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ILLUMINATING INTCAL DURING THE YOUNGER DRYAS

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ABSTRACT. As the worldwide standard for radiocarbon (^{14}C) dating over the past ca. 50,000 years, the International Calibration Curve (IntCal) is continuously improving towards higher resolution and replication. Tree-ring-based ^{14}C measurements provide absolute dating throughout most of the Holocene, although high-precision data are limited for the Younger Dryas interval and farther back in time. Here, we describe the dendrochronological characteristics of 1448 new ^{14}C dates, between ~11,950 and 13,160 cal BP, from 13 pines that were growing in Switzerland. Significantly enhancing the ongoing IntCal update (IntCal20), this Late Glacial (LG) compilation contains more annually precise ^{14}C dates than any other contribution during any other period of time. Thus, our results now provide unique geochronological dating into the Younger Dryas, a pivotal period of climate and environmental change at the transition from LG into Early Holocene conditions.

KEYWORDS: dendrochronology, IntCal, Late Glacial period, radiocarbon AMS dating, Switzerland.

INTRODUCTION

The 2013 International Calibration Curve (IntCal13; Reimer et al. 2013a) is the "gold standard" for geochronological ^{14}C dating over the past ~50,000 years. Based on ^{14}C measurements from tree rings, plant macrofossils, speleothems, corals, and marine sediments, the IntCal dataset is regularly updated towards higher resolution and precision (Reimer et al. 2013a). Accounting for $^{14}C/^{12}C$ variations in various proxy archives of the Holocene (e.g., tree rings) and even well into the Pleistocene (e.g., plant macrofossils, speleothems, and corals), reservoir standardization and intercomparisons between hemispheres and archives are key factors for the establishment and maintenance of IntCal (Reimer et al. 2013b).

Due to their resolution and independent cross-dating (Büntgen et al. 2018), tree-ring-based, annual to subdecadal ^{14}C measurements form the backbone of the calibration curve throughout the Holocene. The "Holocene Oak Chronology" by Becker (1993), together with the "Preboreal Pine Chronology" from Central Europe represent the longest absolutely dated tree-ring record securely extending back to 12,325 cal BP (PPC; Spurk et al. 1998; Friedrich et al. 1999, 2004; Reinig et al. 2018a). A lack of subfossil wood from across the Northern Hemisphere (Reinig et al. 2018a), however, challenges IntCal precision during the preceding Younger Dryas (YD), so that the "Swiss Late Glacial Master

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Chronology" covering the Allerød and Bølling is still floating (SWILM; Kaiser et al. 2012). Although the SWILM positioning has recently been improved by high-resolution ^{14}C measurements from New Zealand's subfossil Kauri wood (*Agathis australis*; Hogg et al. 2016), interhemispheric wiggle-matching (Bronk Ramsey 2001) remains challenging (Muscheler et al. 2014).

In order to better understand IntCal during the Younger Dryas, this study details the dendrochronological characteristics of 1448 new ^{14}C dates between ~11,950 and 13,160 cal BP from 13 subfossil Scots pine trees (*Pinus sylvestris* L.) that were growing in Zurich, Switzerland. The exceptional quality (resolution) and quantity (replication) of this new LG ^{14}C compilation significantly improves ^{14}C wiggle-matching and dendrochronological cross-dating during the YD.

