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New tree-ring evidence for the Late Glacial period from the northern pre-Alps in eastern Switzerland

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ABSTRACT

The rate and magnitude of temperature variability at the transition from the Last Glacial Maximum into the early Holocene represents a natural analog to current and predicted climate change. A limited number of high-resolution proxy archives, however, challenges our understanding of environmental conditions during this period. Here, we present combined dendrochronological and radiocarbon evidence from 253 newly discovered subfossil pine stumps from Zurich, Switzerland. The individual trees reveal ages of 41–506 years and were growing between the Allerød and Preboreal (~13′900–11′300 cal BP). Together with previously collected pines from this region, this world's best preserved Late Glacial forest substantially improves the earliest part of the absolutely dated European tree-ring width chronology between 11′300 and 11′900 cal BP. Radiocarbon measurements from 65 Zurich pines between ~12′320 and 13′950 cal BP provide a perspective to prolong the continuous European tree-ring record by another ~2000 years into the Late Glacial era. These data will also be relevant for pinpointing the Laacher See volcanic eruption (~12′900 cal BP) and two major Alpine earthquakes (~13′770 and ~11′600 cal BP). In summary, this study emphasizes the importance of dating precision and multi-proxy comparison to disentangle environmental signals from methodological noise, particularly during periods of high climate variability but low data availability, such as the Younger Dryas cold spell (~11′700 and 12′900 cal BP).

1. Introduction

The transition from the Late Glacial (LG) into the early Holocene ~15′000–10′000 years ago has been characterized by strong climate variability (Brauer et al., 2008; Haflidason et al., 1995; Hughen et al., 2000; Johnsen et al., 1992; Lauterbach et al., 2011; Litt et al., 2001; Rasmussen et al., 2006; von Grafenstein et al., 1999; Yu and Eicher, 1998). Most lacustrine and marine sediments, as well as terrestrial pollen profiles and ice core records describe rapid warming into the Bølling (~14′700 cal BP; GI-1e; Björck et al., 1998), and again, at the onset of the Holocene (~11′650 cal BP) (Fig. 1a–c). At least three distinct cold phases occurred between ~14′050–11′650 cal BP including the Older Dryas (OD; GI-1d; Thornalley et al., 2010), Gerzensee Oscillation (GI-1b; van Raden

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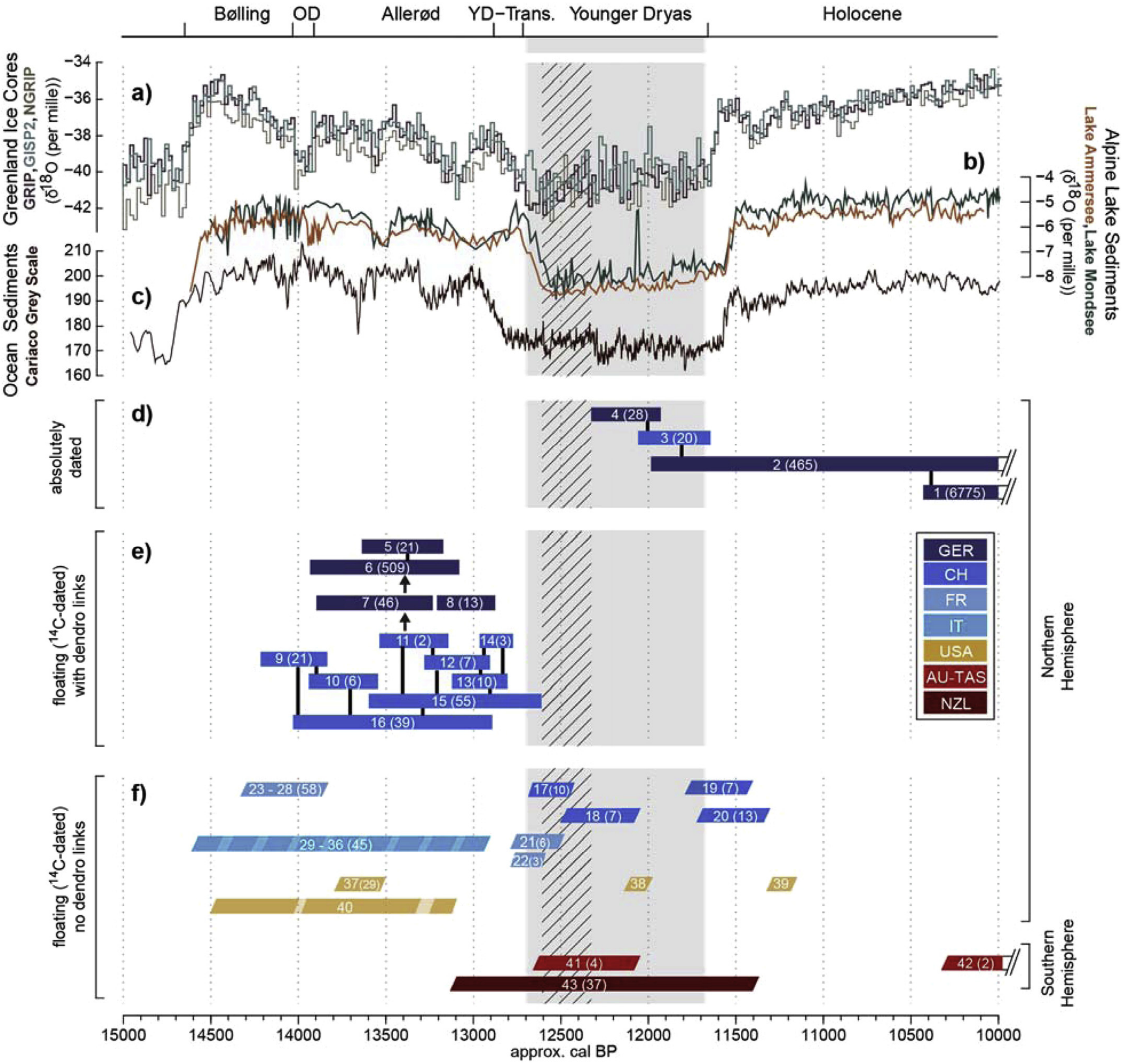

