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Deriving continuous deglaciation chronology from infrequent historical outlines

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Abstract

Glacial retreat exposes previously glaciated land to a wide range of surface processes. Continuing retreat sets up a natural experiment where the duration of impact of these processes increases with the distance to the glacier. Many pedological, ecological and geomorphic studies have leveraged such natural experiments. All such studies require quantification of the year of (most-recent) glacial retreat for positions in the proglacial valley. Sometimes this 'year of retreat' (YOR) is independently known, but often it is not. We present a semi-automatic open-source method that provides spatially exhaustive YOR rasters—from which the time since deglaciation can be simply derived—for proglacial areas by interpolating between glacial outlines of known age. The method guarantees exact reproduction of observed retreat ages, honours multiple retreat and re-advance stages and can deal with retreat into multiple glacial tongues. We illustrate the method for a study site in the Italian Alps (multiple glaciers in the Martelltal, Alto Adige). It is hoped that the easy-to-use method is helpful for a wide range of proglacial studies.

KEYWORDS

chronosequence, glacial retreat, landscape evolution, retreat raster, SEHAG

1 | INTRODUCTION

Glacial retreat is one of the starkest and most visible effects of global warming. The loss of glacial ice temporarily leads to more water flowing from glaciated catchments but ultimately to drought in many mountainous regions worldwide. At the same time, where glaciers retreat, previously glaciated land becomes exposed to weather and a suite of processes including colonization by vegetation, soil formation, erosion and deposition. The development of such postglacial landscapes is studied from a variety of disciplines that prominently include ecology (Greinwald et al., 2021; Mainetti et al., 2021), geomorphology (Altmann et al., 2020; Carrivick et al., 2018; Haas et al., 2012) and paedology (Khedim et al., 2021). In almost all such studies, glacial retreat is leveraged as a natural experiment where the time since deglaciation is the main independent variable and the landscape property of interest, such as plant (e.g., Ramskogler et al., 2023) or microbial community composition, erosion rate or soil pH, is the dependent variable. In this research design, the observation of the target variable(s) at different distances from the present-day glacier substitutes the (unfeasible) recording of chronosequences at a single or multiple sites across decades (space-for-time substitution). Accurate knowledge of the independent variable is crucial for quantifying such false chronosequences (Walker et al., 2010).

Multiple terms have been used to describe the independent variable that captures the retreat history. One (which we term here year of retreat: YOR) describes the year in which a glacier reached or retreated from a certain location; the other (which we term here time since deglaciation: TSD) describes the amount of time passed between the last time a glacier retreated from a location and the time of sampling or observation. YOR is often the primary observation available from maps or other records and that is used for interpolation and mapping. TSD is subsequently derived by subtracting YOR from the year of sampling or observation and is used as the independent variable in chronosequences. Both variables have units of years.

In some studies, it is sufficient to sample the landscape or soil property of interest only at locations for which YOR is accurately known from historical records, aerial photographs or satellite images of glacial extent. For instance, Khedim et al. (2021) studied soil chronosequences from 10 retreating glaciers across four continents using samples taken at locations of known YOR, and D'Amico et al. (2014) established a soil chronosequence of the Lys glacier in Italy (IT) using locations with directly observed YOR.

In other cases, it is necessary to sample the landscape property of interest more spread out across the deglaciated area—also at locations for which YOR cannot be acquired exactly from observations. In such cases, there is a need for interpolation between locations where YOR is known. A variety of methods have been used for this purpose (Table 1). A few examples from the ample literature should serve to illustrate this point. Egli et al. (2010), studying the Morteratsch glacier in Switzerland, first determined soil sampling locations and then interpolated linearly between three observed glacial extents to obtain YOR and then TSD. Bernasconi et al. (2011) used a similar procedure for the Damma glacier (CH) and van Grinsven et al. (2025) used it for the Bachfallenferner in Austria. Temme and Lange (2014) used an essentially one-dimensional approach to create a raster map of YOR for the Morteratsch, Tschierva and Forno glaciers in the Swiss Alps. They combined detailed annual records of glacial retreat lengths with the observation that the shapes of the glacial snout remained essentially the same between the several directly mapped glacial extents, to manually shift the glacial terminus upslope and downslope from the directly mapped 1850 terminus. Direct linear interpolation between the resulting outlines at annual resolution then delivered a raster of YOR, and subsequently of TSD. Betz-Nutz et al. (2023) interpolated between multiple mapped glacier outlines to determine the YOR, which was used to interpret the morphodynamics of lateral moraine sections with different TSD. To accomplish this, glacier outlines were converted into grids, and distance grids were created showing each pixel's Euclidean distance to the nearest glacier outline. Using pairs of distance grids from consecutive glacier extents, the year of deglaciation for each pixel was linearly interpolated based on distance ratios, and the resulting deglaciation grids were then merged for each proglacial glacier forefield. Eichel et al. (2013, Turtmann glacier, CH) and Temme et al. (2016, Gepatschferner, Austria) simply grouped soils between the observed glacial extents from different ages (e.g., 'the group of soils with YOR between 1850 and 1911') without interpolating.

