Fuorn, 1964 at Ova Spin or 1983 above Müstair).

Holocene fire-history studies have contributed to the understanding of fire regimes and ecosystem interrelations in both North America (eg, Patterson *et al.*, 1987; Clark, 1988b; Mohr *et al.*, 2000) and Northern Europe (eg, Bradshaw *et al.*, 1997; Pitkänen *et al.*, 2002). However, in our study area we lack a detailed knowledge of fire history. Charcoal records from the Alps have been examined in a few previous studies, but these projects were either located outside the Central Alps (Berli *et al.*, 1994; Carcaillet, 1998; Tinner *et al.*, 1999) or did not focus on fire-interval reconstruction (Wick and Tinner, 1997; Gobet *et al.*, 2003).

So far the vegetation history of the SNP area has been based on pollen analysis alone (Welten, 1982; Zoller *et al.*, 1996). This has restricted the interpretation of the palaeovegetational data. In contrast, the macrofossil data from this study enable us first to obtain information on the local vegetation history at the coring sites (Birks and Birks, 2000) and second to distinguish the remains of *Pinus mugo* ssp. *uncinata* (mountain pine) and *Pinus sylvestris* (Scots pine).

Our main aim was to estimate natural fire-return intervals in the SNP area. Further, this paper deals with the following questions. (1) How is fire activity connected with human activities, climate and the existing forest type? (2) Which species profit from fires, and which are inhibited? (3) What vegetation can be considered as natural on the basis of the palaeovegetational records in the central SNP area?

Taxonomic nomenclature in this paper follows Lauber and Wagner (1996), who propose '*Pinus mugo* ssp. *uncinata* (DC) Domin' ('upright mountain pine' and the synonyms *P. montana* Miller ssp. *arborea*, *P. montana* grex *arborea* (Zoller, 1995) and *P. uncinata* Miller ex Mirbel).

Material and methods

The coring sites

Two small mires in southeastern Switzerland were cored (Figure 1), both of which cover an area of approximately 10 m × 10 m. Il Fuorn (1805 m a.s.l.) lies in the Fuorn Valley and is referred to as the only boggy location in the whole park area (Welten, 1982). It is surrounded by the largest *Pinus mugo* ssp. *uncinata* stands of the Alps, which are intermingled with few *Pinus cembra* (Swiss stone pine) and *Larix decidua* (European larch) (Zoller, 1995). The second mire (Fuldera-Palü Lunga, 1822 m a.s.l.) is situated on the southern slope of the Müstair Valley. This slope is covered by *Picea abies* (Norway spruce) forests with sparse *Larix decidua*, *Pinus mugo* ssp. *uncinata* and *Pinus cembra* (Zoller, 1995).

Coring and sediments

The cores were taken in September 2002 with a Steif modification of the Livingstone piston corer (Merkt and Streif, 1970). At Il Fuorn, a core of 255 cm length was taken. The sediment consisted of peat in the upper part of the core (< 55 cm) and peaty gyttja beneath. However, the organic sediment is interrupted by gravel layers at 68 to 88 cm, 110 to 145 cm and below 205 cm depth. The core from Fuldera was 215 cm long and comprised a continuous peat body that extended from the top to gravel at 150 cm depth. To investigate fire and vegetation history, only samples of the organic sediment layers (peat and gyttia) were analysed.

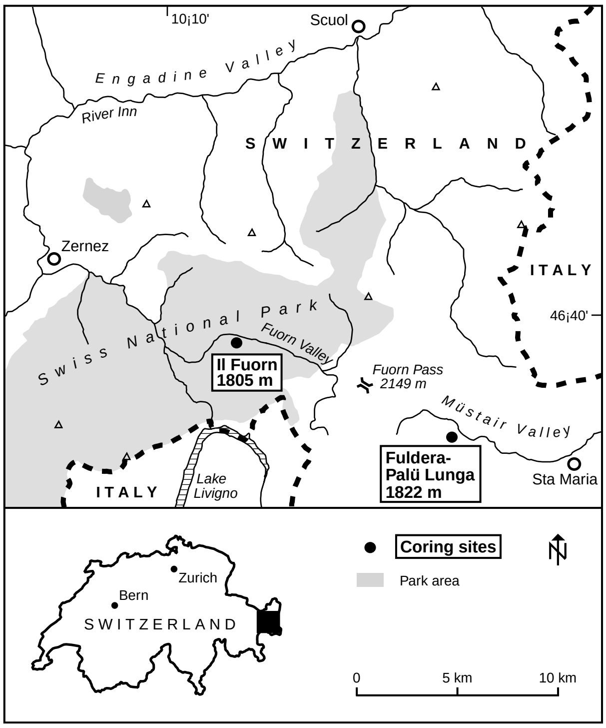

Figure 1 Map of the study area in southeastern Switzerland

Pollen

Sediment cubes of 1 cm^3 were retrieved from every sixth centimetre of the core sections containing organic sediment and from every centimetre between 180 and 190 cm depth from Il Fuorn. Four extra samples from Fuldera (82, 86, 112 and 116 cm depth) were also taken. The samples were treated physically by sieving (at 250 μm) and decanting, as well as chemically (HCl, KOH, HF, Acetolysis), following standard procedures of Bennett and Willis (2001). The residue was stained with fuchsin, mounted in glycerin jelly and analysed at ×400 magnification. Exotic markers were added in order to calculate charcoal, pollen and extrafossil concentration according to Stockmarr (1971). Pollen and spores were identified with the key of Moore *et al.* (1991) and the atlas of Reille (1992, 1995). Numerical zonation was performed with the ZONE program using the method of optimal partitioning (Birks and Gordon, 1985). The determination of statistically significant zone boundaries is based on the 'broken stick model' (Bennett, 1996).

Plant macrofossils

To allow for the analysis of both plant macrofossil and macroscopic charcoal, the sediment was cut into 1-cm-thick slices (10 cm^3) and washed through a sieve with mesh of 200 μm. Botanical remains were identified with the aid of reference material from the Institute of Plant Sciences and the Botanical Garden at the University of Bern and keys by Godet (1983, 1998), Schoch *et al.* (1988), Lévesque *et al.* (1988), Tobolski (1992), and Latalowa (1999). Cross-sections of individual *Pinus* needles were prepared in order to distinguish *Pinus mugo* from *Pinus sylvestris*. According to Zoller (1981), the height/width ratio of epidermis cells in the majority of cases is > 2 for *P. mugo*, but only between 1 and 2 for *P. sylvestris*.

Microscopic charcoal

Charcoal particles longer than 10 μm were counted in all pollen slides with a light microscope at 400 × magnification. Only black, completely opaque and sharp-edged fragments were classified as charcoal (Clark, 1988b; Tinner *et al.*, 1998).

Table 1 AMS-radiocarbon dates from Il Fuorn (Il) and Fuldera (Fu) measured by Ångström Laboratories, Uppsala, Sweden

Sample depth (cm)	Lab code	Conventional ^{14}C age (years BP uncal.)	Calibrated age (calendar year)	2-sigma range (95%)
40 (Il)	Ua-20596	2380 ± 45	404 BC	758–385 BC
89 (Il)	Ua-20597	3910 ± 50	2429 BC	2559–2205 BC
104 (Il)	Ua-20598	4240 ± 50	2882 BC	2918–2676 BC
151 (Il)	Ua-21742	5305 ± 70	4139 BC	4330–3969 BC
173 (Il)	Ua-20599	5875 ± 100	4748 BC	4957–4464 BC
198 (Il)	Ua-20600	7045 ± 70	5946 BC	6051–5739 BC
48 (Fu)	Ua-21740	1035 ± 35	AD 995	AD 897–1025
106 (Fu)	Ua-21741	4150 ± 40	2767 BC	2881–2579 BC
147 (Fu)	Ua-20601	5090 ± 50	3942 BC	3980–3770 BC

The counting of each sample involved a minimum of 30 charcoal particles and 100 *Lycopodium* spores or *vice versa*.