Fig. 1. Overview of Late Glacial proxy records from the Bølling into the early Holocene. (a) Greenland ice cores GRIP, GISP2 and NGRIP (Johnsen et al., 1992; Rasmussen et al., 2006, 2014; Seierstad et al., 2014), (b) Alpine lake sediments from Lake Ammersee (von Grafenstein et al., 1999) and Lake Mondsee (Lauterbach et al., 2011), and (c) marine sediments from the Cariaco Basin (Hughen et al., 2000). (d) Absolutely dated and (e–f) floating LG TRW chronologies from the Southern and Northern Hemisphere. Grey shading denotes the Younger Dryas, with dashed lines indicating the gap between the absolutely dated PPC and floating SWILM TRW chronologies. Numbers in the bars abbreviate the chronologies (see SM1 for further reference), whereas the corresponding sample size is displayed in brackets. Slanted bars refer to floating TRW chronologies, and vertical black bars show cross-dating links between chronologies.

et al., 2013), and Younger Dryas (YD; GS-1; Brauer et al., 1999) (Fig. 1a–c). Dating uncertainty of the available ice core and sediment records, however, still limits cross-comparison within and between the different paleo-archives. The timing of volcanic activity during this period, including the Laacher See Eruption (LSE) ~12′900 years ago (Baales et al., 2002; Brauer et al., 1999; Litt et al., 2003; Schmincke et al., 1999), as well as a sequence of major earthquakes (~13′770 and ~11′600 cal BP) that have been related to the deglaciation process of the Alpine arc (Strasser et al., 2006), also remain insecure.

Although not extending back into the LG period, annually resolved and absolutely dated, multi-millennial-long tree-ring width (TRW) chronologies from living and relict wood have been developed at different locations in New Zealand and Tasmania (Boswijk et al., 2006; Cook et al., 2006), north-western Siberia (Hantemirov and Shiyatov, 2002; Naurzbaev et al., 2002), and northern North America (Leavitt et al., 2006). In Europe, such composite records exist for the Austrian Alps (9111 years; Nicolussi et al., 2009), northern Germany (8000 years; Leuschner et al., 2002), Ireland (6939 years; Baillie, 2009), northern Sweden (7400 years; Grudd et al., 2002), and Finish Lapland (7519 years; Eronen et al., 2002). The initial “Holocene Oak Chronology” (HOC) by Becker (1993), has been revised and extended by the “Preboreal Pine Chronology” (PPC; Friedrich et al., 2004, 1999; Spurk et al., 1998). Its earliest part in the YD, consisting of only a few subfossil pines from Germany and Switzerland, is still subject to improvement (Hogg et al., 2016; Kaiser et al., 2012; Schaub et al., 2008a). Based on new radiocarbon evidence from subfossil New Zealand Kauri wood (Hogg et al., 2016), the earliest part of the PPC has been excluded from this study, and requests further investigation. Continuously reaching back to 12′325 cal BP (Fig. 1d), this reliable part of the PPC in combination with the HOC from southern Germany currently represents the longest absolutely dated TRW chronology. Comparisons of high-resolution beryllium-10 (^{10}Be) in ice cores and radiocarbon (^{14}C) in tree rings, however, suggest a temporal offset between both records at ~12′000 cal BP (Muscheler et al., 2014).

In addition to the various absolutely dated TRW chronologies described above, subfossil wood from gravel pits and mining areas in central Europe enabled the development of floating TRW chronologies that may even reach back into the LG period (Fig. 1d–f). Such records have been introduced for northern and southern Germany (Friedrich et al., 2004, 2001, 1999), southern France and northern Italy (Casadoro et al., 1976; Corona, 1984; Friedrich et al., 2009, 1999; Miramont et al., 2011, 2000a, 2000b). Several floating TRW chronologies from the greater Zurich area in Switzerland cover the Bølling-Allerød transition, and a total of 146 pines have so far been combined into a 1606-year-long “Swiss Late Glacial Master” (SWILM) chronology (Kaiser, 1993; Kaiser et al., 2012; Schaub et al., 2008a, 2008b). Based on radiocarbon dating (Ramsey, 2001), several floating TRW chronologies have been developed in North America (Fig. 1f; Griggs and Grote, 2016; Leavitt et al., 2006; Panyushkina and Leavitt, 2013, 2007), New Zealand (Hogg et al., 2016, 2013), and Tasmania (Barbetti et al., 2004; Hua et al., 2009). Sample size and growth coherency of these chronologies might be reduced during episodes of colder climatic conditions (Hogg et al., 2016; Kaiser et al., 2012). The YD, for instance, exhibits a nearly 300-year-long gap between the absolutely dated PPC and the floating SWILM chronologies ~12′300–12′600 cal BP (Fig. 1d–f). Recently radiocarbon dated against IntCal13 (Hogg et al., 2016; Reimer et al., 2013), subfossil Kauri wood from New Zealand now suggests a slight shift of the Swiss floating YD trees to older ages. Although the new Kauri radiocarbon evidence helps to improve the dating of floating TRW records from around the world, a persistent radiocarbon plateau in the IntCal13 calibration curve ~12.4 kyr cal BP hampers precise wiggle-matching within and between hemispheres.

Here, we present key characteristics, conceptual milestones and first breakthroughs of our Swiss-German *Binz* project. We describe the discovery of 253 LG pine stumps from Zurich, and use a synergetic dendrochronological and radiocarbon dating approach to determine both, the age of newly constructed floating TRW chronologies, as well as their relative position to previously collected and re-evaluated LG material from the same region and time. We assess the potential of the Swiss material to extend the world's longest absolutely dated TRW chronology by ~2000 years. We place these regional findings into a global perspective, and stress cross-disciplinary challenges and chances of a high-resolution paleoenvironmental archive covering the LG to early Holocene transition.