It is clear from the examples above that different ad hoc procedures have been used so far, and no single optimal method to produce a spatially exhaustive retreat raster has yet emerged from the various disciplines interested in deglaciated areas. Here, we propose a method that can deal with infrequent observations of glacial extents, with repeated glacial retreat and advance during the period of interest and with retreat into multiple tongues. It is also globally applicable, easy to use and open-source. The method is designed to leverage glacial extents from the global GLIMS dataset (Raup et al., 2007) and can be used or enriched with glacial extents from other sources, which often describe older glacial extents. In addition to raster-based YOR and TSD maps, the method outputs decadal YOR isolines and time series of the spatial distance to the edge of a glacier for user-specified points in the deglaciated area. Moreover, we show how the generated maps can be analysed not only to determine the (most recent) YOR but also to reconstruct the glaciation history (including deglaciation and intermediate glacial re-advances) of selected sites.

TABLE 1 Published methods to derive TSD information from sparse observations.

Reference	Site	Method
Bernasconi et al., 2011	Damma glacier, CH	Linear interpolation between observed outlines
Egli et al., 2010	Morteratsch glacier, CH	Linear interpolation between observed outlines
Betz-Nutz et al., 2023	10 glacier forefields, AT, IT, DE	Ratios of distance grids to outlines (linear interpolation)
Temme & Lange, 2014	Morteratsch, Tschierva and Forno glaciers, CH	Manual shift of snout shape along observed 1D retreat history
Temme, Heckmann, & Harlaar, 2016	Gepatsch, AT	Grouping of ages between observed outlines
Eichel et al., 2013	Turtmann glacier, CH	Grouping of ages between observed outlines
van Grinsven et al., 2025	Bachfallenferner, AT	Linear interpolation between observed outlines

2 | STUDY SITE

We illustrate the method's operation for a study area in the Italian Alps with a complicated retreat and readvance geometry: the Zufallferner (Vedretta del Cevedale), Fürkeleferner (Vedretta della Forcola) and Langenferner (Vedretta Lunga) glaciers, located at the head of the upper Martell Valley (46.46°N, 10.65°E) in the Ortles-Cevedale group, South Tyrol, Italy. This site is intensively studied in the context of the SEHAG project (SEnsitivity of High Alpine Geosystems to climate change since 1850; Becht et al., 2019). The three glaciers were initially contiguous before retreat separated them into individual tongues (see Figure 1). The elevation ranges from approximately 2372 to 3809 m a.s.l. within the maximum LIA glacier extent.

During the Little Ice Age (LIA), the glaciers reached their maximum Holocene extent probably around 1820, with well-preserved terminal moraines marking this position. After the end of the LIA (1850), intermittent re-advances occurred in the 1890s and 1980s, though none reached the LIA extent (Knoflach et al., 2021). Since the mid-1980s, these glaciers have experienced accelerating retreat, progressively exposing new proglacial terrain. Overall, the combined glacier area decreased by 58% of the original extent.