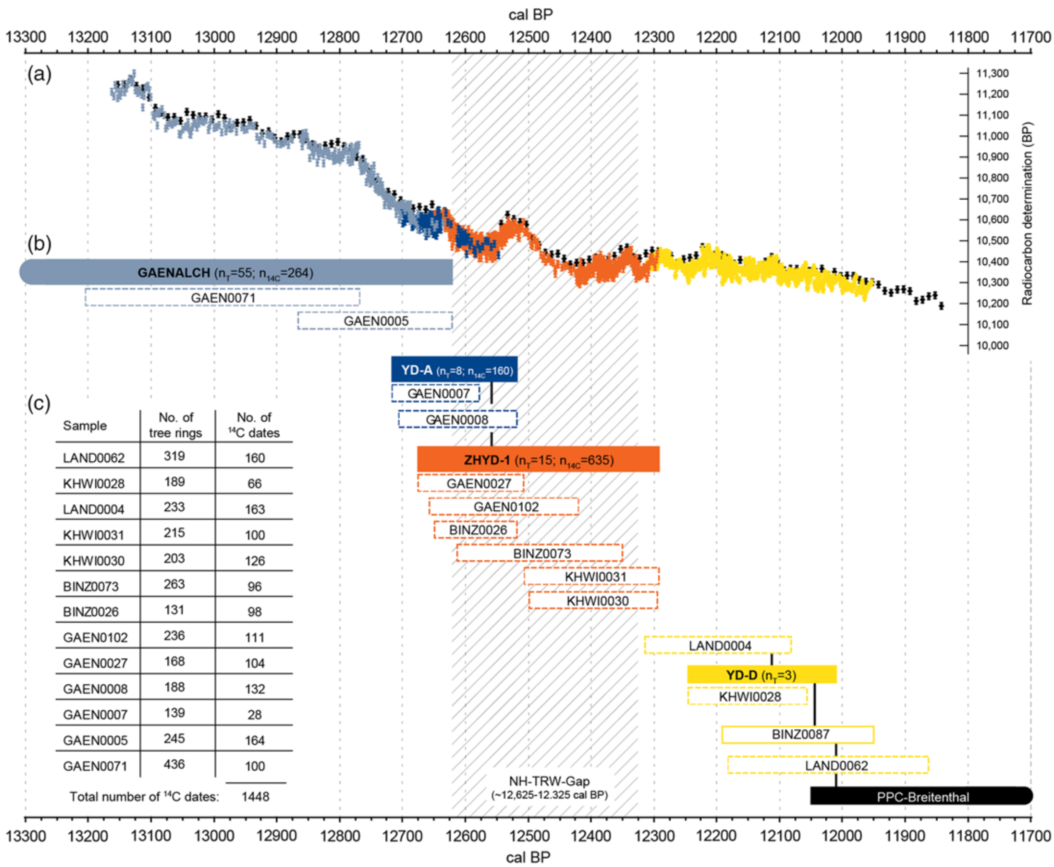
MATERIAL AND METHODS

At various construction sites in Zurich more than 400 subfossil pines were discovered and excavated between 1973 and 2013 (Kaiser et al. 2012; Reinig et al. 2018a). Cellulose-based ^{14}C measurements supported tree-ring width (TRW) dating of the material between ~14,000–11,500 cal BP (Figure 1; Reinig et al. 2018a). After sanding down the samples with up to 400 grain size sandpaper, at least two TRW radii per disc were measured and cross-dated using a LINTAB device (precision of 0.01 mm) and TSAP-Win software (both RINNTECH, Heidelberg). The TRW measurements where visually and statistically cross-dated considering t-values (t_{BP}) and Gleichläufigkeit (Glk) indices (Baillie and Pilcher 1973) in TSAP-Win. Chronologies were established and checked with COFECHA (Holmes 1983).

A subset of 13 YD trees from the Zurich sites Gaenziloo, Krankenheim Wiedikon, and Binz (Reinig et al. 2018a) was selected and individual tree rings separated (Figure 1b). High-precision ^{14}C AMS measurements were performed at the Laboratory of Ion Beam Physics, ETH-Zurich, on a "MIniCArbonDatingSystem" (MICADAS, Sookdeo et al. 2020). Wood of 2–4 consecutive rings was pooled, if material from a single ring was <20 mg. Holocellulose was extracted by the base-acid-base-acid method (Nemec et al. 2010), bleached and graphitized with an AGE system (Wacker et al. 2010). The ^{14}C blanks, standards and references were continuously cross-checked in accordance with the ETH quality protocol (Sookdeo et al. 2019), ensuring the accuracy and comparability of the resulting 1448 ^{14}C dates (Figure 1a). The floating ^{14}C records derived from the individual trees were wiggle-matched to the Southern Hemisphere (SH) ^{14}C Kauri record (Hogg et al. 2016) using a χ^2 test (Sookdeo et al. 2020).