2. Material and methods

2.1. Environmental context and research background

During the Last Glacial Maximum (LGM; 26.5 to 20 ka BP; Clark et al., 2009), the region of modern-day Zurich was carved by the Linth-Rhine and Reuss glaciers. The Uetliberg, as a nunatak composed of upper freshwater molasse, separated todays Sihl and Reppisch valleys (Grossmann, 1934; Haeberli et al., 2003, 1998). As the glaciers retreated after the LGM, meltwater carved drainage channels into the molasse, creating the present landforms (Grossmann, 1934). Solifluction and high-energy mass movements, such as landslides, were characteristic features during the transition from the LGM into the Holocene, when most of the permafrost slopes became instable (Grossmann, 1934; Kaiser, 1993). A prolonged period of more sedate but continuous geomorphological processes most likely followed the more turbulent initial phase. Alluvial soil of clay, silty and sandy sediments were deposited along the bottom and lower flanks of the Uetliberg. These sediments formed a 4 km^2 wide and up to 30 m deep fan on the north-eastern side of the Uetliberg, nowadays partly overbuild by the city of Zurich (Fig. 2a and b) (Pavoni et al., 1992). The varying yet decelerated deposition after the LGM allowed initial herbaceous and pioneer vegetation to (re)establish in the valley bottoms and along the lower parts of the slopes (Johnsen et al., 1992; Kaiser, 1993). Pine (*Pinus* sp.), birch (*Betula* sp.), willow (*Salix* sp.), burkhorn (*Hippophae* sp.) and juniper (*Juniper* sp.) started to populate the region, reforesting the northern pre-Alps after the LGM (Kaiser, 1993; Kaiser et al., 2012; Schaub, 2007; Schaub et al., 2008a). The pioneering post-LGM vegetation cover sharply reduced local sedimentation rates, a feature that was likely common to the northern pre-Alps (Kaiser, 1993). During the subsequent YD (~12′900–11′700 cal BP) and particularly the Allerød deposition rates of predominantly loamy sediments from the Uetliberg slopes have been estimated to ~2.3 mm/a during the Allerød and up to 5.0 mm/a during the YD. This material most likely killed and buried most of the pine trees (Kaiser, 1993; Schaub, 2007; Schaub et al., 2005) that are neither able establish epitropic root systems nor develop adventitious roots, and could therefore not adequately cope with high and continuous sedimentation rates (Grossmann, 1934; Kaiser, 1993; Schaub et al., 2005; Schweingruber, 1996).

2.2. Sample collection and preparation

In 2013, a total of 253 well-preserved, subfossil pine (*Pinus* spp) stumps were excavated due to dredging activities at a construction site – the so-called Binz find. All material was found in an eight-meter-deep, homogeneous clay package at the north-eastern flank of the Uetliberg mountain in Zurich, Switzerland (Fig. 2c and d). While bark was present on most individuals, less than 20 stumps showed initial signs of rot. Whenever possible, at least three disc samples of 10–15 cm thickness were taken from each of the 1–1.5 m high pine stumps (Fig. 2e). Discs from just above the root system ideally facilitate the estimation of germination dates (Schaub et al., 2008b), whereas discs from higher stem positions are generally less affected by reaction wood (Schweingruber, 1996). While the remaining stump parts were stored under stable temperature and air humidity (Fig. 2f), each disc was sanded and polished with up to 400 grain size sandpaper. At least two radii were cut from each disc and TRWs were measured using a LINTAB measuring device with a precision of 0.01 mm and the TSAPWin software (Rinn, 1996). TRW measurements where visually and statistically cross-dated considering *t*-values and Gleichläufigkeit indices (Baillie and Pilcher, 1973) in TSAPWin, PAST4, and COFECHA (Holmes, 1983).

Performed at the Laboratory of Ion Beam Physics, ETH-Zurich, both the well-established high-precision ^{14}C Accelerator Mass Spectrometer (AMS) dating (Synal et al., 2007; Wacker et al., 2014, 2010), as well as the novel ‘Speed Dating’ (Sookdeo et al., 2016), were used for radiocarbon dating (Güttler et al., 2015, 2013; Němec