Macroscopic charcoal

Along with the plant macrofossils, charcoal particles larger than 200 μm in diameter were counted with a binocular microscope at 6 × to 50 × magnification. The surface area of each particle was determined with the ruler of the microscope objective. Charcoal selection was restricted to completely black, glittery fragments that would collapse if touched with tweezers. Further, particles with a length/width ratio larger than 3 were excluded from the analysis as they are more likely to originate from burned grass than from burned wood (Umbanhowar and McGrath, 1998).

Although single pieces of charcoal can be transported over long distances (> 1 km), particles longer than 200 μm are largely deposited in the vicinity of a fire. Therefore macroscopic charcoal provides a record of local fires, whereas regional fire history can be derived from microscopic particles (Clark, 1988a; Whitlock and Larsen, 2001; Carcaillet *et al.*, 2001). To allow for fire-event dating, the macroscopic record was counted in contiguous samples.

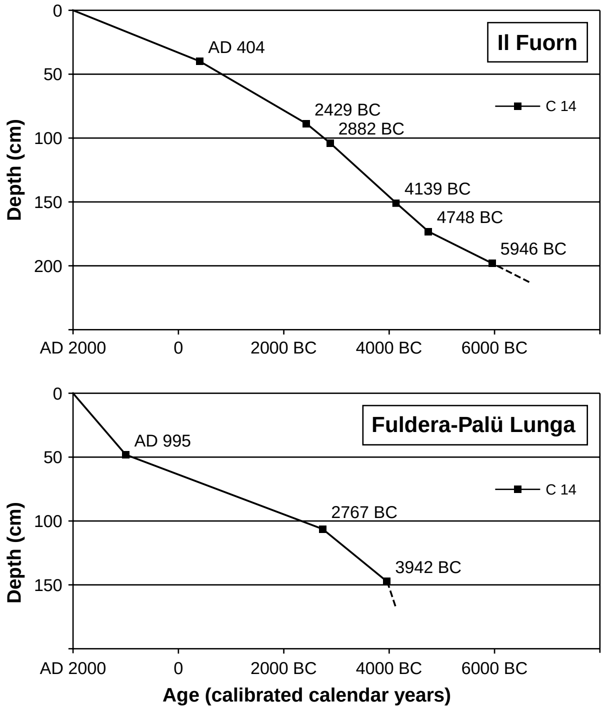

Figure 2 Depth–age models of the sediments from Il Fuorn and Fuldera

Estimation of fire-return intervals

According to Whitlock and Larsen (2001), we drew a distinction between primary charcoal, which is deposited during or shortly after a local fire, and secondary charcoal, which originates from distant fires or from sediment-mixing. In order to eliminate the effect of secondary charcoal, the macroscopic charcoal influx (mm^2/m^2 per yr) was smoothed with a locally weighted regression model (Lowess; span = 10%; see Tinner *et al.*, 1998). The smoothed values were then subtracted from the raw figures to isolate positive residual peaks, which are assumed to represent local fire events (Long *et al.*, 1998; Lynch *et al.*, 2004). Fire-return intervals are the time between two adjacent peaks. However, only peaks with a charcoal concentration of > 3 mm^2/10 cm^3 were identified as fire events regardless of their residual values.

Mean fire-return intervals (MFI) usually result from averaging individual intervals. Slightly different from the common definition (eg, Whitlock and Larsen, 2001), MFI were here calculated as the number of years covered by a sediment section divided by the number of fire events that occurred during the respective time span. In this manner, fire-free periods at the beginning or at the end of every sediment section are also taken into account in the analysis.

Chronology

Core chronologies for Il Fuorn and Fuldera were based on six and three AMS radiocarbon dates, respectively (Table 1). Wooden twigs with remaining bark fragments were selected for dating because bark remains generally do not persist long before being sedimented (Oswald *et al.*, 2005). Radiocarbon dates were calibrated to calendar years (BC/AD) using Calib 4.3 (Stuiver *et al.*, 1998). If several dates resulted from the calibration, the average value was chosen for the depth–age models. Linear interpolation or extrapolation was used to assign ages both between the dated layers and under the lowest dated depths. The depth–age curves turned out to decrease steadily (Figure 2). Within the gravel layers of the Il Fuorn core, the dates remain uncertain, as such gravel is not likely to have been deposited continuously. However, this limitation is without consequence, as the results of this study are based only on sediment sections with organic matter.

Results and interpretation

Vegetation history of Il Fuorn

The pollen records suggest that *Pinus* was usually the dominant tree in the forests around Il Fuorn (Figure 3). Although we did not differentiate pollen of *Pinus mugo* and *Pinus sylvestris*, we assume that the vast majority of *Pinus* pollen (*P. mugo*-type) in the core from Il Fuorn originates from *P. mugo* because (1) all *Pinus* needles selected for cross-sections