RESULTS AND DISCUSSION

The combination of TRW cross-dating and high-resolution ^{14}C wiggle-matching of 13 trees from Zurich closes the geochronological gap in the YD (Figure 1b). The samples are grouped into three distinct YD periods from ~11,950 to 13,160 cal BP, during which good agreement is found within and between the TRW and ^{14}C measurements. Low sample size, juvenile growth disturbance and enhanced wood decay in the outer section of the samples (Reinig et al. 2018b), however, still challenges the establishment of a continuous, absolutely dated tree-ring chronology throughout the entire YD. The youngest trees are securely linked by dendrochronology and ^{14}C to the absolute chronology (12,314–11,863 cal BP), whereas the older trees yet remain floating.



Sample	No. of tree rings	No. of ^{14}C dates
LAND0062	319	160
KHWI0028	189	66
LAND0004	233	163
KHWI0031	215	100
KHWI0030	203	126
BINZ0073	263	96
BINZ0026	131	98
GAEN0102	236	111
GAEN0027	168	104
GAEN0008	188	132
GAEN0007	139	28
GAEN0005	245	164
GAEN0071	436	100
Total number of ^{14}C dates:		1448

Figure 1 Temporal distribution of the Swiss YD tree-ring records and corresponding 1448 ^{14}C measurements (Sookdeo et al. 2020). High-resolution ^{14}C measurements of the Northern Hemisphere GAENALCH (light blue dots), YD-A (dark blue) and ZHYD-1 (orange dots) chronology and single tentative linked trees (yellow dots) wiggle-matched against the SH ^{14}C Kauri record (black dots, Hogg et al. 2016) now bridge the YD (a). An absolute dendrochronological link between the corresponding ^{14}C-measured trees (dashed bars) and Swiss TRW chronologies (filled bars) throughout the YD has not yet been established (b). However, the overall potential window for a temporal shift of the TRW records is minimal (± 8 yr, 2σ). Dashed lines indicate the Northern Hemispheric TRW gap between the absolutely dated PPC (Friedrich et al. 2004) and floating SWILM chronology (Kaiser et al. 2012). Sample replication (n_T) and total amount of ^{14}C dates (n_{14C}) of each chronology is provided in parentheses. (c) Table of high-resolution ^{14}C-measured trees, outlining the trees' total number of rings and ^{14}C dates. (Please see electronic version for color figure.)

Link between YD Swiss Trees and the PPC

The ^{14}C record of PPC was recently extended back to 12,049 cal BP by including previously undated trees from Breitenthal in southern Germany (PPC-Brei, Sookdeo et al. 2019), which allows the tentative cross-dating of two trees from the Zurich collection against the now improved German record. These two Swiss trees indicate good comparative t-values (t_{BP} = 4.6, GLK = 66; OVL = 231) and synchronicity in both high frequency and long-term trends (see SM2). The ^{14}C measured tree "LAND0062" cross-dates with an overlap (OVL) of 187 years with PPC-Brei at t_{BP} = 3.1 (Glk = 59), while BINZ0087 cross-dates to PPC-Brei at t_{BP} = 2.9 (Glk = 57) over 99 years (Table 1). The YD-D ring width chronology, compiled from three trees from the site Krankenheim-Wiedikon in Zurich,

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Table 1 Cross-dating results of all high-resolution ^{14}C dated Swiss trees and BINZ0087 in the obtained three dendrochronological YD periods (SM5).