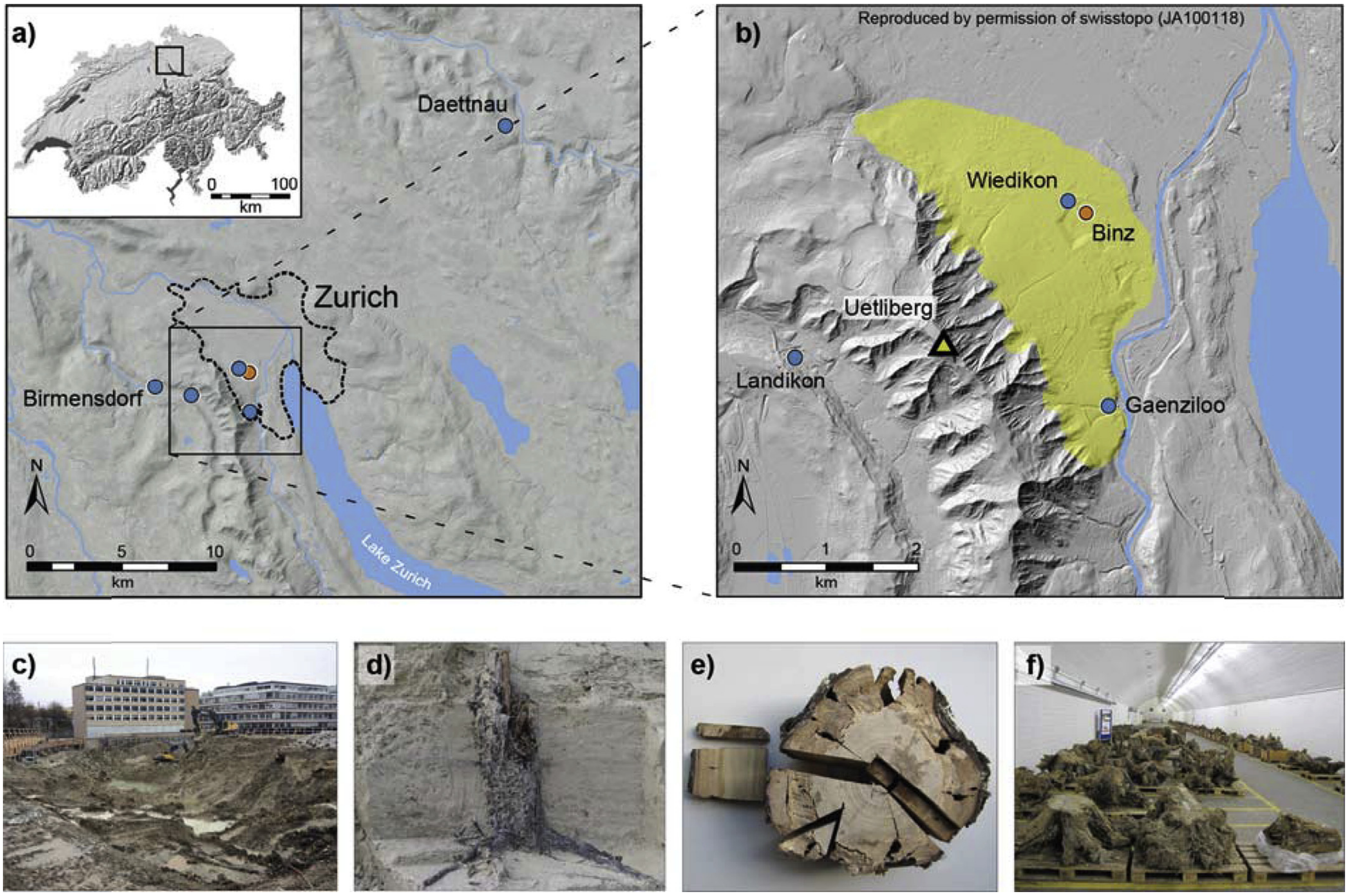

Fig. 2. Location of subfossil pine finds in the greater Zurich area and impressions of the Binz site and trees. (a) The newly discovered Binz material (orange dot), together with the previous finds of Landikon, Gaenziloo, Birmensdorf and Wiedikon (blue dots). (b) Location of the clay package on the lower flanks of the Uetliberg (yellow shading). (c) The construction site in the Binz quarter in Zurich (2013); (d) an excavated in situ Binz trunk with bark and root system located in the Uetliberg clay; (e) a dried Binz disc indicating sapwood decomposition; (f) all of the 253 Binz trunks stored under constant air humidity and temperature in an old military bunker. Kartendaten: DTM-AV DOM-AV © 2017 Eidg. Vermessungsdirektion (DV033531). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

et al., 2010). While high-resolution AMS-dating (±20–25-year 1-sigma) can reveal accurate tree ages along the IntCal13 calibration curve (Reimer et al., 2013), the simplified ‘Speed Dating’ technique provides rough estimates of the expected age range. Since radiocarbon measurements generated with the ‘MIni-CArbonDAtingSystem’ (MICADAS) require no more than 20 mg of organic material, the method enables ^{14}C measurements of annual or bi-annual resolution of even narrow tree rings. Cellulose was extracted via the base-acid-base-acid method (Němec et al., 2010), and then bleached and graphitized with an AGE system (Wacker et al., 2010). Out of a total of 835 ^{14}C measurements from both, the newly discovered as well as the previously collected subfossil LG pines from the greater Zurich area, 62 high-precision values from the inner, middle, and outer part of the floating chronologies were used for wiggle-matching (Ramsey, 2001).

3. Results

The Binz find represents a wide range of individual tree ages (Fig. 3a). Ten trees exceed 300 years, and the youngest and oldest samples contain 41 and 506 rings, respectively. Most of the pines ($n = 153$) contain between 100 and 200 rings. Out of the 225 samples with ring numbers >40, 187 trees cross-dated into nine individual groups (Table 1; we hereafter consequently refer to groups, as low replication in some prohibits their chronology entitlement), whereas no dendro linkage has been found for the remaining 38 trees. A negative exponential trend is evident in the relationship between the average growth rate (AGR) and segment length (SL) of all cross-dated, as well as the non-cross-dated trees (Fig. 3b). The majority of samples with a SL < 100 years could not be cross-dated, while almost all trees with a SL > 200 years could be cross-dated. The mean segment length (MSL) of all (non) cross-dated trees is (140) 168 years, with an AGR of (1.34) 1.25 mm/yr (Fig. 3c). The opposite is observed for the cross-dated trees. Replication between the single groups of the cross-dated trees varies from two to 80 individuals. While two groups span more than 500 years (Binz Group 1a and Binz Group 10), Binz Group 1 d covers only 104 years, and all other Binz groups reach at least 200 years. Six out of the nine Binz groups express an inter-series correlation above 0.5 (Rbar). The groups' inter-series correlation fluctuates between 0.43 in Binz 1 b and 0.62 in Binz 1 d (Table 1). The majority of trees in Binz Group 2, 2 b and 6 have starting dates within a few years, while the other groups suggest temporally less defined establishment phases (Fig. 4).

Radiocarbon wiggle-matching against IntCal13 and the New Zealand Kauri chronologies (Hogg et al., 2016) suggests that the nine floating Binz groups are distributed over almost 2′500 years between the OD and the Preboreal (Fig. 4). Seven floating Binz groups are positioned from the Allerød into the YD transition. In a first step, care was taken to either positioning the groups on behalf

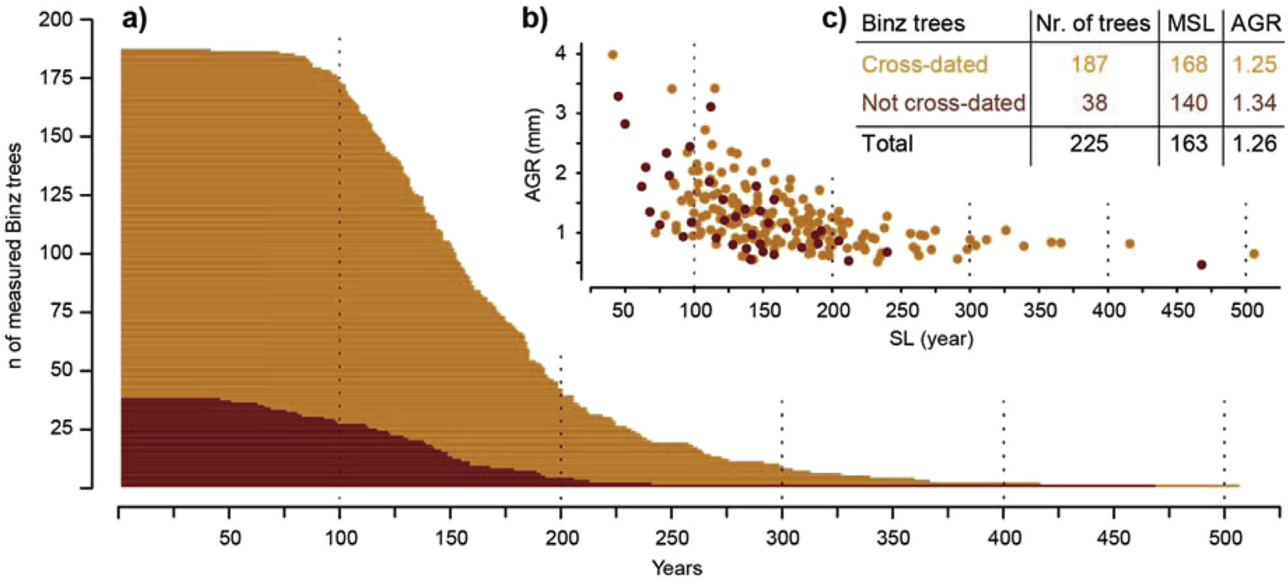

Fig. 3. (a) Age distribution of 225 Binz trees split into 187 cross-dated and 38 non-cross-dated TRW series. (b) Average growth rate (AGR) in mm/year of the Binz trees plotted against their segment length (SL) in number of years, with the inset (c) providing further details on the AGR and mean segment length (MSL).