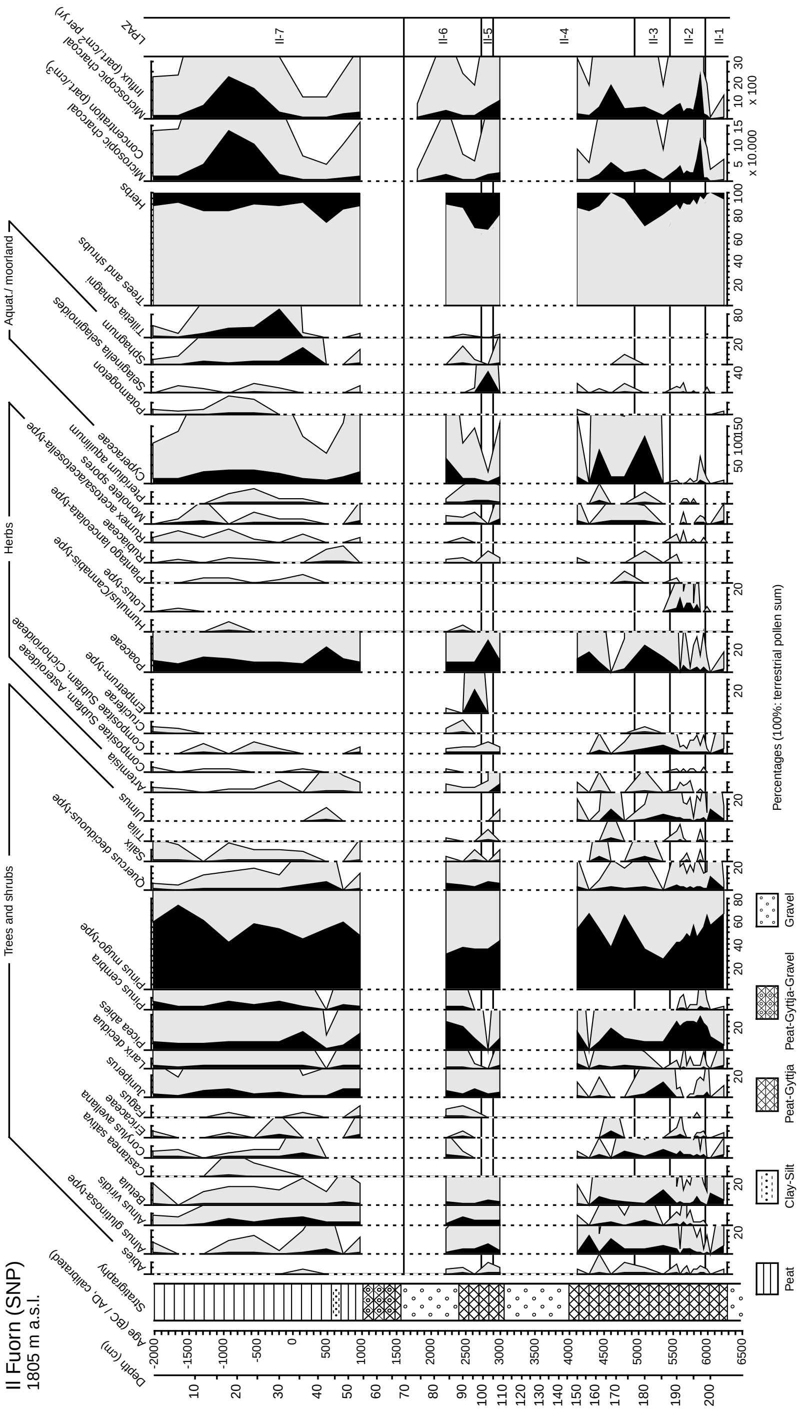

Figure 3 Diagram showing pollen percentages of selected taxa as well as microscopic charcoal concentration and influx for Il Fuorn. Analysis: W. Finsinger (pollen), M. Stähli (charcoal)

were identified as *P. mugo*, (2) because *P. mugo* ssp. *uncinata* is today dominant in the forests around Il Fuorn, and (3) in southeastern Switzerland *P. mugo* is known to grow preferentially on calcareous bedrock (Zoller, 1995), which can be found in the surroundings of Il Fuorn (dolomite). Mountain-pine forests were intermingled with varying amounts of *Picea abies*, *Larix decidua* and *Pinus cembra*. However, *Picea abies*-dominated forests temporarily replaced them.

The pollen stratigraphy was split up into seven local pollen assemblage zones (LPAZ) that showed statistically significant differences. In the 34 samples, a total of 66 pollen and spore types from terrestrial plants, five pollen and spore types from aquatic and moorland plants and three ferns were identified.

LPAZ Il-1 (204–198.5 cm, 6230–5970 BC) reveals a *Pinus mugo*-dominated community, as *Pinus mugo*-type pollen accounts for more than 60% of the terrestrial pollen sum. Thus, *Pinus mugo* was widespread, even though its pollen is usually over-represented in pollen assemblages (Lang, 1994; Burga and Perret, 1998). Mountain-pine stands were mixed with *Picea abies* (*Picea* pollen increases form 3% to 20% in the course of this zone) and *Larix decidua* (*Larix* pollen reaches 4%). *Pinus mugo*-type periderm fragments (*P. mugo*/*P. sylvestris*) confirm the existence of pine-dominated forests (Figure 4).

During LPAZ Il-2 (198.5–188 cm, 5970–5470 BC), *Picea abies* pollen constantly exceeds 20%, whereas *Pinus mugo*-type pollen declines from over 50% to 40%. The macrofossil record shows numerous periderm fragments of *Picea abies* or *Larix decidua*. According to this, Norway spruce stands temporarily replaced the former mountain-pine stands. We suppose that warmer summer temperatures facilitated the spread of *Picea*

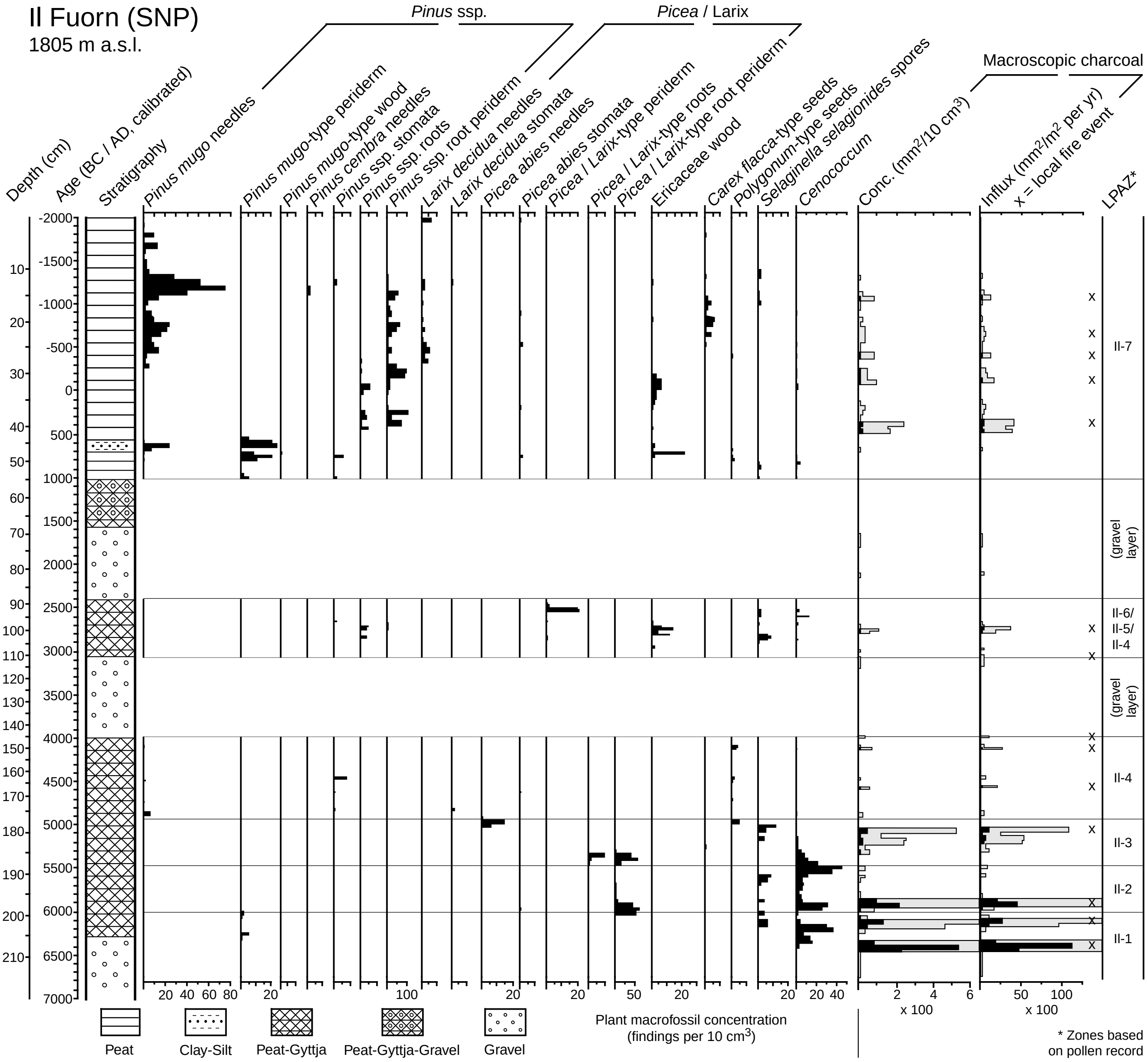

Figure 4 Diagram showing selected plant macrofossil concentrations as well as macroscopic charcoal concentration and influx for Il Fuorn. Analysis: M. Stähli

abies, which today grows at slightly lower altitudes (Welten, 1982). In fact, the later part of LPAZ Il-2 is situated between two ‘Central European cold-humid phases’ identified by Haas *et al.* (1998) (CE-3: 6420–5740 BC, CE-4: 5575–5130 BC).