Sample	Reference	YD-period	t_{BP}	Gleichläufigkeit (Glk)	Overlap (OVL)
LAND0062	PPC-Brei	Tentative linked to PPC	3.1	59	187
BINZ0087	PPC-Brei	Tentative linked to PPC	2.9	57	99
LAND0062	BINZ0087	Tentative linked to PPC	4.6	66	231
BINZ0087	YD-D	Tentative linked to PPC	3.5	54	180
BINZ0087	YD-D(cut)	Tentative linked to PPC	4.8	60	103
KHWI0028	YD-D	Tentative linked to PPC	16.5	78	189
LAND0004	YD-D	Tentative linked to PPC	4.1	64	164
LAND0004	KHWI0028	Tentative linked to PPC	3.5	60	164
GAEN0027	ZHYD-1	Floating YD chronologies	7.0	70	162
GAEN0102	ZHYD-1	Floating YD chronologies	3.1	58	236
BINZ0026	ZHYD-1	Floating YD chronologies	6.1	69	131
BINZ0073	ZHYD-1	Floating YD chronologies	5.3	63	263
KHWI030	ZHYD-1	Floating YD chronologies	5.0	61	203
KHWI0031	ZHYD-1	Floating YD chronologies	4.6	70	213
GAEN0007	YD-A	Floating YD chronologies	3.4	65	130
GAEN0008	YD-A	Floating YD chronologies	6.6	71	152
GAEN0005	GAENALCH	YD Transition	6.3	64	207
GAEN0071	GAENALCH	YD Transition	11.1	68	436

including ^{14}C data of tree KHWI0028 (Reinig et al. 2018a; Sookdeo et al. 2020), shows good visual and statistical coherence with BINZ0087 (Table 1; SM2). Cross-correlation of BINZ0087 improves to $t_{BP} = 4.8$, when excluding the 77 outermost and disturbed rings from YD-D (YD-Dcut). LAND0004, the oldest ^{14}C dated tree of this absolutely dated chronology, is securely connected to YD-D (see SM2) and extends the chronology back to 12,314 cal BP. All established dendrochronological placements were found to be in accordance with the overlapping 389 high-resolution ^{14}C dates of the three trees (Figure 1c; Sookdeo et al. 2020). While the dendrochronological link between the Swiss and German pines is tentative, as the underlying Swiss sample size is low ($n = 6$), the good agreement with ^{14}C wiggle-matching (± 8 years (2σ); Sookdeo et al. 2020) securely links these tree-ring chronologies. This Swiss record represents with its ^{14}C support an important YD anchor to the PPC, for both ^{14}C wiggle-matching and future dendrochronological cross-dating.

Floating Swiss YD Chronologies

Two floating TRW chronologies and corresponding high-resolution ^{14}C measurements have been produced for the YD. ZHYD-1 is a chronology of 15 trees from the Zurich sites Gaenziloo ($n = 4$), Krankenheim Wiedikon ($n = 3$) and Binz ($n = 8$), reaching a cumulative length of 384 years. The six trees selected for ^{14}C measurements indicate good agreement to establish a robust mean curve, independent of their site of origin (see SM3). Interseries correlations between these trees range from $t_{BP} = 3.1$ to $t_{BP} = 7.0$, and all trees overlap by at least 131 years within the ZHYD-1 chronology (Table 1). The TRW-based dating is reinforced by 635 high-resolution ^{14}C measurements (Figure 1c; Sookdeo et al. 2020), supporting the chronology particularly during periods of relatively weak replication. When developing ZHYD-1, two trees from Birmensdorf, originally included in the YD-B chronology (Kaiser et al. 2012), were removed, as their revised TRW measurements and additional ^{14}C dates proved their dating to be incorrect. Instead, the Binz material discovered in 2013 serves as the link between the oldest Gaenziloo and youngest Krankenheim Wiedikon trees in the chronology. The ^{14}C dates from ZHYD-1, wiggle-matched against the SH Kauri ^{14}C record (Sookdeo et al. 2020), suggested an TRW overlap of ~20 years to LAND004 from the absolutely dated Swiss trees (Figure 1a,b). However, no valid dendrochronological link could be established as decay in the outermost rings of KHWI0030 and KHWI0031, as well as juvenile growth disturbances in LAND0004, challenge the extension of the absolute record.