3 | METHODS

We propose four basic requirements for appropriate glacial retreat rasters. The first is that ages at directly observed glacial extents are exactly reproduced. The second is that ages of places that are spatially between two directly observed glacial extents are also temporally between the ages of the two extents. The third is that curvature in

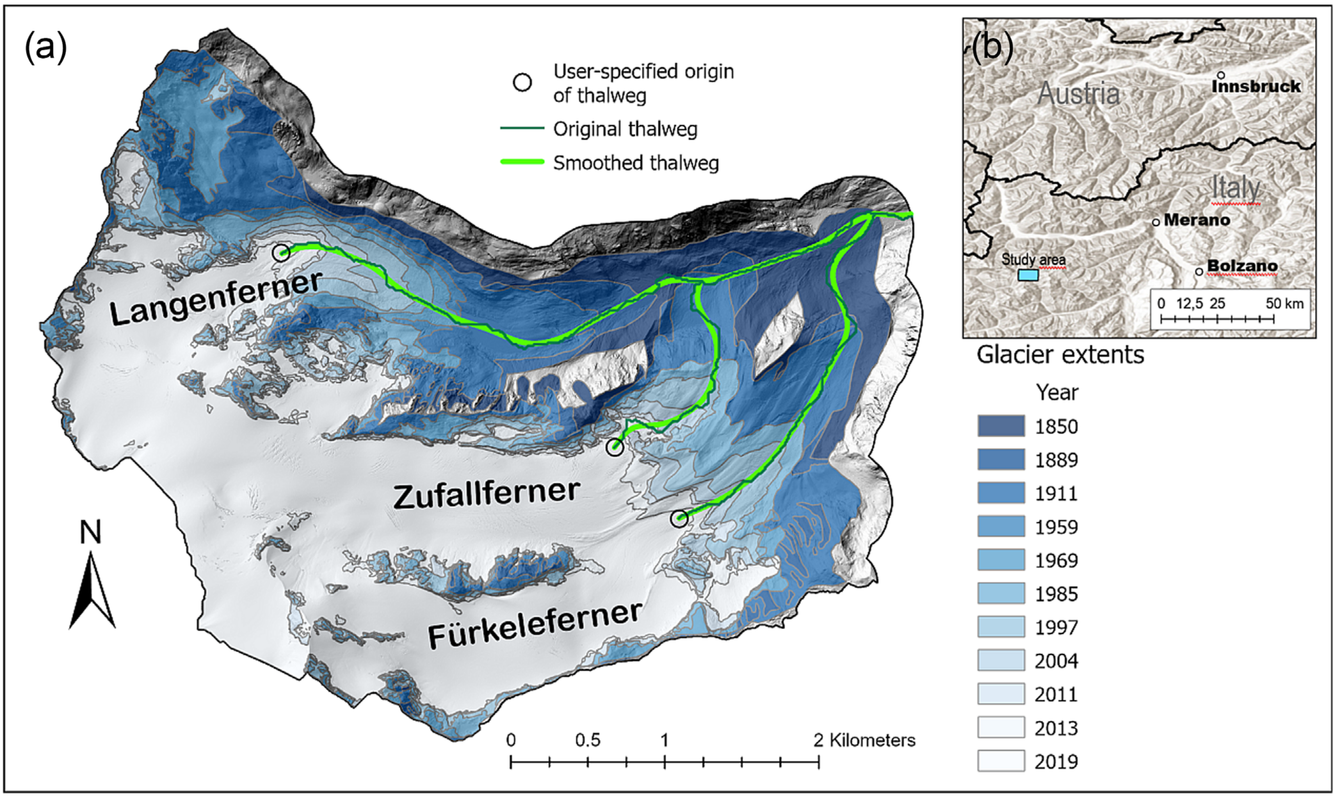

FIGURE 1 The study site with the Zufallferner, Fürkeleferner and Langenferner glaciers (a) and its location in the European Alps (b). The map furthermore shows the automatically delineated thalweg lines and their smoothed counterparts. The latter are used to generate additional age points supporting the interpolation of YOR where glaciers have the shape of a tongue.