Table 1
Basic statistics of the Binz TRW groups (MSL = mean segment length; AGR = average growth rate).

Group	No. of trees	Group length (years)	MSL (years)	AGR (mm)	Inter-series correlation (Pearson's r)
Binz 1a	44	523	214	1.02	0.507
Binz 1 b	5	249	181	0.93	0.425
Binz 1c	13	334	162	0.98	0.530
Binz 1 d	2	104	103	1.06	0.623
Binz 2a	80	238	144	1.5	0.558
Binz 2 b	6	210	194	0.92	0.522
Binz 6	22	216	128	1.2	0.465
Binz 7	8	298	185	1.06	0.544
Binz 10	7	557	264	1.12	0.431

of a robust amount of ^{14}C-dates (see SM2), and/or secure dendro links with other Binz groups (Fig. 5). Binz Group 2a and 2 b cross-date with a T_{BP} of 6.0 and were further wiggle-matched by eleven ^{14}C-dates. Sound cross-dating results were also obtained between Binz Group 1a-d, secured by a total of 22 ^{14}C-measurements. The original eight ^{14}C-dates from Binz Group 7 indicate a position within the YD, while Binz Group 10 dates within tvhe Preboreal (twelve ^{14}C-measurements).

After initial cross-dating and independent positioning of the individual Binz groups through ^{14}C-dating, the groups were cross-dated against the previously constructed floating SWILM and Swiss YD chronologies, as well as the southern German PPC (Fig. 5). The subdivision of SWILM into its contributing chronologies provides further insight into regional TRW variations. The integration of new and old material strengthens the positioning of the floating chronologies and helps identifying gaps and periods of weak replication within the Swiss LG material. The reassessment of the SWILM chronology reveals high *t*-values between the LANDIKON and GAENZILOO chronologies originating from either side of the Uetliberg in Zurich (Figs. 2b and 6). Their comparison to the six floating Daettnau chronologies collected ~40 km northeast of Zurich reveals a slight decrease in correlation. Notably, the floating chronologies reaching into the Bølling, DABEOAL and DABOEACH, indicate a reduction in correlation to the oldest and least replicated portion of LANDIKON. Within the Allerød, the weakest statistical correlation within the SWILM composite is obtained from DAELACH3, the chronology indicating the LSE eruption (Friedrich et al., 1999), and is positioned on the basis of ^{14}C-dating and good cross-dating results against chronologies from southern Germany. Kaiser's floating chronologies in the YD (YD-A, YD-B; Kaiser et al., 2012) do not correlate at their current position, nor do they correlate with most recent part of the SWILM. After revision of the previously constructed YD-C chronology, cross-dating and ^{14}C-(dis-)agreement resulted in its separation into a modified YD-C and a new YD-D chronology (Fig. 4). Preboreal YD-C now consists of four trees and spans 375 years, indicating good *t*-values compared to the German and Swiss chronologies of the PPC (Fig. 5). The newly developed floating YD-D chronology (235 rings) consists of three trees from the Wiedikon site and is ^{14}C-dated into the younger part of the YD (see SM3). No dendro link to further YD trees or chronologies could be verified so far.

The Binz groups demonstrate good cross-dating results between each other and/or to the SWILM chronologies, except for Binz Group 6 that does not indicate a valid dendro link (Fig. 5). While the Binz Groups 2a and 2 b show a secure dendro link (T_{BP} of 6.0), Binz Group 2 b indicates similar high values compared to the LANDIKON chronology (T_{BP} of 6.0). A decrease in coherency is found when comparing Binz Group 2a and LANDIKON (T_{BP} of 2.3). Similarly, during the Allerød, comparison between the Binz groups to the SWILM chronologies from Zurich result in reliable *t*-values. Cross-dating results generally improve between groups and chronologies during periods of increased sample replication (Fig. 5). Binz

