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Dendroglaciology

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Introduction

Dendroglaciology is a branch of dendrochronology that uses tree rings to study and date the movement of glaciers (Luckman, 1988; Schweingruber, 1988). Most early dendroglaciological investigations focused on determining annually-resolved moraine ages to date the timing of maximum glacier extent (Tarr and Martin, 1914; Matthes, 1939; Mathews, 1951), or on documenting glacial recession rates by dating successional trends on recently deglaciated surfaces (Cooper, 1916; Lawrence, 1950; Sigafoos and Hendricks, 1961). The age of moraines and other glacial deposits are commonly determined by counting the annual growth rings of the oldest tree found growing on the surface, taking into account sampling protocol and the lag between glacier retreat and tree germination. More complex scenarios involve dating changes in stem geometry or ring-width patterns, scars, and the inclusion of glacier-killed trees.

The substantial glacier recession of this century has continued to expand the opportunities for advancing dendroglaciological studies by exposing the remains of forests buried by glacier advances at various times in the Holocene (Reyes and Clague, 2004; Wood and Smith, 2004,) and Little Ice Age (Luckman, 1995; Smith and Laroque, 1996). These discoveries have allowed for the development of millennia-long tree-ring chronologies in glaciated environments worldwide (Luckman, 1994; Barclay *et al.*, 1999), significantly increasing the spatial and temporal potential of using dendroglaciological methodologies to discern Holocene glacier fluctuations.

An advantage of traditional dendroglaciological methods over other geobotanical dating methods (i.e., lichenometry) is the ability to determine the age of glacier deposits with annually resolved accuracy. The development of lengthy tree-ring chronologies also allows for comparison of accurately dated deposits over large areas, essential for assessing the synchroneity of global glacier activity to climate forcing mechanisms at different timescales (i.e., decadal vs. century) (Luckman and Villalba, 2001).

Applied Dendroglaciology

Although traditional dendroglaciological techniques make it possible to date the timing of glacier advances and the maximum glacier extent (Luckman, 1988), they provide little insight into the attendant climate conditions or duration of glacier advances (Porter, 1981; Luckman, 2000). By contrast, applied dendroglaciological research has successfully established linkages between glacier mass balance and tree-ring-width variability, with Bray and Struik (1963) being among the first to relate below average tree-ring growth (narrow rings) to Little Ice Age glacial advances. LaMarche and Fritts (1971) and Matthews (1977) subsequently directly related tree-ring-width variability to climate conditions, and subsequently to glacier fluctuations. They discerned that high winter snow accumulation, and short, cool, and cloudy summers favored positive glacier mass balance, but were detrimental to tree growth and resulted in narrow annual tree rings. Conversely, warm summer air temperatures and a greater number of sunny days were shown to result in enhanced glacial ablation, as well as increased radial growth rates and the production of wider annual growth rings.

Since the growth rings of climatically sensitive trees respond inversely to the same variables that drive glacier mass balance, dendroglaciological techniques provide a means for developing glaciological histories in remote areas without mass balance data (Lewis and Smith, 2004; Larocque and Smith, 2005; Pelfini *et al.*, 2005). This recognition has led to the construction of proxy glacier mass balance records (Nicolussi and Patzelt, 1996; Lewis and Smith, 2004; Watson and Luckman, 2004). Given the robust nature of these dendroglaciologically derived multi-century reconstructions, the development of millennial-scale high-resolution tree-ring records has the potential to develop continuous glacier mass balance records back through the Holocene. These records can be used in conjunction with tree-ring dated moraines to provide a more complete picture of paleoglacier-climate relationships, useful for understanding how glaciers may respond to predicted future climate change scenarios (Matthews and Briffa, 2005).

Dendroglaciological Methodologies

Various types of tree-ring evidence are used to date glacial fluctuations and their associated deposits:

(1) the age of the oldest tree found on a landform within the glacial forefield;
(2) dating of abrupt changes in growth rates or ring symmetry of trees that were tilted or in close proximity to the glacier;
(3) the date of ice-related corrasion scars on trees produced either by glacial contact, or by contact with ice proximal debris ‘bulldozed’ forward by the glacier; and
(4) the age of trees that were killed by an advancing glacier (**Table 1**) (Sigafoos and Hendricks, 1969; Luckman, 1998; Schweingruber, 1988). In most cases, trees that were directly affected by an advancing glacier (i.e., tilting or ice-contact scarring) but continued to live, provide for the most precise dating of glacial events.