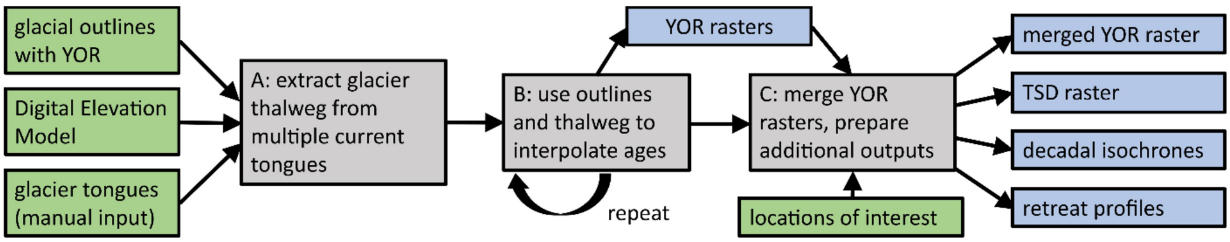

FIGURE 2 Main steps of the proposed method. Inputs are in green, main steps in grey and outputs in blue. YOR is year of retreat; TSD is time since deglaciation.

the age surface is minimized, to avoid artificial jumps in the glacial retreat rate. The fourth is that repeated retreats and readvances, as well as retreats into multiple tongues, are accepted as input and honoured in the output. None of the methods presented in literature (Table 1) so far meet these requirements.

Our method is designed to meet the four requirements and has three main steps (Figure 2). In the first step (A), based on polygon glacial outlines, a DEM and interactively entered starting points for possibly multiple glacial tongues, the method extracts an approximation of the glacier thalweg(s) that we found necessary to aid in interpolation of age surfaces where glaciers form tongues (Figure 1). It does this by extracting the steepest descent flow path over the deglaciated landscape from the starting point of each glacial tongue, converting to a line representing the thalweg and then smoothing the line to account for the fact that glacial flow follows topography less directly than water flow. The smoothing algorithm used is the smoothing via iterative averaging (SIA) method (Mansouryar & Hedayati, 2012). The smoothing parameter was set at 3, 30 iterations were used, and preservation was set at 7.

The second step (B) uses the outlines and the smoothed thalweg to interpolate YOR. In each case, the set of outlines used for interpolation is composed of a pair of chronologically consecutive glacial outlines. First, points are placed every 10 m along the outlines and the thalweg, and these points are assigned ages. Points on outlines are assigned the age of the outlines. Points on the thalweg line are assigned ages based on their relative position between outlines, assuming linear retreat or readvance, so that a point on the thalweg line exactly halfway between an 1850 outline and a 1910 outline gets assigned an 1880 YOR. It is conceivable that known linear glacial retreat records at high temporal resolution (such as from GLAMOS, 2024) are used instead to assign this age in future upgrades to our method. Both sets of points are merged and used as inputs in interpolation using natural neighbour interpolation, which is an exact interpolator and is parameter free: no additional user inputs are required, but we set the optional 'minimum weight' parameter to −0.2. The resulting interpolated YOR raster is clipped to the area between the outlines, also in cases where parts of the glacier advanced, whereas others retreated. Clipping and separate output of YOR rasters for every pair of subsequent glacial extents is necessary to later enable the analysis of re-advances that cover previously deglaciated terrain.

The third step (C) merges the clipped YOR rasters from each pair of outlines by selecting the youngest age interpolated at each location. This ensures that the merged YOR raster records the last time a glacier occupied every location. Then, the TSD raster is calculated by subtracting YOR from the youngest glacier outline (units of *y*). Finally, the TSD raster and the partial YOR rasters are analysed in a GIS (we used SAGA GIS, Conrad et al., 2015) to reconstruct the deglaciation history of user-specified points of interest on the surface. For this purpose, the TSD raster is first processed to fill gaps and 'sinks' that can occur, for example, at the contact of adjacent partial YOR rasters forming the basis of TSD. For the sink filling, we used the algorithm of Wang and Liu (2006) implemented in SAGA GIS. The sink-filled TSD surface is then used to automatically delineate 'steepest descent' profiles that start from any user-specified point inside the deglaciated area and run perpendicular to the isochrones until they end at the most recent glacier extent (where TSD reaches a value of zero). Extracting the values of all partial YOR rasters (not merely the merged YOR raster) along this profile allows us to track the evolution of both receding and advancing glaciers relative to the user-specific origin of the profile.

In summary, our method produces the following outputs:

a. The single partial YOR rasters plus the merged YOR raster (units of *y*).
b. Decadal isochrones of YOR (units of *y*)
c. Time-since-deglaciation (TSD) raster (units of *y*)
d. History of distance to the glacial front over time for user-specified locations.