The revised YD-A chronology from Kaiser et al. (2012), excluding decayed and disturbed TRW sections, represents the second floating chronology from Switzerland in the YD comprising of a total of eight trees and reaching a length of 199 years. The chronology is well-replicated over the first 140 years, but sample depth rapidly decreases thereafter. The youngest 35 years are represented by only one tree (GAEN0008). Due to the low replication, the TRW chronology displays increased variability over the most recent 60 years, limiting a secure cross-dating to ZHYD-1 and leading the obtained dendrochronological link to remain tentative. However, within YD-A the two high-resolution ^{14}C dated trees show good agreement to the YD-A mean curve (Table 1; see SM3). GAEN0007 (28 ^{14}C dates) cross-dates at $t_{BP} = 3.4$ to the YD-A mean (Glk = 65; OVL = 130), while GAEN0008 (132 ^{14}C dates) is securely integrated in this chronology ($t_{BP} = 6.6$, Glk = 71; OVL = 152). These placements are coherent with the ^{14}C wiggle-matching results (Figure 1c; Sookdeo et al. 2020). Based on ^{14}C wiggle-matching of the individual Swiss chronologies to the SH ^{14}C Kauri record and their obtained dendrochronological linkage, the combined record was shifted by seven decades, compared to the former YD-B position obtained through calibration using IntCal13 (Sookdeo et al. 2020). Nonetheless, additional dendrochronological analyses are necessary to conclusively verify the link between YD-A and ZHYD-1. The improved sample size in the YD may allow the cross-dating of additional ^{14}C dated YD tree-ring samples from Switzerland and Central Europe, facilitating temporal and spatial extensions of the record. The investigation of potential climate signals throughout the YD will hopefully become feasible.

Younger Dryas Transition

GAEN0005, with 245 rings, is the youngest tree included in the Gaenziloo chronology (GAENALCH; $n = 55$; Kaiser et al. 2012) and represents the final portion of SWILM (Kaiser et al. 2012). With an overlap of 207 years, GAEN0005 is securely cross-dated into GAENLACH ($t_{BP} = 6.3$; Glk = 64, Table 1; see SM4), and the now new 164 ^{14}C measurements (Sookdeo et al. 2020) cover the transition from the Allerød into the YD (Figure 1c). The striking ^{14}C increase of GAEN0005 is confirmed by high-resolution ^{14}C measurements on LG pines from southern France (Capano et al. 2018). Nonetheless, no dendrochronological link could be established between the southern and northern Alpine sites. The distance between the sites, the varying climatic forcing, and the changing micro-site growth conditions might all contribute to their disagreement in TRW.

The long overlap (436 years), and high correlation ($t_{BP} = 11.1$; Glk = 68; Table 1), demonstrate a secure link between GAEN0071 and the well-replicated GAENALCH chronology (see SM4). The now newly obtained 100 additional ^{14}C dates at 3-yr resolution from GAEN0071 (Sookdeo et al. 2020) will further improve the calibration towards the end of the Allerød (Figure 1c). In addition, the confirmed decreasing ^{14}C structure between

~12,800–12,550 cal BP serves as an important period for wiggle-matching LG ^{14}C records globally. Their alignment along this distinct ^{14}C feature, obtained through the new high-resolution data, will support the correction of dating discrepancies among various ^{14}C records. Accordingly, as the SWILM chronology is now shifted by 35 ± 8 years (2σ) after wiggle-matching to the SH Kauri ^{14}C record (Sookdeo et al. 2020), it can serve as a basis for additional high-resolution ^{14}C measurements back to ~14,226 cal BP. In comparison to the dating precision of IntCal13 (± 20, 1σ), this marks a significant improvement. Cross-dating and ^{14}C wiggle-matching of additional European and global tree-ring records can now be performed at higher temporal precision, which will eventually also improve dating accuracy throughout the Bølling and Allerød.

CONCLUSIONS

This study provides dendrochronological insight into 1448 new ^{14}C dates from 13 pine trees that were growing in Switzerland between ~11,950 and 13,160 cal BP. Coherency between TRW cross-dating and ^{14}C wiggle-matching substantially improves the dating accuracy during the transition from the LG into the Early Holocene. Compared to their previous placement in IntCal13, the Swiss YD chronologies and the SWILM were shifted older by 70 and 35 years, respectively.

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SUPPLEMENTARY MATERIAL

To view supplementary material for this article, please visit https://doi.org/10.1017/RDC.2020.15

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