LPAZ Il-3 (188–177 cm, 5470–4940 BC) is characterized by high percentages of non-arboreal pollen, especially in the sample from 180 cm depth (5080 BC), in which Poaceae and Cyperaceae pollen reach maxima of 22% and 122%, respectively. This indicates that the forests thinned out significantly, in response to either the cold-humid phase CE-4 (5575–5130 BC) or the fire event that dates from 5100–5000 BC (Figure 5).

Tree and shrub pollen no longer fall below 80% during LPAZ Il-4 (177–152/108-105 cm, 4940–4170/2990–2910 BC). The coniferous forests thus recovered from the preceding collapse. However, the tree composition within the pollen zone seems non-uniform. *Pinus mugo*-type pollen is dominant and constantly exceeds 50% with the exception of the sample from 168 cm depth (*Pinus mugo*-type: 36%). *Larix decidua* pollen remains stable between 3% and 4%, whereas *Picea abies* pollen varies between 7% and 18%. In the macrofossil sample at 177 cm depth, 15 *Picea abies* needles were found. Mixed mountain-pine stands covered the Fuorn Valley, but *Picea abies* managed to invade temporarily. As *Larix decidua* pollen is usually strongly under-represented (Lang, 1994; Burga and Perret, 1998), its low abundance indicates that it has been widespread form *c.* 4800 BC until the present time.

LPAZ Il-5 (105–99 cm, 2910–2730 BC) consists of a single pollen sample (102 cm), which shows high percentages of non-arboreal pollen (Poaceae: 27%) and spores (43% of *Selaginella selaginoides* microspores in the pollen slide as well as several macrospores). Similar to LPAZ Il-3, an opening is implied in the forest canopy, affecting *Picea abies* in particular. It remains uncertain whether this breakdown reflects a reaction to the cold-humid phase CE-6 (3360–3020 BC) or whether it was caused by an individual disturbance event, such as windthrow, a landslide or fungal decay. However, the charcoal records do not suggest forest clearance by fire.

During LPAZ Il-6 (99–84 cm, 2730–2220 BC), tree and shrub pollen again increase to over 90%. This is with the exception of the lowest sample (96 cm), which resembles the previous pollen zone (LPAZ Il-5) despite its position in the statistical zonation. Then, after *c.* 2600 BC, the forest canopy recovered. *Picea abies* pollen percentages range from 20% to 25% and *Pinus mugo*-type from 30% to 35%. Thus we can refer

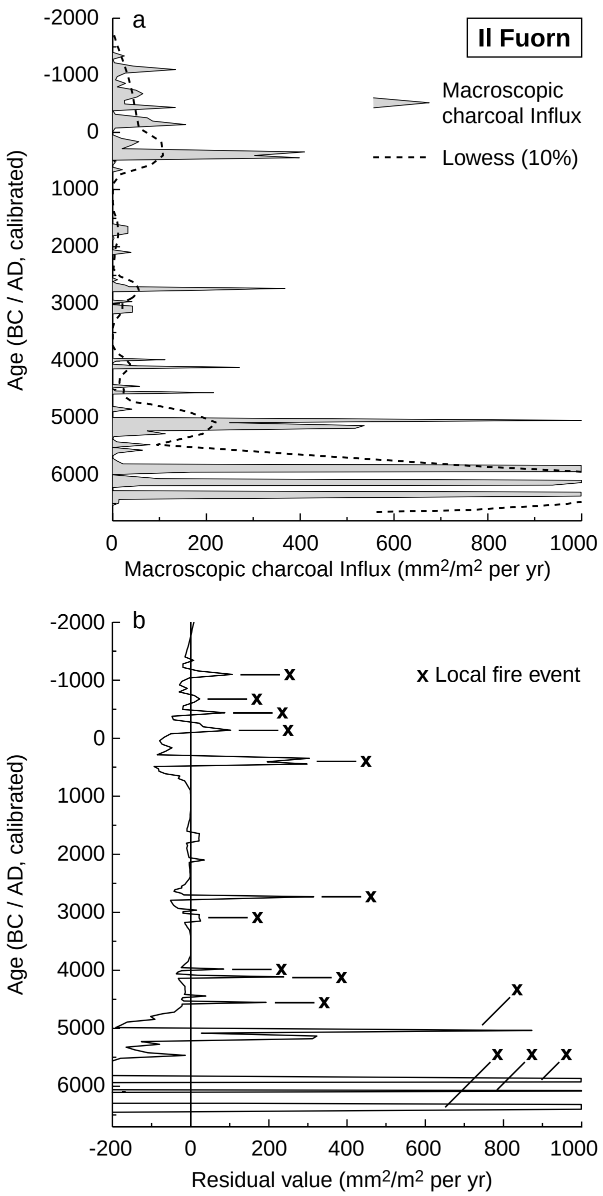

Figure 5 (a) Smoothed curve of macroscopic charcoal influx for Il Fuorn (Lowess; span = 10%). (b) Residual peaks (difference between influx and smoothed values) that were interpreted as local fire events

to the regional vegetation as mixed spruce–mountain-pine stands. *Pinus cembra* pollen reaches 3% to 6% from *c*. 2500 BC to the present. As percentages of 5% can already stand for local presence of *Pinus cembra* (Burga and Perret, 1998), a considerable number of *Pinus cembra* have been intermingled with *Picea abies* and *Pinus mugo* ssp. *uncinata* since then.

In LPAZ Il-7 (54–0 cm, 980 BC–present), tree and shrub pollen again exceed 80%. *Pinus mugo*-type pollen ranges from 45% to 70%, whereas *Picea abies* pollen was less frequently found than in older sediment sections. The macrofossil record, which here shows numerous needles, confirms the dominance of *Pinus mugo* ssp. *uncinata*. According to the pollen record, the re-established mountain-pine forests have been mixed with *Picea abies, Larix decidua* and *Pinus cembra* with a closed canopy until the present time. Only at around 480 BC (42 cm depth), do they appear to have thinned out temporarily. Here, tree pollen decline at the expense of Poaceae (22%). Again, an individual disturbance event could have caused this decline. On the other hand, it is striking that it also coincides with a cold-humid phase, namely CE-8 (800–400 BC) (Haas *et al.*, 1998).

This youngest pollen zone is characterized by a modest increase in pollen taxa that indicate human land use. Poaceae reach more than 10% after 1000 BC, and individual pollen grains of *Plantago lanceolata*-type, *Rumex* and *Humulus/Cannabis*-type were found. However, no herb pollen apart from Poaceae ever exceeds 2% – such a percentage can also be achieved by mere long-distance transport from the lowlands. Furthermore, Cerealia pollen is entirely absent. By Central European standards, this reflects a very low human impact on the landscape. It seems that the Fuorn Valley is situated at too high an altitude (*c*. 1800 m a.s.l.) and at the same time too remote from a lower valley for early settlers to use the land regularly for grazing or even for tillage. At most, livestock might have been occasionally brought up here during summer. Timber exploitation in the Fuorn Valley is documented for the past few centuries (Parolini, 1995), but no significant effect of forestry on the species composition can be detected. Eventually, the temporal resolution chosen for pollen analysis may be too coarse for this purpose.

Vegetation history of Fuldera

In contrast to the situation at Il Fuorn, pollen analysis revealed that the mire Fuldera-Palü Lunga was surrounded by Norway spruce (*Picea abies*) forests most of the time (Figure 6). In 30 samples from this stratigraphy, a total of 71 pollen and spore types from terrestrial plants, six fern taxa and three aquatic and moorland plants were identified by pollen analysis. Numerical zonation revealed five local pollen assemblage zones (LPAZ). In addition, LPAZ Fu-5 was split up into subzones (Fu-5a/Fu-5b) because a clear difference in the pollen diagram could be seen.