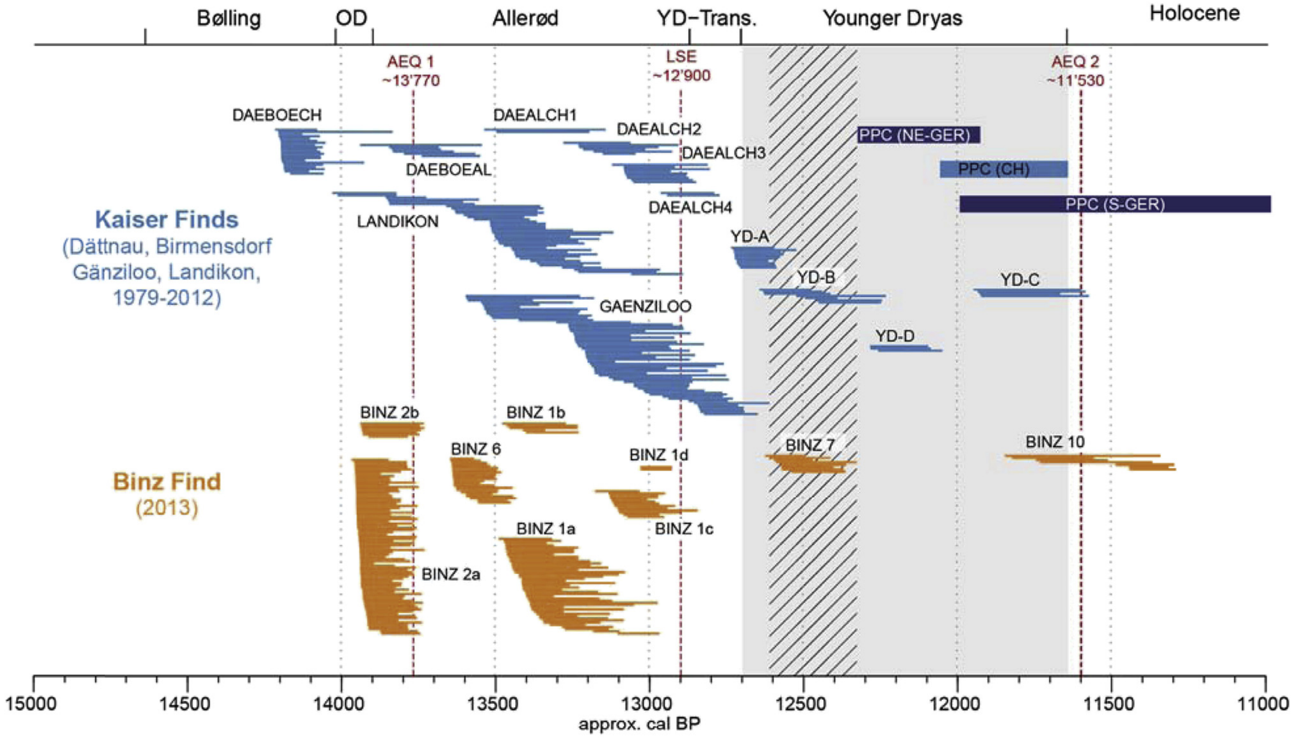

Fig. 4. Temporal distribution of all Swiss LG chronologies, including the Binz material (orange), and the absolutely dated PPC (blue) (Kaiser et al., 2012; Friedrich et al., 2004). Each horizontal bar represents one tree. The grey shading refers to the YD with dashed lines indicating the gap between the absolutely dated PPC and floating SWILM TRW chronologies. The vertical dashed red lines show the Laacher See Eruption (LSE, Litt et al., 2003) and two Alpine earthquakes (AEQ, Strasser et al., 2006). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

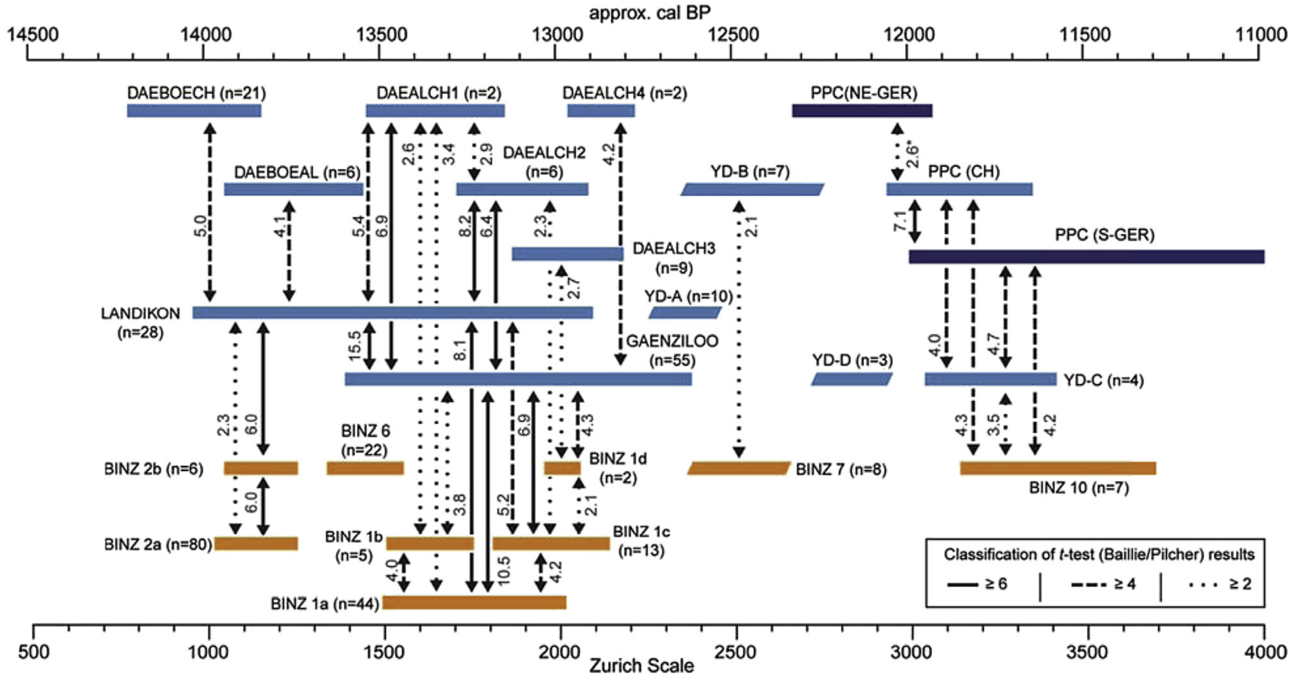

Fig. 5. Cross-dating statistics between the Swiss TRW chronologies (light blue), the Binz groups (orange), and the absolutely dated PPC (dark blue; Friedrich et al., 2004; Kaiser et al., 2012). The t-values (Baillie and Pilcher, 1973) between different chronologies and groups are shown next to the cross-dating-dependent scaled arrows. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