The entire procedure is available to users as an R-script that employs the open-source SAGA GIS (version 9.9.0) through the Rsagacmd package (version 0.4.3; Pawley, 2024), which is available as Supporting Information S1. A walkthrough of the steps to use the script is provided as Supporting Information S2.

Glacier outlines for the Martell Valley example were compiled from multiple sources: The LIA extent (1850) and outlines from 1911 to 2019 were initially mapped during the Crysoil_TRANSFORM project (Knoflach, 2022). The 1889 glacier extent was digitized from the map by Finsterwalder (1890). Data sets for 1969, 1985, 2004, 2013 and 2019 were subsequently refined using corresponding DEMs of difference (DoD).

4 | RESULTS

Figure 3 shows the interpolated TSD raster together with YOR isochrones at 10 years equidistance. The isochrones closely match the

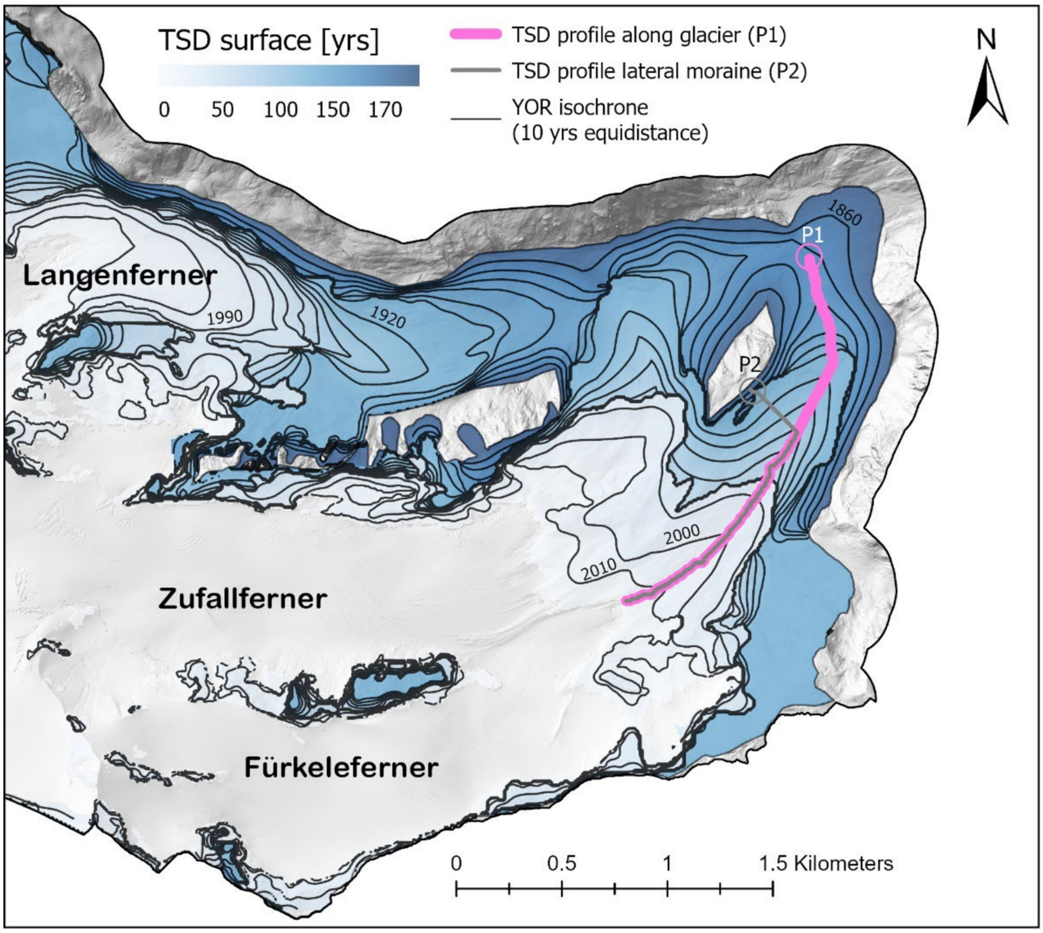

FIGURE 3 Interpolated TSD map with YOR isochrones (10 years equidistance) and the location of two TSD profiles (see Figure 4).