LPAZ Fu-1 (150–115 cm, 4030–3020 BC) shows a high abundance of *Picea abies* pollen (60–80%). Pollen percentages of other coniferous tree species are instead rather low, with a maximum of 15% for *Pinus sylvestris/mugo*-type, 6% for *Pinus cembra* and 1% for *Larix decidua*. Tree and shrub pollen add up to over 90% of the terrestrial pollen found. *Picea abies* thus was the dominant tree species on the southern slope of the Müstair Valley and grew in closed and almost pure stands. Contrary to the situation in Il Fuorn, it remains uncertain whether *Pinus sylvestris/mugo*-type pollen is evidence for *P. mugo* or for *P. sylvestris* in Fuldera, as no needles suitable for cross-sections could be found.

LPAZ Fu-2 (115–113 cm, 3020–2970 BC) consists of only one sample at 114 cm depth. It is characterized by a huge pollen percentage of *Alnus viridis* (74%) and a much lower abundance of *Picea abies* pollen (22%) than in the previous zone. According to this, the forest canopy literally collapsed, and green alder shrubberies developed instead. It seems probable that this temporary shift in vegetation was linked to the proceeding Central European cold-humid phase CE-6 (3360–3020 BC) (Haas *et al.*, 1998), the more so as a later peak of *Alnus viridis* pollen (Fu-4) again coincides with a cold-humid phase. However, a local disturbance event would also explain this breakdown of the forest canopy.

During LPAZ Fu-3 (113–88 cm, 2970–1600 BC), *Picea abies* pollen again continuously reaches percentages of over 60%. Moreover, numerous needles of *Picea abies* were found in the macrofossil samples. Percentages of *Pinus sylvestris/mugo* pollen type vary between 10% and 20%. Other coniferous tree pollen, however, were found only sporadically (> 1%). Consequently, closed Norway spruce forest re-established after the collapse at *c*. 3000 BC and continued to cover the area until *c*. 1600 BC, when they were again replaced by green alder shrubberies. In all three samples within LPAZ Fu-4 (88–80 cm, 1600–1080 BC), *Alnus viridis* pollen exceeded 65%.

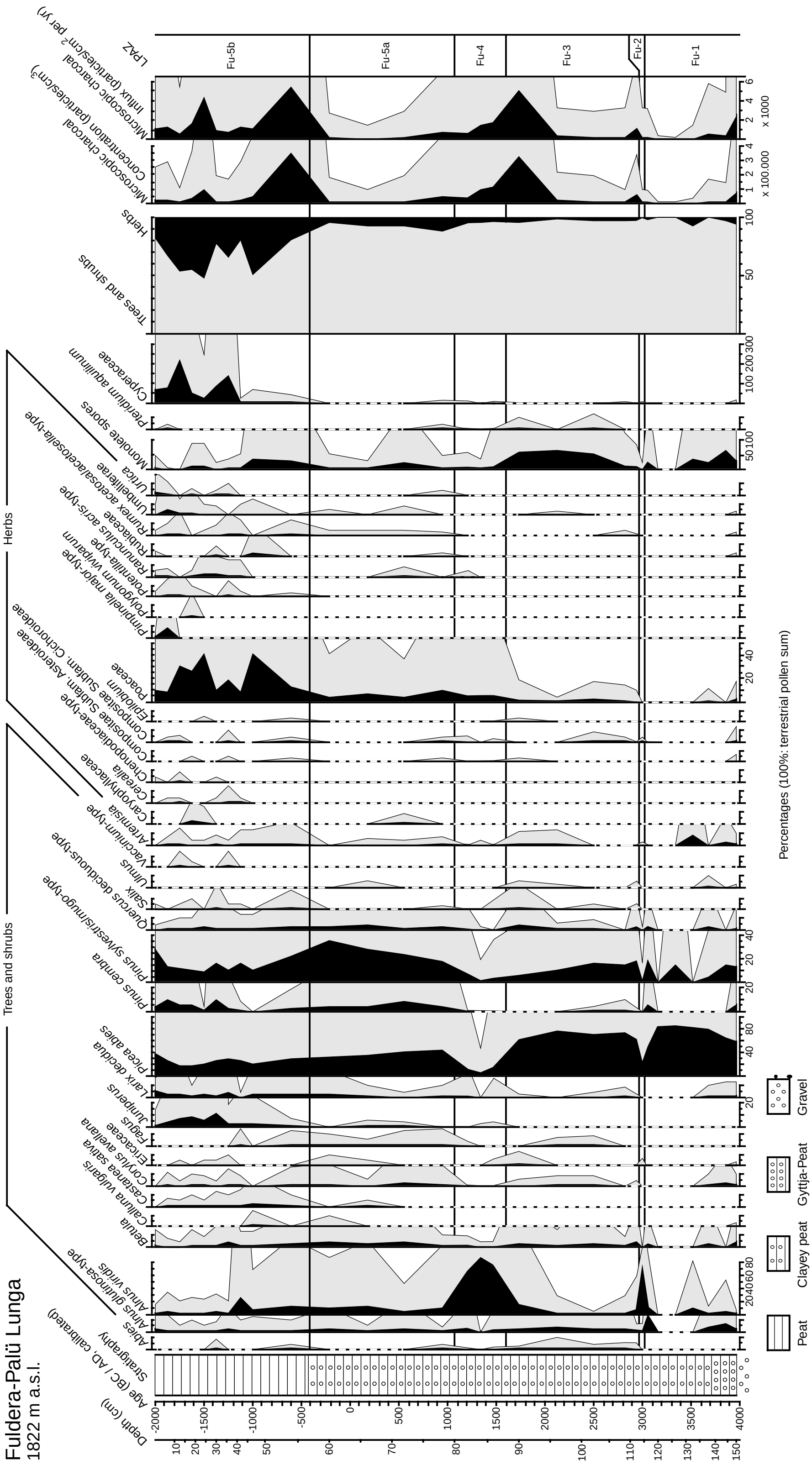

Figure 6 Pollen percentages of selected taxa as well as microscopic charcoal concentration and influx for Fuldera. Analysis: W. Finsinger (Pollen), M. Stähli (Charcoal)

At the beginning of LPAZ Fu-5a (80–57 cm, 1080 BC–AD 410), tree pollen again become prevalent. In the course of this subzone, *Picea abies* pollen steadily decreases from 44% to 30% whereas *Pinus sylvestris*/*mugo*-type pollen increases from 17% to 35%. Further, Fu-5a shows the highest percentages of *Pinus cembra* (between 3% and 8%) as well as *Larix decidua* pollen (between 1% and 2%). Therefore, the vegetation can be referred to as mixed spruce forests. A slight increase of Poaceae pollen possibly suggests first relevant effects of land use on species composition.