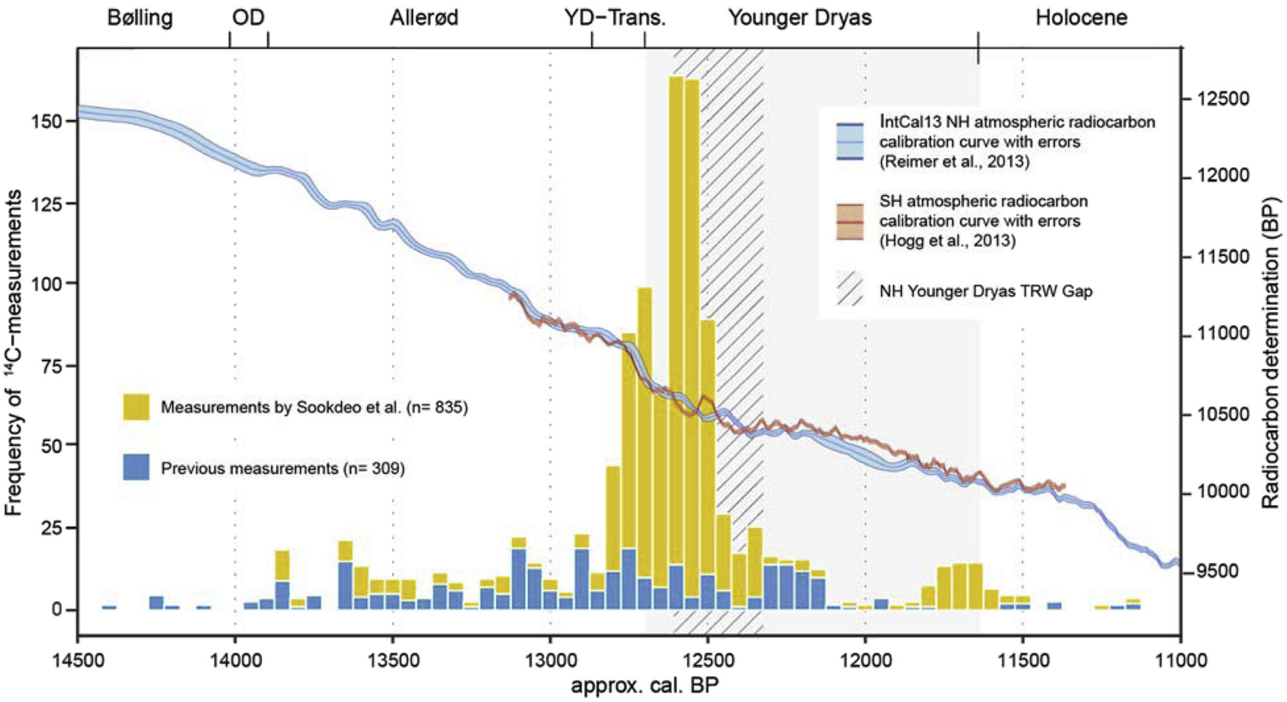

Fig. 6. Radiocarbon measurements so far included in IntCal13 (blue), as well as those produced within the Binz project (yellow). Grey shading denotes the YD with dashed lines indicating the gap between the absolutely dated PPC and floating SWILM chronologies. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Group 1 (n = 44), for instance, is securely linked to LANDIKON (n = 28; T_{BP} of 8.1) and GAENZILOO (n = 55; T_{BP} of 10.5). In addition, a longer overlap between chronologies supports the cross-dating. Similar to the previously constructed Zurich chronologies, correlation of the Binz groups to the Daettnau chronologies is lower. Within the YD, a weak dendro link is established between Kaisers' floating YD-B chronology and Binz Group 7. However, careful re-evaluation of the composite chronology YD-B indicates partly diverse TRW signals between the three contributing sites (Gaenziloo, Birmensdorf and Wiedikon). Revised cross-dating depicts a clear dendro-link (T_{BP} of 4.8) between Binz Group 7 and the mean of three Gaenziloo trees of YD-B (YD-B_GAE) over 160 years (see SM4), whereas the link to the other sites is weak. No link is found between Binz Group 7 and YD-A. Furthermore, Binz Group 10 is absolutely dated against the Southern German and Swiss PPC, now showing good agreement to the revised YD-C chronology.

4. Discussion

4.1. Dendrochronological characteristics of the Binz find

The discovery of 253 subfossil pines in Zurich, Switzerland, resulted in nine independent LG TRW groups. The distribution of the new Binz groups throughout most of the LG period is in good agreement with previously discovered subfossil trees from Switzerland (Kaiser et al., 2012; Schaub et al., 2008b). The majority of the Swiss LG trees grew in the Allerød, yet, a few samples are positioned in the YD (Fig. 4). The unique geomorphological situation on the flanks of the Uetliberg with its dense and hermetically sealing clay packages facilitated the preservation and recovery of LG subfossil material of excellent quality. Disturbance signals during the trees' juvenile growth, together with high decomposition rates of the outer sapwood rings, however, complicated the chronology development process (Fig. 3b and c). Synchronized germination dates of the Binz Group 2a possibly indicate a first reforestation phase in the Swiss northern pre-Alps around 14′000 BP. The observation of a consistent dieback of these trees is inhibited by the applied conservative measurements approach, as measurements were terminated as soon as clear tree-ring identification at the outer, decayed part of a sample was questionable. However, germination and steady die-off, as well as the subsequent decrease in sample replication could indicate an ecological response. The now abundant replication during the dynamic geomorphological transition from the LGM into the Holocene possibly captures major Alpine earthquakes (Strasser et al., 2006) (Fig. 4). Assessment of the MSL and AGR of the individual Binz groups does not reveal obvious relationships (Table 2). Yet, slightly higher SL during putative periods of more stable climate can be observed, such as in those Binz groups dated into the Allerød and Preboreal.

Although the new Binz material improves the Swiss LG records, its material is not equally distributed throughout time. Clusters of abundant replication match previously recovered material dated into the Bølling and Allerød, which represent relatively warmer and climatically more stable periods (Fig. 6). Furthermore, the newly dated material does not extend the Swiss chronologies back in time, prohibiting additional annually resolved insight into the environmental conditions in the Bølling. The limited number of only eight Binz trees securely cross-dated into the YD emphasizes the challenge of recovering samples within this period. The missing statistical link and weak visual similarities of DAELACH3 and Binz Group 6 to all others could be related to different ecological site conditions. The good cross-dating results among several Swiss chronologies during the LG, however, indicate a similar climatic forcing, Both, the cautious merging of new and previous Swiss LG material and establishment of a revised Swiss LG chronology is inevitable before drawing final conclusions towards environmental signals encoded in the trees.

4.2. Radiocarbon characteristics of the Binz find

The still limited replication of Swiss YD material continues to hinder secure cross-dating of single trees characterized by disturbed growth periods (SM3) and the linkage of the floating with the absolutely dated chronologies. The dependence on these single YD trees can inevitably lead to unsecure chronology positioning, particularly when additional methodological evidence from ^{14}C dating is lacking. As the precision of the IntCal13 reference curve decreases with the end of the absolutely dated tree-ring record (0–12.4 kyr cal BP; Fig. 6), the positioning of single trees through wiggle-matching on the basis of marine records (foraminifera and corals; beyond 12.4 kyr cal BP) deteriorates. As a result, trees from previous sites (LAN004, LAN0062, GAE022, GAE023), that were ^{14}C dated into the YD could not securely be positioned (Schaub, 2007; SM3). The same applies for Binz tree BIN087, also ^{14}C dated into the YD. The decadal-resolved ^{14}C dates bridging the YD from the recently published New Zealand Kauri chronology (Hogg et al., 2016) now allow a more exact placement along the ^{14}C plateau (Fig. 6).