The first three dating methods utilize living or dead trees to provide dating control, whereas the last method involves using evidence collected from glacially-buried stumps, boles, or detrital wood. When using trees for dating control, a count of the annual growth rings provides a minimum age for the landform, the year the tree was tilted, or the date of the damage to the stem (Lawrence, 1950; Luckman, 1988). When a glacier front recedes in response to ameliorating climate conditions, ‘fresh’ substrate exposed at the ice front may be progressively colonized by tree seedlings, with progressively younger trees found closer to the glacier front (Sigafoos and Hendricks, 1969). If this was the case, the germination date of the oldest tree growing on a substrate provides a minimum estimate of the surface age and the minimum date for the glacier event associated with stabilization of the glacial deposit (Sigafoos and Hendricks, 1969; McCarthy and Luckman, 1993). Trees found growing on deposits within the glacial forefield also provide a bracketing date for the transition to climate conditions favouring glacial retreat (Porter, 1981).

All wood samples must be cross-dated with a master tree-ring chronology to minimize the possibility of including missing or false rings, which can result in over- or under-estimation of the actual tree age

Table 1 Dendroglaciological dating methods

Type of Evidence	*Dating Precision*	*Information Provided*	*Potential Limitations*
Trees growing on landforms in the glacier forefield.	– 10 years or greater.	– Age of the oldest tree provides minimum estimate for surface age.	– Ecesis interval can be difficult to estimate. – Assumption that the oldest tree has been sampled.
Abrupt change in ring symmetry as a result of tilting.	– Exact calendar date of tilting event.	– Date of eccentric or abnormal growth indicates onset of event.	– Event may be severe enough to kill the tree and would require crossdating.
Ice-contact scars.	– Exact calendar date of damage or ice-contact event.	– Damage date indicates glacier position at a specific time.	– Scarred, living trees are often difficult to find. – Dead trees require crossdating.
Trees killed by glacier.	– Exact calendar date of tree death.	– *In-situ:* kill date indicates glacier position at a specific time. – *Detrital wood* provides limiting date for glacial event.	– Requires crossdating to determine tree age or kill date. – Dating precision for an event depends on preservation of wood and loss of outer rings.

(**Fig. 1**). Sampling uncertainties that need to be addressed when using trees to date glacier deposits include:

(1) whether or not the oldest tree on the moraine has been sampled;
(2) the number of years (growth rings) lost when samples are recovered on the stem above ground level;
(3) if the pith was not reached during sampling;
(4) the number of years to the tree center;
(5) the ecesis interval – the time between surface exposure and colonisation of the first tree (**Table 2**) (Lawrence, 1950; Sigafoos and Hendricks, 1969; McCarthy *et al.*, 1991).

Figure 1 Seventeen glacially-sheared stumps in growth position were exposed by stream avulsion at the terminus of the Saskatchewan Glacier in 1999. The stumps were buried beneath the glacier until historical recession and stream incision exposed the 225- to 262-year-old stand of sub-Alpine fir, Englemann spruce, and whitebark pine trees. Crossdating showed that all the subfossil stumps and boles exposed at this location were killed during a Neoglacial advance of the Saskatchewan Glacier (2,910 ± 60 to 2,730 ± 60 ^{14}C years BP).

Oldest Tree

On heavily forested moraines, the oldest tree is often hard to identify, as the relationship between tree age and girth, height, or branch spacing is uncertain and varies greatly between species. Although there is no absolute method for ensuring the oldest tree has been identified, sampling all of the trees on the landform, or at least an adequately large sub-sample of the population, will increase the probability of identifying the oldest tree. Another sometimes more difficult consideration is whether the trees on the deposit are first-generation trees or not (Sigafoos and Hendricks, 1969). If large dead boles litter the forest floor, the living, upright trees may be of a later generation and only a minimum surface age can be assigned if only live trees are sampled.

When dating moraines using trees it is also important to consider the location where the tree was sampled: was it growing on a proximal face, a crest, or the distal face of a deposit? For instance, trees sampled from the proximal face of a moraine were only able to colonize after the glacier had retreated and the surfaced stabilized. In contrast, trees growing on the distal face of a moraine may have germinated while the glacier was still in contact with the proximal face.