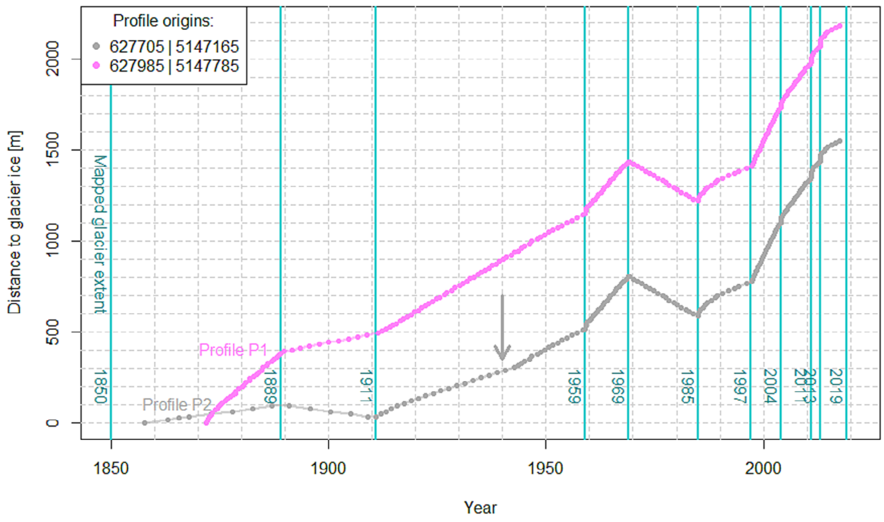

FIGURE 4 Age–distance plots created from profiles P1 and P2. The UTM coordinates mark the user-specified profile initiation points from where the steepest descent profiles were delineated on the TSD surface. See text for a detailed explanation.

mapped glacier extents shown on Figure 1. At very few sites, the map shows interpolation artefacts; overlaying contour lines indicate locations where the retreating glaciers intermediately readvanced, for example, at the tongue of Fürkeleferner (Profiles 1 + 2). These locations are also characterized by sudden changes in age (and sharp contrast in colour, accordingly), whereas the continuously receding Langenferner tongue shows a smooth colour gradient.

Although the YOR and corresponding TSD maps allow for the dating of the deglaciation of points or polygons by extracting (and aggregating, for polygons) the raster value(s), a less straightforward but more interesting option lies in the automated delineation of 'steepest descent' profiles on the TSD surface (Figure 3). Such profiles, starting from user-specified points, run perpendicular to the isochrones (that also represent the estimated extent of the glacier at the respective time) until they reach the most recent glacier extent. These profiles have both a spatial and a temporal meaning; they show the distance of the user-specified point from the glacier as it evolves with time when the extent of the glacier changes. As we use the TSD surface only for the delineation of the profile but extract the YOR from the partially interpolated surfaces (between every pair of subsequent glacier extents), a plot of distance against YOR is capable of representing readvances of the glacier and decreasing distance of the point of interest from the glacier margin (Figure 4). The origin of profile P1 was set in the outer proglacial area of the Fürkeleferner, whereas that of profile P2 lies on a lateral moraine of the same glacier, almost 700 m away (as the crow flies) and c. 400 m upslope of the first point. The corresponding lines in the diagram indicate that the two sites became deglaciated around the year 1870 (P1) and 1858 (P2), respectively. Although the pink line (P1) shows a fast, nearly constant increase in distance until the year 1969 (at rates between 4.5 and 30 m/year, 14 m/year on average), the grey line (P2) indicates very limited change until the year 1911, with a retreat by merely 100 m between 1858 and 1889 and a subsequent decline of distance until 1911. The latter is due to the glacier tongue thickening; a corresponding re-advance is not visible in P1. Overall, the distance of the origin of P2 to the glacier increases markedly more slowly than that of P1 until c. 1940 (marked by grey arrow), with an average rate of c. 10 m/year. After 1940, the rate accelerates towards c. 30 m/year (1959–1969) also found in profile P1. This is because, until 1940, the growing distance from Point 2 reflects only the thinning of the glacier tongue while it remains at the foot of the lateral moraine. After 1940, the glacier tongue is no longer merely thinning but has retreated past the point on the lateral moraine; consequently, the distance between the profile origin and the glacier margin increases as quickly as it does in profile P1.