A characteristic of LPAZ Fu-5b (57–0 cm, AD 410–present) is the appearance of pollen types commonly known to indicate human activity, including both livestock farming and tillage (eg, Cerealia, *Juniperus*, *Pimpinella major*-type *Ranunculus acris*-type, or *Urtica*; Behre, 1981; Lang, 1994; Burga and Perret, 1998). Strong increases of Poaceae pollen (up to 40%)

Table 2 Overview of mean fire-return intervals (MFI) and influx of microscopic charcoal (particles/cm^2 per yr) in selected sections of the sediment (the analysis considers only layers consisting of organic sediments; all gravel layers were excluded)

Sediment section	Pollen zones	MFI	Number of fire events	Microscopic charcoal, influx (particles/cm^2 per yr)
Il Fuorn				
Entire record	–	440	14	610
Older sediment section (before 2390 BC)	Il-1 to Il-6	350	9	605 (665[a]/440[b])
Younger sediment section (after 1020 BC)	Il-7	605	5	635
Fuldera				
Entire record	–	505	12	
Phase before intensive human land use (before AD 410)	Fu-1 to Fu-5a	740	6	975
Phase with intensive human land use (after AD 410)	Fu-5b	265	6	1900
Vegetation specific analyses				
Mountain-pine forests	Il-1, Il-3, Il-4, Il-5	230	8	530
Mixed forests	Il-2, Il-6	(> 600)	1	690
Norway spruce forests	Fu-1, Fu-3	595	4	1110

[a] 6230–4110 BC.
[b] 2990–2390 BC.

as well as the presence of numerous herb seeds in the macrofossil record (mainly from *Chenopodium album* and *Stellaria alsine*) are most probably caused by livestock farming. Further, the occurrence of *Castanea sativa* pollen (sweet chestnut) is connected with the introduction of chestnut cultivation during the Roman period in the Insubrian lowlands across the Swiss–Italian border (Conedera *et al.*, 2004). Altogether, human impact at Fuldera is clearly stronger than at Il Fuorn, although it started at least 1000 years later in Fuldera than at similar altitudes (1500–1800 m a.s.l.) in the Engadine valley (Zoller *et al.*, 1996; Gobet *et al.*, 2003).

Regional fire history of Il Fuorn

Empirical studies have shown that microscopic charcoal can be used to reconstruct past regional fire activities (ie, within 20–100 km around the site; MacDonald *et al.*, 1991; Tinner *et al.*, 1998). We regard microscopic charcoal particles (> 10 µm) as an evidence for fires in the upper catchment area of the Fuorn Valley (see map in Figure 1). As the valley is surrounded by high mountain ridges, it seems unlikely that a large number of particles were introduced by long-distance transport, even though the catchment area amounts to *c.* 40 km^2 only.

Microscopic charcoal concentration and influx were determined in 35 samples (Figure 3). Generally, they show influx values of 200 to 800 particles (particles/cm^2 per yr) with an average of 610 particles/cm^2 per yr. Converted into surface area, this corresponds to values between 0.1 and 0.3 mm^2/cm^2 per yr when the regression model by Tinner and Hu (2003) is used.

To outline the results, the microscopic charcoal curve can be divided into three sections. Fire activity was relatively high before 4000 BC. In the lowest part of the sediment, the mean charcoal influx reaches 665 particles/cm^2 per yr (Table 2). Afterwards, the accumulation decreases to 440 particles/cm^2 per yr on average in the period from 3000 to 2400 BC. This decline is likely to have been caused by climate change, for summers became colder and, more importantly, wetter between 3500 and 2500 BC (Tinner and Theurillat, 2003). The appearance of *Pinus cembra* pollen provides further indication for a cooling transition. In the youngest sediment section (after 1020 BC), charcoal influx again increased to 635 particles/cm^2 per yr on average, probably because of to intensified human land use at regional level.

Regional fire history of Fuldera

Microscopic charcoal concentration and influx were determined in 30 samples. They contained an average of 1305 particles/cm^2 and year (particles/cm^2 per yr), but most individual influx values range from 300 to 1200 particles/cm^2 per yr (Figure 6). Using the regression model by Tinner and Hu (2003), we estimate the surface area influx at 0.12 to 0.45 mm^2/cm^2 per yr. Two samples (120 cm, 126 cm) were excluded from these calculations because both charcoal and pollen concentration were very low and the counting is based on too few particles.

Accumulation of microscopic charcoal particles is generally higher in the younger sediment section. Influx averages 1900 particles/cm^2 per yr in LPAZ Fu-5b (after AD 410), compared with 975 particles/cm^2 per yr before (Table 2). This increase in regional fire activity was most probably caused by intensification of human activities.

The regional setting suggests that the vast majority of microscopic charcoal particles (> 10 µm) found in the core 'Fuldera' originate from fires in the upper part of the Müstair Valley (west of Santa Maria; see map in Figure 1).

Local fire history of Il Fuorn

Macroscopic charcoal concentration and influx are presented in Figure 4. Charcoal particles were found over the whole core, exept for the gravel layers. Concentration is highest in the oldest part of the core. Yet many individual samples contain no charcoal at all. Fourteen residual peaks were identified on the basis of the smoothed influx curve and according to the method described in the section 'material and methods' (Figure 5). Five additional peaks can be seen in the curve, but here charcoal concentration did not reach the specified threshold values. Fire-return intervals ranged strongly from a minimum of 54 years up to 900 years, with an average of 440 years (Table 2).

Fires were more frequent in the early and middle Holocene than afterwards. The mean fire-return interval (MFI) drops to 350 years when only the older sediment sections (before 2390 BC) are considered. In contrast, the late Holocene shows a value of 605 years, as only five local fires have occurred since 1000 BC. Climatic influence seems evident also in respect of fire frequency, as the reduction of fire activity corresponds with the decline of microscopic charcoal influx around 2700 BC. Furthermore, the extension of fire intervals reinforces the