Table 2 Potential tree-ring dating errors and associated correction factors

Potential Dating Error	*Error Term*	*Method of Calculation*
OT = Oldest Tree	= 0 if all trees are sampled	Sample all trees if possible
HE = Height-Age Error	= 0 if sampled at root crown = *n*, depends on height sampled above the root crown	Estimate time to grow to sampling height: – determine mean apical growth rate – sample at given intervals up the stem – factor in environmental stressors
PE = Pith Error	= 0 if pith sampled = *n*, depends on years from pith	Estimate distance to pith in years based on ring curvature from similar aged trees
EI = Ecesis Interval	= 1…*n*, depends on seed source, microclimate, and substrate	Calculate ecesis interval by subtracting seedling age from a known substrate age

An estimation for the minimum date of a glacial deposit (i.e., moraine) can be summarized by:
Landform Date = **Germination Date** + **EI**
Where *Germination Date* = Age of the Oldest Tree = **ER** + **HE** + **PE**
And,
ER = year of Earliest Ring
HE = Height Error
PE = Pith Error

Sampling Height-Age Correction

Dating inaccuracy can also be introduced when samples are taken from the stem above the ground surface. Tree age is most accurately determined by counting the annual growth rings from multiple radial paths on a cross-section taken from the root crown, as close to the ground surface as possible (McCarthy *et al.*, 1991). However, destructive sampling is not always desired or permitted, and branches or other obstacles may force sampling higher on the stem. In such cases, the tree can be sampled above the obstacle and a ring count correction added to compensate for the time taken to grow to the sampling height (McCarthy *et al.*, 1991). Commonly a correction factor is established by determining the mean rate of annual apical growth within a representative sample of saplings and seedlings. Cross-dated ring counts are determined at regular intervals from the root crown upwards to create an appropriate age-height correction factor (Lewis and Smith, 2004). Additional age-height correction methods also include an additional environmental stress factor; whereby the morphological characteristics of the tree rings found nearest to the pith are evaluated and a range of correction values reflecting environmental stressors included (Winchester and Harrison, 2000). Complacent (wide) rings are indicative of rapid apical growth, and a correction factor of relatively few years needs to be added. Narrow rings, the presence of compression wood, or evidence of trauma are indicative of slower seedling growth, requiring an addition of a correction factor with a greater number of years to the total ring count.

Pith correction

Dating uncertainty can also be introduced when non-destructive sampling (increment coring) is used to determine tree ages; particularly with older trees, as the possibility of missing the pith increases with the size of the tree. Asymmetric growth, or the presence of branches or other obstacles, may also result in off-pith sampling. This problem can be resolved either by removing successive cores until the pith is recorded or, when the extraction of multiple samples is not possible, by applying a correction factor based on ring width and ring curvature data. In such cases, an appropriate year-to-pith correction factor can be assigned to the off-pith core, which is then subtracted from the date of the earliest ring to establish an estimated pith date (Applequist, 1958) (**Fig. 2**).

Ecesis Interval

Once the ages of the trees on a site are established, the ecesis interval, or lag-time between stabilization of the surface and germination of the first seedling (i.e., oldest tree on the surface), has to be determined (Lawrence, 1950). The ecesis interval for a given tree species is a function of local environmental conditions, including the existence of a sufficient seed source, characteristics of the seedbed, and the climate conditions during the ecesis interval (Sigafoos and Hendricks, 1969). Ecesis intervals have been determined for a number of tree species in the North American Cordillera and range from 1 to 100 years (Sigafoos and Hendricks, 1961, 1969; McCarthy *et al.*, 1991; Smith *et al.*, 1995; Luckman, 2000; Lewis and Smith, 2004). With