In addition, the recent progress in measurement accuracy of ^{14}C-dating and reduction of required sample material has, likewise, boosted efforts towards improving the resolution of the ^{14}C-calibration curve beyond the YD. A total of 835 ^{14}C measurements, so far produced within the Binz project, have predominantly been performed on single trees dating between the onset of the YD and the Preboreal with annual or bi-annual resolution (Fig. 6). This exceptional number of new high-resolution ^{14}C measurements will not only improve the resolution and replication and thus the quality of the IntCal calibration curve, but will also foster the dating precision of additional single-tree ^{14}C measurements. These improved records will also help tackling questions arising from the observed time-scale offset between ice-core ^{10}Be and tree-ring ^{14}C around 12′000 cal BP (Muscheler et al., 2014). A reassessment on the basis of TRW and new ^{14}C measurements of independent tree-ring chronologies from Switzerland and Germany will shed further light on the cosmogenic radionuclides variation captured by ice-core and tree-ring proxies. The combined assessment of annual TRW and ^{14}C measurements will be particularly important to confirm and may even prolong the earliest part of the PPC, for which consideration of subfossil New Zealand Kauri wood will be essential (Hogg et al., 2016).

The high-resolution results of the Swiss YD material as well as the SH reference curve will be key components for closing the NH ^{14}C gap during the YD. ^{14}C-fluctuations, such as the ~12′800 BP ^{14}C-drop at the onset of the YD, allow now more detailed investigation with the hope of gaining insight into their cause, effect and teleconnection between the hemispheres. This marks a major step in the joint effort of dendrochronological and ^{14}C sciences; towards bridging the gap between absolutely dated and floating TRW chronologies, and aligning NH and SH ^{14}C records. In addition, improved high-resolution ^{14}C measurements will support the dendrochronological cross-dating of Swiss YD tree-ring material. High-resolution AMS measurements on undated tree-ring series can now reduce possible dating uncertainties to 10–20 years, which will ultimately improve cross-dating. The multi-proxy approach will consolidate sample positioning beyond former tentative cross-dating, so far limited by growth disturbances and low replication. Correspondingly, the measurement of additional tree-ring parameters, including maximum latewood density and stable isotopes, might improve cross-dating results (Wilson et al., 2017), facilitating the reconstruction of summer temperatures and hydroclimate, respectively.

4.3. Interdisciplinary relevance of the Binz find

With respect to the still negligible number of European and global LG TRW chronologies, the Swiss material represents an important archive providing unique annually resolved insights into paleo-environmental conditions of the LG. Its local provenance is beneficial compared to existing composite chronologies from central Europe. The data allow to assess regional climatic shifts during the OD and YD cooling periods. Furthermore, the in-situ origin of the Swiss material is of benefit when determining the timing and effect of local geomorphological events potentially triggered by prehistoric earthquakes. Distinct seismic-stratigraphic horizons in sediment cores taken from Lake Zurich and Lake Lucerne show two simultaneous sublacustrine mass-movement deposits before 10′000 cal BP, resulting from subsurface landslides triggered by large earthquakes (Strasser et al., 2006) (Fig. 4). The response of tree-growth to earthquakes has been studied extensively (Carrara and O'Neill, 2003; Jacoby, 1997; Sheppard and Jacoby, 1989). We believe that also the Swiss LG trees on the flanks of the Uetliberg were affected by landslides triggered by alpine earthquakes (Strasser et al., 2008, 2006). Wood anatomical features, such as compression wood and growth reductions, could refer to geomorphological stress, which may provide seasonal resolved dating accuracy.

In the case of a successful bypassing of the YD TRW gap, and expansion of the absolutely dated tree-ring chronology into the LG, the annually resolved archive would advance as a temporal anchor point for multiple LG proxies indicating distinct LSE fingerprints. While its immediate tephra layers are observed in several European lake sediments, LG tree-ring chronologies underlie an implicit climatic reaction aggravating a clear indication dependent on the climatic forcing of the eruption. Nonetheless, reduced tree-ring growth most likely related to the LSE has been identified in the DAELACH3 (Friedrich et al., 1999; Kaiser et al., 2012) and can be used as a reference point. In this respect, high-resolution ^{14}C measurements of DAELACH3 and comparison to both, ^{14}C measurements from Swiss reference chronologies as well as from trees buried by the Laacher See's pyroclastic flow (Baales et al., 1999; Litt et al., 2003), are needed to endorse their correct alignment. Consequently, bridging the YD TRW gap would enable the precise dating the LSE.

The geomorphological conditions of the Uetliberg (Fig. 2) most probably hold potential for further expansion of the Swiss LG archive. Our results hopefully encourage future explorations of construction sites in the greater Zurich area, and promote public awareness of the scientific value and quality of subfossil wood. The successful application of ancient DNA (aDNA) studies on the Binz material is an indication of the woods' well-preserved state exemplifying the broad scientific outreach underlying this find (Lendvay et al., 2018). Laser irradiation coupled with bleaching and surface removal eliminated modern contaminating DNA and allowed metabarcoding screening on eleven Binz samples. Through this newly developed systematic pretreatment method the existence of aDNA within the material could be verified (Lendvay et al., 2018) facilitating future in depth aDNA analysis of population dynamics at one location during a uniquely dynamic period. Additionally, all selected samples could be genetically determined as Scots pine (*Pinus sylvestris* L.) giving further insight into the LG Swiss ecosystem. The distinction between Scots pine and mountain pine (*Pinus uncinata* Ramond) is not feasible through wood anatomical analyses (Schweingruber, 1990) and therefore the exact species classification was subject of debate (Kaiser, 1979; Kaiser et al., 2012; Schaub et al., 2008a, 2008b, 2005).

5. Conclusions

The now available quality and quantity of this Swiss LG material will eventually help to extend the absolutely dated chronology beyond the YD. We emphasize the cross-disciplinary scientific applications and potential of these LG pines. The combination and joint evaluation of various proxy archives will lead to an improved understanding of environmental changes during the LG. The Swiss LG tree-ring archive will hopefully contribute to such studies.

Author contributions

UB, DN and FR initiated the study, and all authors contributed to discussion. AS and LW performed radiocarbon measurements and interpreted the results together with BK, while DN, MF and FR carried out TRW measurements. BK and MF provided relevant information on previous attempts to build dendrochronological records for the Younger Dryas. FR and UB wrote the paper with input from all authors.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.quascirev.2018.02.019.

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