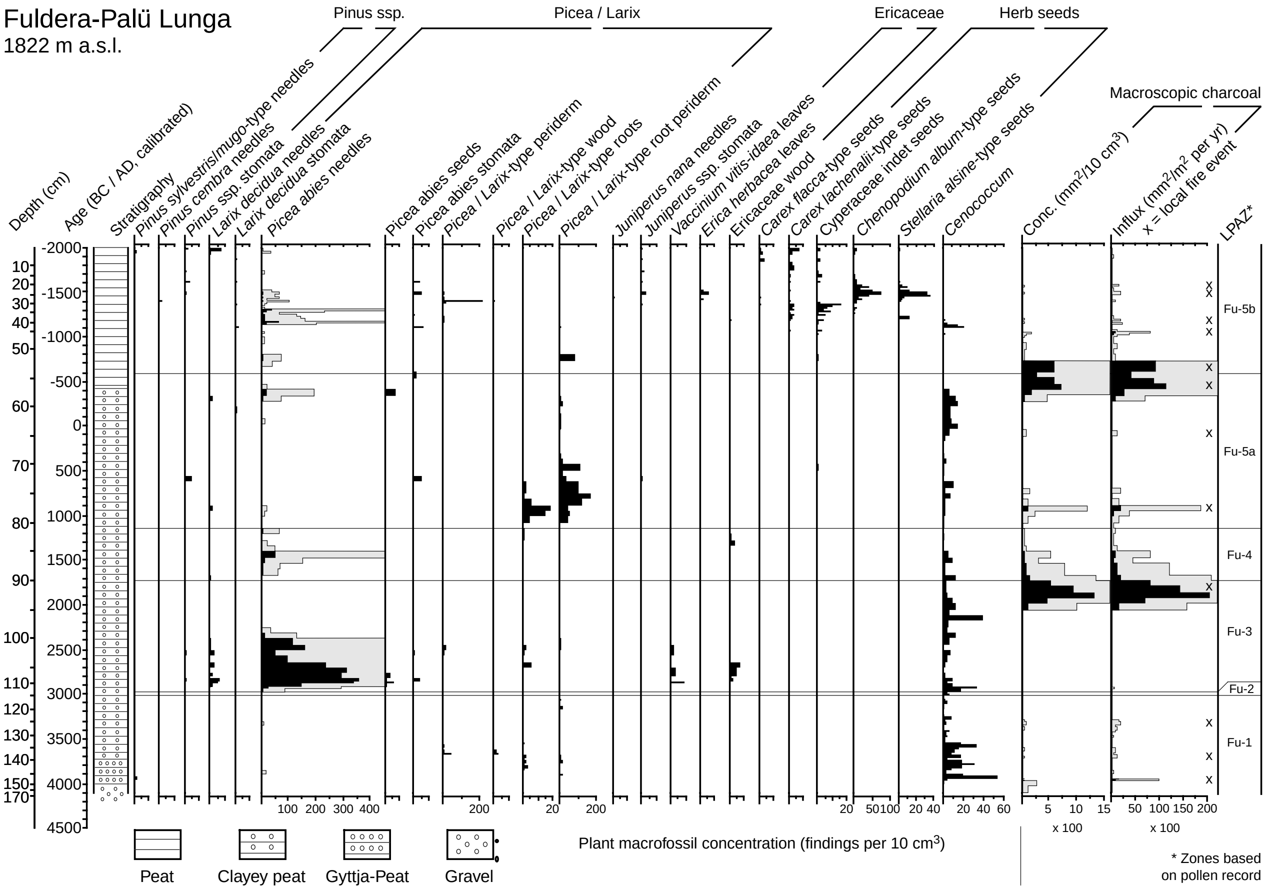

Figure 7 Diagram showing selected plant macrofossil concentrations as well as macroscopic charcoal concentration and influx for Fuldera. Analysis: M. Stähli

view that agricultural land use (pasture farming and tillage) was very limited around Il Fuorn. However, we know from historical sources that during the past few centuries timber was exploited intensively for ore smelting and exportation (mainly to the salt-mine in Hall, Tirol) (Parolini, 1995). Our results suggest that timber exploitation did not cause an increase in fires, but actually prevented fuel build-ups that would favour fire ignition and intensity.

Local fire history of Il Fuldera

Concentration and influx of macroscopic charcoal for Fuldera are shown in Figure 7. Influx values remain low (< 1000 mm²/m² per yr) from 4000 BC to 2000 BC. After this, the charcoal record is characterized by two phases of massive accumulation (*c.* 1800 BC and AD 500). However, curve smoothing revealed a total of 12 residual peaks and thus 12 fire events (Figure 8). The resulting fire-return intervals are as different as the ones at Il Fuorn. On average over the whole profile, wildfires occurred every 505 years. However, frequency was inconstant over time: half of the fire events (six out of twelve) occurred after AD 410 (ie, within LPAZ Fu-5b). Consequently, an MFI of 265 years after AD 410 compares with only 740 years in the period from 4030 BC until AD 410. Human activities are very likely to have caused the increase in regional fire activity, the more so as it is in accordance with both pollen and microscopic charcoal results.

Fire history and forest type

The chosen multiproxy approach enables the investigation of fire activity with respect to different vegetation types. We divided sediment sections of both cores (Il Fuorn and Fuldera) into three distinct groups characterized by similar vegetation types. ‘Mountain-pine forests’ correspond to pollen zones in which *Pinus mugo* ssp. *uncinata* is the dominant tree species (LPAZ Il-1, Il-3, Il-4 and Il-5). Sections with high percentages of both *Picea abies* and *Pinus mugo*-type pollen are referred to as ‘mixed forests’ (LPAZ Il-2 and Il-6), whereas ‘Norway spruce forests’ include LPAZ Fu-1 and Fu-3 (> 60% *Picea abies* pollen). (Pollen zones containing evidence of human activities are not included in this comparison.) Subsequently, the MFI was calculated for each individual group.

Fires were most frequent in mountain-pine forests with an MFI of 230 years compared with 595 years in Norway spruce forests (Table 2). This difference is hardly coincidental, even if the MFI data result from only five or four fire events, respectively. During the periods with mixed forests, which lasted for *c.* 1000 years in total, only one fire event occurred. Although no MFI value can be calculated, this suggests that fire frequency in mixed forests was also low.

In contrast, in Norway spruce forests (1110 particles/cm² per yr on average), more microscopic charcoal was deposited than in mountain-pine forests (530 particles/cm² per yr), whereas accumulation was intermediate between these two in mixed forest (690 particles/cm² per yr). Stands dominated by *Pinus mugo* ssp. *uncinata* clearly burned more often than spruce stands. However, we presume that the individual fire events were less severe.

Fire-induced changes in vegetation

The investigation of short-term vegetational changes in this study remains preliminary because of the fairly coarse temporal resolution of the pollen analyses. Nevertheless, we were able to track changes after seven distinct local fire events (Il Fuorn: 39, 99, 182 and 197 cm depth; Fuldera: 45, 56 and 92

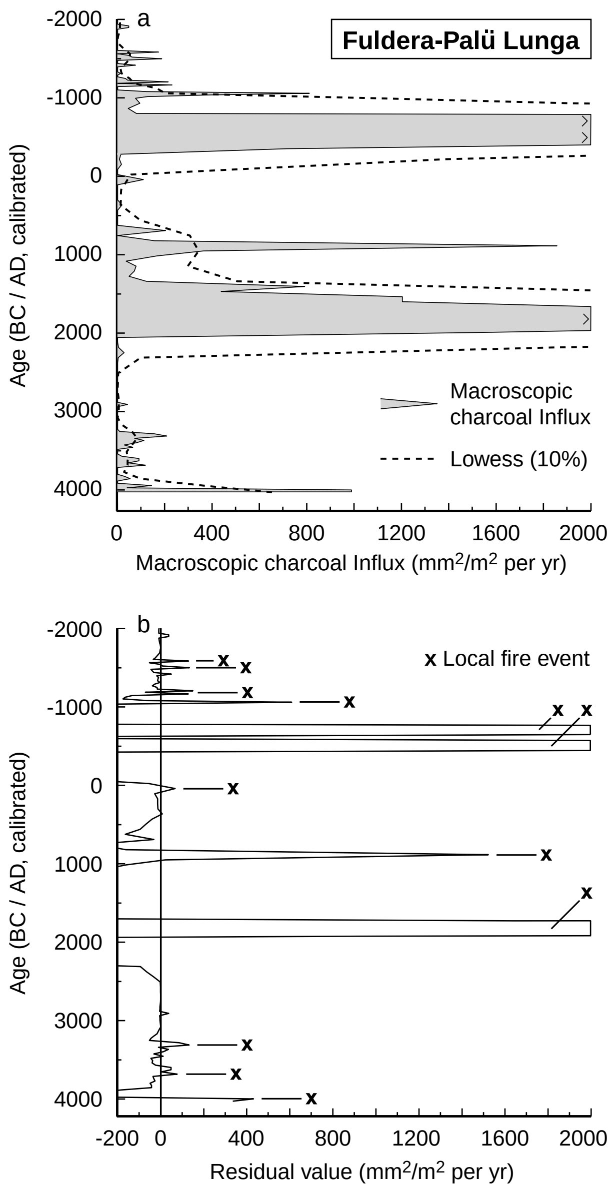

Figure 8 (a) Smoothed curve of macroscopic charcoal influx for Fuldera (Lowess; span = 10%). (b) Residual peaks (difference between influx and smoothed values) that were interpreted as local fire events

cm depth). Following fires, prominent rises and drops in pollen percentages were observed. Pollen types that increased most often were *Salix* (in five cases), *Alnus viridis* (four), Cyperaceae (three), *Epilobium* (three) and *Pteridium aquilinum* (three). These species were previously found to sprout well after Holocene fires (Tinner *et al.*, 1999; Gobet *et al.*, 2003) and recent burns (Delarze *et al.*, 1992; Schönenberger and Wasem, 1997). Pollen of *Pinus mugo/sylvestris*-type twice shows a post-fire rise and a drop in one case. *Picea abies* pollen both increases and decreases twice. According to this, forest fires favoured the above-named shrubs and herbs but did not affect the tree composition within the remaining forests in the short term.