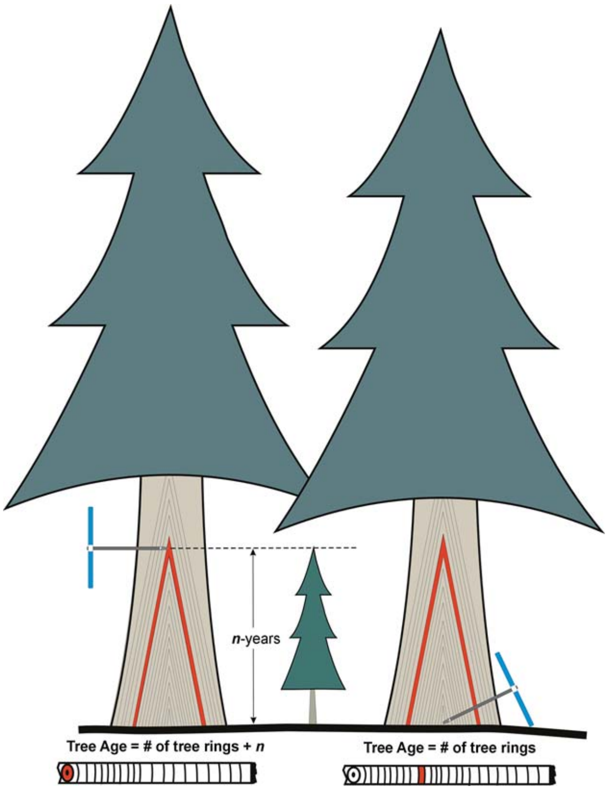

Figure 2 Schematic diagram illustrating the problems associated with coring above the root crown interface. The tree on the left is cored at a height of 1.5 m, the same height as the sapling in the middle, and the tree on the right is cored at the root crown interface. The red line in the trees and their associated cores below provides a marker year that illustrates the loss of rings (*n*) when determining tree age. If, for example it took the sapling 30 years ($n=30$) to reach the height at which the tree on the left was cored, the core taken from that tree would underestimate the age of the surface it is growing on by 30 years. The age and height of saplings growing adjacent to trees of interest is used to determine an apical growth rate (i.e., age-height correction) of 30-years/1.5 m (2 yrs/cm) for this example. Applied to the tree on the left, a more accurate surface date is obtained by multiplying the age-height correction by the height of the sample taken.

Figure 4 Mountain hemlock ecesis site below Colonel Foster Glacier in Strathcona Provincial Park. The photo shows recent forest regeneration adjacent to a stand of trees that survived a landslide induced displacement wave in June 1946 that removed most of the surface cover site down to bedrock. The ecesis interval at this location was four years.

such a large variation, it is necessary to determine a local ecesis interval that reflects local growing conditions. The key to determining a representative ecesis interval is the presence of a precisely dated surface in close proximity to the study area. (**Figs. 3 and 4**).

It is sometimes possible to date the culmination of a glacier advance by determining the age of trees that were scarred, tilted, or killed by the glacier that advanced into a proximal forest (Lawrence, 1950). This information can come either from dating abrupt changes in tree-ring growth patterns that are a direct consequence of glacier proximity (Lawrence, 1950, Bray and Struik, 1963; Porter, 1981; Nicolussi and Patzelt, 1996), from dating corrasion scars resulting from abrasion (Luckman, 1988; Schweingruber, 1988), or from dating when the glacier killed, overrode, and buried the trees (Smith and Laroque, 1996; Wood and Smith,

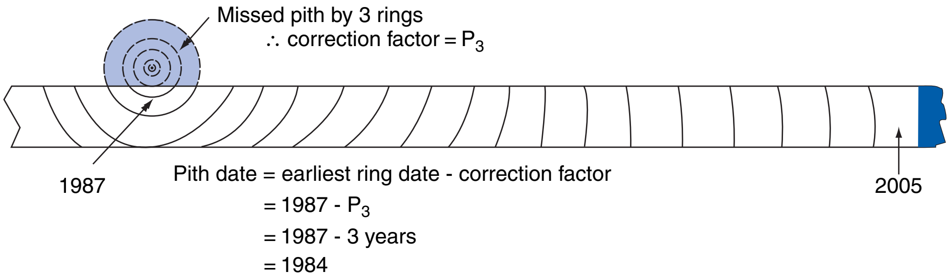

Figure 3 Schematic diagram illustrating the year-to-pith correction for core samples that were close to, but did not include, the pith. For an 18-year-old tree that missed the pith, a correction factor of 3 years was determined by tree ring data (width, curvature, concentricity) of adjacent trees. For trees growing in stressed environments such as glacier forefields, the slow grow rates would likely produce missed-pith errors one magnitude larger.

2004). Trees sheared off above the root crown often leave behind a fully rooted *in situ* stump (**Fig. 5**). If all of the perimeter tree-rings are intact and the ring-width record can be crossdated to a master tree-ring chronology, the last year of growth indicates the glacier position when the tree was killed (Schweingruber, 1988; Luckman, 1995). If the *in situ* stumps cannot be crossdated, the 'floating' ring-width records are frequently radiocarbon dated to provide a relative age for the event (Wood and Smith, 2004) (**Fig. 6**).