Another remarkable detail of the retreat distance profile (Figure 4) is the marked readvance of the Fürkeleferner glacier tongue between 1969 and 1985 indicated by the reverse slope of both lines. The readvance amounts to c. 200 m, at a rate of c. 13 m/year. After 1985, deglaciation resumes, reaching a peak rate of 43 m/year between 1997 and 2011. Note that the readvance of the Fürkeleferner is mirrored by Zufallferner, but not by Langenferner according to both the mapped and the interpolated glacier extents.

Together, these results highlight the ability of our approach to reconstruct YOR and TSD even in the presence of spatio-temporal complexities such as non-uniformly stagnating or readvancing glaciers. Where such a reconstruction involves areas located under ice at the time of DEM acquisition, it has to resort to sub-glacial topography being estimated from modelling and geophysical surveys (Helfricht et al., 2019; Huss & Farinotti, 2012)

5 | DISCUSSION

5.1 | Efficiency and availability of the method

The method presented here uses exclusively open-source software (R and SAGA). Publicly available data sources such as GLIMS (Raup et al., 2007) can be used to obtain input data for most glaciers in the world, although especially older outlines may need to be gathered from other sources. Script runtime for the example dataset used in this study is less than 30 s on a standard laptop. Manual selection of thalweg starting points for supporting the interpolation of YOR where the glacier has the shape of a tongue costs about 10 s if done via the interactive prompts in the script. For larger datasets of multiple valleys with dozens of glaciers, automatic identification of glacier tongues would be an interesting further development to limit manual interaction.

5.2 | Accuracy of the outputs

This novel method is the first to meet all four criteria that we laid out above and thus can provide consistent glacial retreat datasets for complex glacial retreat and readvance histories and geometries. Nonetheless, the output retreat rasters and associated data products remain uncertain estimates. First, this is because of the scarcity of, and positional and chronological uncertainty in, the input glacial outlines. The number (and hence temporal density) and quality of the available historical glacial outlines are the fundamental limiting factor for the quality of our interpolations and derived data products. Second, our method assumes linear retreat between known glacial outlines. In the absence of other information, this seems a reasonable choice to us, but in reality, most glaciers do not retreat linearly between consecutive observations of their outline. Here as well, the quality of our outputs is conditional on the number and quality of the historical glacier outlines. Users should carefully assess whether their input paleo-glacial outlines cover the key retreat and/or advance behaviour of each glacier. Finally, natural neighbour interpolation is but one of many options for interpolation.

5.3 | Application of different outputs

We expect YOR and TSD rasters to be of use in studies that explore the impact of the age of the deglaciated surface on environmental variables. Sampling design for such chronosequence studies often requires that the age of each deglaciated location is known to ensure that the range of ages is appropriately sampled. For this purpose, knowledge of the retreat age can either be used to stratify the deglaciated area into similarly-aged regions or as a component in multi-variable random sampling schemes such as conditional Latin Hypercubes (Minasny & McBratney, 2006) as used in Temme, Heckmann, & Harlaar (2016). This could be along with other geomorphometric variables such as slope steepness, terrain ruggedness index (Riley, DeGloria, & Elliot, 1999), topographic wetness index (Beven & Kirkby, 1979), or the distance to slope breaks (Temme, Schoorl, & van der Meij, 2022).

Moreover, YOR and TSD rasters are useful for studies investigating paraglacial adjustment following deglaciation (Ballantyne, 2002). Such studies often analyse morphodynamic processes on lateral moraine slopes, either through multitemporal observations (e.g., Altmann et al., 2023; Betz-Nutz et al., 2023; Lane et al., 2017) or using a space-for-time substitution approach (e.g., Curry, Cleasby, & Zukowskyj, 2006; Eichel, Draebing, & Meyer, 2018). Since the geomorphological processes on these slopes are strongly influenced by the extent to which the glacier still covers and buttresses the slope, accurate YOR values for individual raster cells are valuable for a better understanding of process development. Furthermore, YOR rasters allow the determination of the time of complete deglaciation of specific moraine sections, which is important because from that point on moraine slopes develop with little or no disturbance (depending on other factors such as the presence of dead ice).

