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Limits to lichenometry

Swenja Rosenwinkel [a, *], Oliver Korup [a], Angela Landgraf [a], Atyrgul Dzhumabaeva [b]

[a] Institute of Earth and Environmental Sciences, University of Potsdam, 14476 Potsdam, Germany
[b] Kyrgyz Institute of Seismology, 720060 Bishkek, Kyrgyzstan

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ABSTRACT

Lichenometry is a straightforward and inexpensive method for dating Holocene rock surfaces. The rationale is that the diameter of the largest lichen scales with the age of the originally fresh rock surface that it colonised. The success of the method depends on finding the largest lichen diameters, a suitable lichen-growth model, and a robust calibration curve. Recent critique of the method motivates us to revisit the accuracy and uncertainties of lichenometry. Specifically, we test how well lichenometry is capable of resolving the ages of different lobes of large active rock glaciers in the Kyrgyz Tien Shan. We use a bootstrapped quantile regression to calibrate local growth curves of *Xanthoria elegans*, *Aspicilia tianshanica*, and *Rhizocarpon geographicum*, and report a nonlinear decrease in dating accuracy with increasing lichen diameter. A Bayesian type of an analysis of variance demonstrates that our calibration allows discriminating credibly between rock-glacier lobes of different ages despite the uncertainties tied to sample size and correctly identifying the largest lichen thalli. Our results also show that calibration error grows with lichen size, so that the separability of rock-glacier lobes of different ages decreases, while the tendency to assign coeval ages increases. The abundant young (<200 yr) specimen of fast-growing *X. elegans* are in contrast with the fewer, slow-growing, but older (200–1500 yr) *R. geographicum* and *A. tianshanica*, and record either a regional reactivation of lobes in the past 200 years, or simply a censoring effect of lichen mortality during early phases of colonisation. The high variance of lichen sizes captures the activity of rock-glacier lobes, which is difficult to explain by regional climatic cooling or earthquake triggers alone. Therefore, we caution against inferring palaeoclimatic conditions from the topographic position of rock-glacier lobes. We conclude that lichenometry works better as a tool for establishing a relative, rather than an absolute, chronology of rock-glacier lobes in the northern Tien Shan.

1. Introduction

Lichenometry is an inexpensive and straightforward dating technique based on a systematic relationship between the lichen thallus size and the age of the rock surface the lichen grows on. If adequately calibrated, this relationship can be used to estimate the exposure age of an undated rock surface assuming it has remained stable and undamaged (Beschel, 1973). Lichenometry is a common tool for dating Holocene glacier advances, earthquakes, and floods using moraines (Solomina et al., 1994), rock-fall debris (Nikonov and Shebalina, 1979; Bull and Brandon, 1998), and fluvial sediments (Foulds et al., 2014), respectively. The basic four variants of lichenometry involve measuring (i) the largest lichen(s) on a landform of interest; (ii) the largest lichen(s) within a specified unit area; (iii) different lichen-size distributions; and (iv) the relative fraction of a rock surface covered by lichens (Bradwell, 2009).

The growth curve is at the core of lichenometry, and models the systematic change of thallus diameter with age. Directly measured growth rates are roughly between 0.02 and 1.5 mm yr^{-1} for *Rhizocarpon* subgenus (Matthews and Trenbirth, 2011), positively correlated with lichen diameter (Roof and Werner, 2011), and reproduced best by concave-upward to linear growth-rate models (e.g., Trenbirth and Matthews, 2010). Direct measurements cannot capture any long-term changes, and reveal only contemporary growth rates (Roof and Werner, 2011). This is why indirect measurements, such as fitting a regression model to lichen diameters with known calendric dates, remain widely used for determining

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* Corresponding author. Institute of Earth and Environmental Sciences, University of Potsdam, Karl-Liebknecht-Str. 24 (Hs 1), D-14476 Potsdam, Germany.

E-mail addresses: rosenwinkel@geo.uni-potsdam.de (S. Rosenwinkel), korup@geo.uni-potsdam.de (O. Korup), landgraf@uni-potsdam.de (A. Landgraf), arose3.60@mail.ru (A. Dzhumabaeva).

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growth curves, at least for geomorphic purposes. These regression models show negative correlations between growth rate and lichen diameter. The convex upward shape of most associated growth curves may reflect phases of fast growth for smaller lichens followed by linear growth for larger lichens (Solomina et al., 1994; Bull and Brandon, 1998). Part of this nonlinear growth possibly mirrors changes in environmental conditions during the long life spans of lichens: one specimen of *Rhizocarpon geographicum* on East Baffin Island has an estimated age of 9500 years (Miller and Andrews, 1972). Loso and Doak (2006) argued that the convex-upward shape of lichen-growth curves is consistent with the linear growth observed in direct measurements, if accounting for lichen mortality and the decreasing probability of finding the largest lichen with increasing surface age. They suggested using indirect measurements together with estimates of the probability to find the largest lichen by including ecological parameters such as the rates of colonization, growth, and survival. Direct lichen measurements of *R. geographicum* in Wales (Armstrong, 1983) and Iceland (Bradwell and Armstrong, 2007) confirm that lichen size depends on growth rates as detected by indirect measurements. These studies show a parabolic relationship between growth rates and thallus diameter with increasing growth rates for small lichen thalli, constant rates for larger thalli, and decreasing rates for the largest lichen thalli. However, indirect measurements in recently deglaciated areas in southern South America returned linear growth curves for *R. geographicum* during the past 30 years, with rates as high as 0.63 mm yr^{-1} (Sancho et al., 2011).