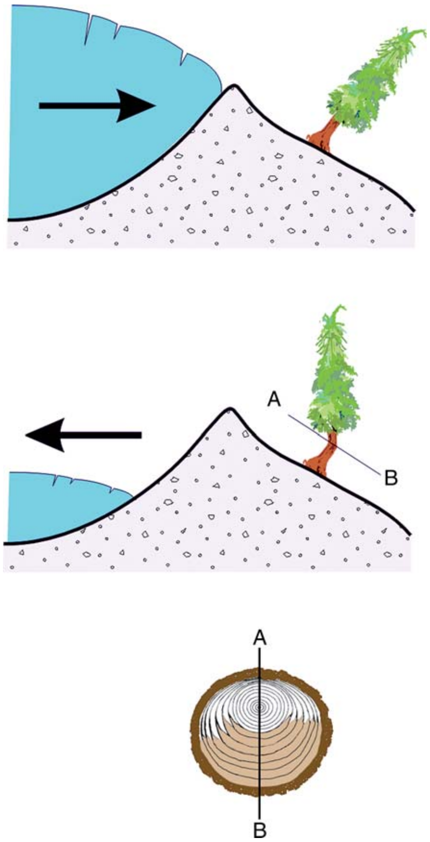

Figure 5 Schematic diagram illustrating the change in wood structure as a result of an advancing ice front tipping a preexisting tree growing in front of the glacier. The tilting of the tree results in the formation of both reaction wood and a change from concentric to distorted ring patterns on the underside of the tree. The year the tree was tilted provides a minimum date for the advance of the glacier at that location.

Future Directions

While the continued development of millennial-length tree-ring chronologies potentially provides annually resolved glacier-climate insights extending through the Holocene, further study is required to improve the reliability of these long-term proxy mass balance records. Dendroglaciological methods can provide useful first approximations of glacier-climate relationships in areas of sparse meteorological and mass balance data, but require further refinement to address relationships between glacier geometry changes and subsequent mass balance change, as well as the constant relationship between climate and tree growth inferred over long time periods. Future studies in dendroglaciology might address the question of how to incorporate the effect of glacier size on mass balance response, as dendroglaciological techniques consider a relatively static glacier size.

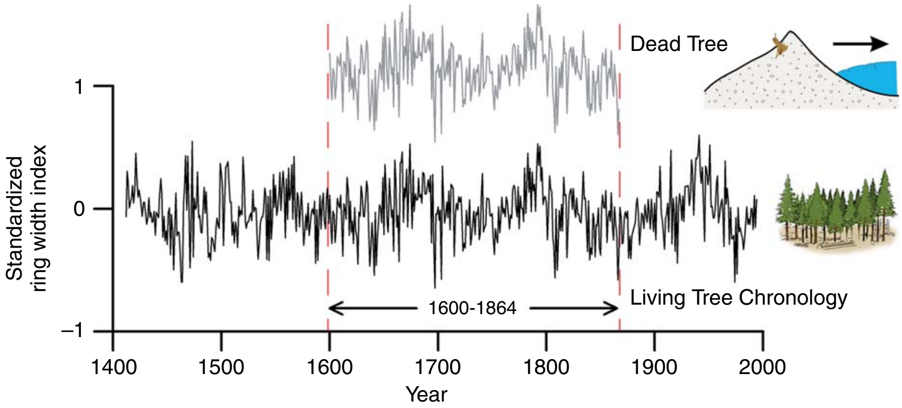

Figure 6 Schematic diagram illustrating how a calendar date for the growth rings of an undated wood sample (e.g., subfossil stump) can be determined by crossdating with a dated living chronology. The upper line (gray) in the graph is the undated/floating chronology of the subfossil wood, and the lower (black) line is the master chronology developed from live trees growing adjacent to the moraine being dated. By anchoring the floating chronology of the stump to the living chronology, it is possible to determine the kill date of the stump. In this example, the ring width pattern from the subfossil wood cross-dates with the master chronology suggesting it began growth in AD1600, and assuming all perimeter rings are present, was killed by the advancing glacier in AD1864.

See also: **Dendrochronology**. **Glacial Landforms, Ice Sheets**: Growth and Decay; Evidence of Glacier and Ice Sheet Extent; Paleo ELAs. **Glacial Landforms, Tree Rings**: Dendrogeomorphology.

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