The inverse of the first derivative of the TSD raster in space (i.e., the glacial retreat rate at the time of the most recent retreat for each deglaciated location, expressed in dimensions of L/T), which could easily be calculated based on the TSD raster, may also be of value in the analysis of data gathered in the proglacial area. The rate of retreat when the glacier front last passed a location in the proglacial valley would be a proxy for how long such a location has been near the ice edge, where it may have experienced raised water flow because of yet-unchanneled ice- and snow-meltwater and deposition of supra- and sub-glacial sediment (Lane et al., 2017). When calculating and using such a proxy, it would be important to avoid the artificially high retreat rates calculated at the edge of readvances.

Finally, the retreat distance profile (of dimension *L*, and unit m) combines the spatial information (distance from the—interpolated—glacier outline at time YOR) with the temporal information (YOR). It offers more temporal detail than a local retreat rate raster could, by expressing how (possibly multiple) retreats and advances have changed the distance to the ice edge over time. It is expected that this data product can, among others, be of value for studies that focus on wetland development. Proglacial soil, wetland and lake biogeochemistry is heavily influenced by the distance from the glacier. Locations within the proglacial valley receive deposits, originating either from the catchment area or from the glacier itself. As these processes are impacted by the distance to the glacier (Delaney et al., 2024) and proglacial area size (Delaney et al., 2018), accurate assessments of glacial retreat are invaluable. The distance to the glacier has been shown to be an important metric for the microbial community in surface- and groundwater (Purkamo et al., 2022), which in turn affects the potential for nitrogen and greenhouse gas cycling. Although distance to the glacier also seemed to affect the microbial abundance in proglacial lakes, no clear trends were observed thus far (Marsh et al., 2024). Other research has also shown that glacial stream temperature, carbon content and algal biomass are affected by the distance to the glacier (Kohler et al., 2024). Nutrient dynamics in soils are correlated to TSD, and although distance to the glacier may affect the delivery of dissolved and suspended compounds, the correlation is most likely due to the establishment of microbial communities over time in these soils, such as nitrogen-fixing microbes. Glacial lakes have been shown to become emitters of methane over time, with a relationship between methane oversaturation and distance to the glacier (Wei et al., 2023), likely due to the build-up of rich sediments that harbour methanogens and methane precursors. To understand the formation of these sediments, it helps to understand the proglacial catchment history. The composition of sediments in proglacial lakes and wetlands determines the (redox) biogeochemistry of these systems, with major impacts on nutrient availability and greenhouse gas dynamics.

Sediment transport from the deglaciated catchment area is known to be affected by time since glaciation (Delaney et al., 2018; Piermattei et al., 2023), both in terms of sediment load and composition. These sediments may be transported further downstream, out of the proglacial valley, or be deposited in nearby locations within the proglacial area (Delaney et al., 2024). Recent studies have modelled glacial sediment transport in an attempt to improve predictions of sediment load into downstream reservoirs, to improve their functioning and limit risks (Guillén-Ludeña, Manso, & Schleiss, 2018; Li et al., 2022; Schmidt et al., 2024). An accurate estimation of the deglaciation history and catchment development can improve such models, given the importance of TSD and proglacial area size for sediment transport (Delaney et al., 2018).

6 | CONCLUSIONS

We have presented and illustrated a new method to calculate deglacial retreat rasters based on sparse glacial outlines. The method produces datasets that meet several requirements: They are fully consistent with the information in the input glacial outlines, they can reflect retreat dynamics that split a glacier into multiple tongues, and they can reflect repeated glacial retreat and readvance. The set of data products that are produced by the method potentially has value in geomorphic, pedological and ecological studies in deglaciating regions. We provide the script that contains the method as well as example data to the community.

AUTHOR CONTRIBUTIONS

Conceptualisation: A.T. and T.He.; *Data curation:* T.Hi.; *Coding and formal analysis:* T.He.; *Figures:* T.Hi., T.He.; *Discussion, writing and reviewing:* A.T. *with contributions from* S.B.-N., S.v.G., T.He. and T.Hi.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

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