Lichenometry has earned repeated critique because of inconsistent and partly irreproducible measurement and sampling strategies, data handling, treatment of errors, and several questionable assumptions regarding lichen growth (Osborn et al., 2015). Traditional approaches to lichenometry rely on sampling the largest lichen(s) on a rock surface or landform of interest (Solomina et al., 1994), assuming that the largest lichens are the first colonizers. Using only a few of the largest lichens to establish a growth curve via regression models can produce misleading results compromised by a small sample size or several outliers (Calkin and Ellis, 1984), although the thresholds for these outliers are arbitrary (Loso and Doak, 2006). Averaging across the largest lichen diameters helps to decrease the error due to, for example, anomalously large lichens that could have survived the transport from older surfaces. Size-frequency distributions of many samples (n ~1000) also help to identify anomalous large lichens, and can further aid dating purposes based on mean diameter–age correlations (Innes, 1983; Winchester and Harrison, 1994). Other researchers used digital image analysis to estimate the age of a rock surface from the degree of lichen coverage that is assumed to increase with time (McCarthy and Zaniewski, 2001).

In meeting these potential shortcomings, lichenometrists have suggested several statistical approaches to quantify the uncertainties tied to the method. Jomelli et al. (2007) compared the effects of different sampling strategies by applying them on dated tombstones, and found that methods measuring only the largest, the five or the ten largest lichen diameters were unable to reliably predict the tombstone dates. Instead they suggested to use a hierarchical Bayesian model based on a Generalized Extreme Value (GEV) distribution for analysing only the largest lichen measurements (Cooley et al., 2006). Cluster analysis is another statistical approach to distinguish between two lichen-size distributions and returns a goodness-of-fit parameter (termed Watson's U^2) describing the proximity of the two distributions in parameter space (Watson, 1961). Watson's U^2 can be used to distinguish significantly different lichen populations and their habitats, for example moraine surfaces, and mainly offers a relative rather than absolute dating tool (Orwin et al., 2008). Regardless of the level of success, the complexity and lacking user friendliness of these approaches have been recognised a major disadvantage when compared with the original simplicity of the method (Bradwell, 2009).

Here we contribute to this discussion on the accuracy, uncertainty, and choice of methodological complexity of lichenometry. We explore bootstrapped quantile regression as a robust technique for objectively fitting nonlinear growth curves to a number of the largest lichen diameters of known ages. This method allows quantifying the temporal resolution and precision of lichenometry as a function of thallus size. We then use a Bayesian analogue to the classic analysis of variance or ANOVA (Kruschke, 2012) as a means to test whether lichenometry is capable of resolving the formation ages of large active rock-glacier lobes in the Kyrgyz Tien Shan. We test whether differences in lichen diameters and inferred ages on selected rock-glacier lobes reflect different phases of inception or mobility, and discuss some of the potential causes of multiple lobes on the rock glaciers. The actively deforming surfaces of creeping rock glaciers provide many fresh but partly unstable rock surfaces for lichen colonisation in a highly continental climate, and thus put lichenometry to a stringent test. Another motivation for focusing on rock glaciers is that they are popular indicators of mountain permafrost and past climatic cooling episodes; yet despite their increasingly acknowledged relevance worldwide (Haeberli et al., 2006), few rock glaciers have been dated. Moreover, rock glaciers store significant volumes of freshwater that, per unit area, is comparable to, or even higher, than in glaciers (Gorbunov et al., 1992), and may therefore play a seminal role in the hydrology of semiarid high-mountain ecosystems (Azócar and Brenning, 2010). Thus rock glaciers become increasingly important in the context of temperature increase and pronounced melting of glaciers during the last decades (Bolch and Marchenko, 2006), and especially so in the northern Tien Shan, which has a higher spatial density of rock glaciers than the Swiss Alps or parts of the Nepal Himalaya (Bolch and Gorbunov, 2014).

2. Study area

The high topography of the Tien Shan mountains is the result of the ongoing Indian-Eurasian collision (Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1979). The Tien Shan still exhibits uplift and seismic activity. Our study area around Lake Issyk Kul in the northern Tien Shan was affected by a series of major earthquakes in the late 19th and early 20th centuries, among them some of the strongest intracontinental events such as the M_{lh} 8.1 Chon Kemin (1911), M_{lh} 6.9 Kemino-Chu (1938), M_{lh} 6.9 Belovodskoe (1885), M_{lh} 7.3 Verny (1887), M_{lh} 8.3 Chilik (1889), and M_{lh} 6.8 Sarykamysh (1970) earthquakes (Magnitudes from Love surface wave amplitudes, Kalmetieva et al., 2009) (Fig. 1).

In the northern Tien Shan, mean annual air temperature (MAAT) ranges from −4 °C at the Tuyuksu glacier station (3434 m asl) (Fig. 1) to ~9 °C at the northern edge of the Zailisky Range (850 m asl) (Bolch, 2007). A temperature increase of ~0.02 K yr^{-1} was recorded at different stations in northern Tien Shan since the 1950s (Aizen et al., 1997; Bolch, 2007). Compared to lowland areas, Aizen et al. (1997) detected a higher temperature increase at >2000 m asl, whereas Bolch (2007) reported a less pronounced positive trend; Giese and Moßig (2004) even reconstructed a temperature decrease. The highest precipitation occurs in early summer with locally variable annual precipitation of 1000 mm on windward northern slopes, and 800 mm on leeward southern slopes; precipitation has been more variable since the 1950s, though without a clear trend (Aizen et al., 2007; Bolch, 2007). Summer precipitation is derived from North Atlantic, Mediterranean, and Black Sea cyclones and recycled moisture from the Aral-