Discussion

Fire history and fire ecology

Macroscopic charcoal analysis is considered a suitable method to reconstruct local fire history and to estimate mean fire-return intervals (MFI) (Long *et al.*, 1998; Millspaugh and Whitlock, 1995; Whitlock and Larsen, 2001). The most critical point is probably to define a threshold of charcoal accumulation that is still regarded to represent a fire event. In this study, all fire events are based on sediment samples with a charcoal concentration of at least 3 mm^2/10 cm^3. Further, all of these samples contain several particles >1 mm in diameter. According to Clark and Patterson (1997), the vast majority of charcoal fragments in this size class are deposited near a fire (<100 m), which means that the MFI presented in this paper are very unlikely to be underestimated.

The MFI in the surroundings of the Swiss National Park (SNP) (down to 250 years in mountain-pine forests) turn out to be shorter than the few previous fire history studies in the Alps might suggest.

For southern Switzerland, at the edge of the Alps, a natural MFI of *c.* 1500 years has been proposed (Berli *et al.*, 1994, Tinner *et al.*, 1999; Allgöwer *et al.*, 2003). In our opinion, the difference between this situation and that around the Swiss National Park (SNP) is due to the fact that southern Switzerland is partly covered by broadleaved forests, which are generally less fire-prone (Pyne *et al.*, 1996).

Further, in soils of the dry, inner alpine Maurienne Valley (France) with a climatic setting comparable with the SNP, Carcaillet (1998) did not find charcoal particles from the period before anthropogenic deforestation started. This contradicts the results of our study, and the question is whether stratified deposits such as peat or lake sediments would have revealed natural fires. However, comparable natural fire intervals (200 to 600 years) are indicated by a macroscopic charcoal time series from Lago Basso (Italy), although MFI were not calculated explicitly in this study (Wick and Tinner, 1997). Lago Basso, situated *c.* 70 km southwest of the SNP, also represents an inner alpine site surrounded by coniferous forests (mainly *Pinus cembra* and *Larix decidua*).

Shorter fire intervals in mountain-pine forests (*Pinus mugo* ssp. *uncinata*, 230 years) compared with Norway spruce forests (*Picea abies*, >600 years) are not a surprise, given the fact that *Pinus sylvestris*, a relative of *Pinus mugo*, is considered the most fire-tolerant tree in the boreal forests of Europe (Sannikov and Goldammer, 1996; Agee, 1998). These two pine species may react similarly to fire (Tapias *et al.*, 2004). Allgöwer *et al.* (1998), on the basis of fuel sampling, likewise concluded that mountain-pine forests are more susceptible to forest fires than are other coniferous forest communities in the SNP. But altogether, there has been little research on fire ecology of *P. mugo* ssp. *uncinata*.

Further, similar outward appearance and habitats (severe microclimate/infertile soils) lend themselves to compare *Pinus mugo* ssp. *uncinata* with the North American *Pinus contorta* (lodgepole pine). Forests dominated by *P. contorta* support fires ranging from crown fires to slow-spreading smouldering fires and show an MFI of *c.* 60 to 80 years (Agee, 1998), which is clearly shorter than for *P. mugo* ssp. *uncinata*.

In our opinion, fire events identified in this study also represent a mixture of crown fires and surface fires–particularly in mountain-pine forests–for the following reasons. First, the pollen record suggests that fire did not significantly modify the occurrence of tree species on a short-term basis but did affect the dispersion of shrub and herb species–a situation likely to be observed after surface fires. Second, forest regeneration after severe crown fires can be very slow in subalpine environments, particularly on steep slopes and when soil material is destroyed (Schönenberger and Wasem, 1997). Thus these forests seem unlikely to have supported severe crown fires at intervals of 300 years. Similarly, Tapias *et al.* (2004) claim that late flowering and absence of serotiny indicate that both *P. mugo* ssp. *uncinata* and *P. sylvestris* do not develop with frequent crown fires. We propose to assign the forests in the SNP to moderate fire regimes, as Agee (1998) did for *P. sylvestris*. Moderate fire regimes are characterized by the occurrence of both crown and surface fires.

Fire history, human land use and climate

Earliest evidence of grazing activities in the valley bottom of the Engadine dates back to *c.* 3600 BC, whereas there are no signs of crop farming until as late as *c.* 2000 BC (Zoller *et al.*, 1996; Gobet *et al.*, 2003). According to our pollen results, agricultural activities appear to have started even later (Fuldera: *c.* 1100 BC) or to have been almost absent until the present day (Il Fuorn) in the vicinity of our study sites. Thus the fire intervals that are based on the older parts of the cores can, in fact, be considered natural. Fire activity clearly increased with intensified land use in Fuldera (Table 2). Hunter-gatherer societies certainly had sporadically visited high-altitude areas in the Alps during the Mesolithic (Fedele, 1999; Pignat and Crotti, 2002) and might have caused single fires–deliberately or unintentionally. However, at a regional scale the effect of man on the pre-agricultural landscape can be neglected. Accordingly, Whitlock and Knox (2002) claim that fire activity before Euro-American settlement in the northwestern USA was largely controlled by climate, not by Native American hunting practices. At Il Fuorn, fire frequency decreased between 3500 and 2500 BC, most probably for climatic reasons (Table 2), even if some tens of kilometres away the first herdsmen left their marks in the Engadine.

In conclusion, this study supports the point of view that fire is in fact a natural process in the (Central) Alps, a view that has only recently been proposed (eg, Berli *et al.*, 1994; Tinner *et al.*, 1998; Allgöwer and Gleason, 2001; Allgöwer *et al.*, 2003). Although our results cannot be generalized to the whole Central Alps, especially not to areas covered with different forest type, there is strong evidence that the dry, inner alpine valleys all have their natural fire histories.

Potential vegetation of the Fuorn Valley

So far it has commonly been assumed that the vast mountain-pine forests around Il Fuorn reflect an early-successional state resulting from extensive clear-cuts in the late nineteenth century and will gradually be replaced by Swiss stone pine/larch communities in the future (*Pinus cembra/Larix decidua*) (Parolini, 1995; Zoller, 1995; Risch *et al.*, 2004). Our pollen and macrofossil records, however, suggest that *Pinus mugo* ssp. *uncinata* had a strong natural potential during the Holocene and represented the dominant tree in forests that were composed of varying proportions of *Pinus cembra*, *Larix decidua* and *Picea abies*. In contrast, *Pinus cembra* was much less widespread than, for example, in the Upper Engadine Valley (Gobet *et al.*, 2003). These results support an earlier statement by Ellenberg (1986), who presumed that, 'due to low precipitation (by alpine standards) and infertility of the prevailing dolomite soils, probably some of the extensive mountain-pine stands had already existed before human interference'. Dominating occurrence of *Pinus mugo* ssp. *uncinata* in the Holocene has previously been reported from the French Alps by Ponel *et al.* (1992) and Ali *et al.* (2004).

On the basis of their investigation of forest succession in the SNP, Risch *et al.* (2004) conclude that, after a clear-cut, a minimum of 205 to 235 years is required to reach the late-successional Swiss stone pine/larch forest, which replaced the early-successional mountain-pine forest. Coincidentally, this is exactly the duration of the mean fire-return interval we proposed for mountain-pine forests (Table 2). It seems that forests in the Holocene in the Fuorn Valley hardly ever reached a late-successional stage (ie, *Pinus cembra/Larix decidua*) as proposed by Risch *et al.* (2004). Instead, our results suggest that fire disturbance and the particular environmental conditions (dry continental climate, dolomite bedrock) allowed mountain-pine stands to persist in the Swiss National Park throughout the mid and late Holocene.

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