Lichenometric dating: a commentary, in the light of some recent statistical studies

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Abstract
This commentary article discusses the relative merits of new mathematical approaches to lichenometry. It highlights their strong reliance on complex statistics; their user un-friendliness; and their occasional mistreatment of existing lichenometric techniques. The article proposes that the success of lichenometric dating over the past 50 years has stemmed from its relative simplicity, transparency, and general field applicability. It concludes that any new techniques which ignore these principles are likely to be unjustified, unsuitable to the user community and inappropriate for the subject matter. Furthermore, the article raises a more general philosophical question: can statistical complexity and high precision in a 'geobotanical' dating technique, fraught with high degrees of environmental variability and in-built uncertainty, ever be scientifically valid?

Introduction

Lichenometric dating has come a long way since its first use in the 1930s. Proposed as a relative dating technique by Knut Faegri (1934) and developed by Roland Beschel (1950, 1958, 1961, etc.), lichenometric dating has now been employed in over 600 studies worldwide and on all 7 continents. (See recent reviews by Noller and Locke 2001; Solomina and Calkin 2003; Muller 2006; Bradwell and Armstrong 2007; Benedict 2009). Various different methodologies and data collection techniques have been adopted – these range from measuring the single or several largest lichens on a surface to measuring whole populations of several thousand lichen thalli (Table 1). Measurement parameters also vary. The long axis, short axis, average diameter, the mean diameter of a number of lichens, the modal frequency of lichen sizes, and the percentage of lichen cover have all been used as metrics to estimate surface age. All of these sampling strategies have marked effects on the construction of lichenometric dating curves, the reported lichen 'growth' rate, and consequently the lichenometric age and precision of the surface being dated.

Lichenometry started out as a botanical science – field based in essence, primarily the domain of the ecologist or geographer. As its use as a dating technique became more established in the 1960s and 70s, lichens were measured more often by geomorphologists and geologists eager to know the age of recent landforms, especially in high latitude and alpine settings. In the past decade, however, several papers have pushed lichenometry further towards the statistical sciences. Data collected in the field is now subjected to increasingly complex statistical procedures back in the office. In the past 3 years, 2 groups have presented lichen data using new and different statistical approaches: (1) The GEV (Generalized Extreme Value) group [Naveau *et al.* 2005, 2007; Cooley *et al*. 2006; Jomelli *et al*. 2007, 2008] and (2) The U^2 group [Orwin *et al*. 2008].

The GEV group aim to determine the age of a surface by modelling the lichen population distribution using a Bayesian treatment of Generalized Extreme Value (GEV) distribution theory. The authors go on to claim that each lichenometric surface is characterised in time by varying the GEV *location* and *scale* parameter functions, and is characterised in space by fixing the GEV *shape* parameter (Naveau *et al*. 2005). The whole process involves several complex steps, following collection of the field data, including: (1) generation of a statistical function considered to be a "growth curve"; (2) application of a Bayesian model; (3) many iterations using a Monte Carlo Markov Chain procedure to obtain parametric convergence; (4) computation of an expected 'empirical' distribution for each parameter; and finally (5) calculation of 'surface-age' and derivation of confidence intervals. In a recent assessment study of lichenometric dating techniques, Jomelli *et al*. (2007) find their GEV technique to be the best performing and most accurate method. The GEV group have repeated their statistical approach and their arguments several times in a number of recent similar publications (i.e. Naveau *et al*. 2007; Rabatel *et al*. 2007; Jomelli *et al*. 2007).

The second new approach is not a dating technique per se but a way to distinguish between lichen populations with different size-frequency distributions. The authors use the U^2 statistic to group lichen populations and, after numerous statistical steps (e.g. observation ranking, cluster analysis and similarity matrices), to assign relative ages to recent glacial deposits and highlight complex depositional histories (Orwin *et al*. 2008).

Both new lichenometric approaches are novel and interesting but will probably be of limited use and applicability to the wider community. Essentially this is because they are over-complicated and opaque to the non-statistician user. Unfortunately, both techniques also contain different flawed assumptions and inaccuracies. These are discussed within this article.

Lichenometry as a dating technique

Arguably, the beauty of lichenometry as a dating tool is its simplicity. It provides clear, powerful, quantitative results in a relatively quick, non-destructive and transparent way. It is particularly well suited to decoding Late Holocene glacial histories and has been used most often, and most successfully, in high latitude and alpine settings. In short, it has been demonstrated by many workers that a survey of largest-lichen diameters or lichen size-frequency distributions across recently deglaciated terrain will yield a good impression of the age of glacial landforms, whilst in the field. The size of the largest lichens acts as a good relative guide to the age of surfaces; which can be converted to absolute ages if a site-specific calibrated dating curve is available. It is this geobotanical phenomenon that was first noticed by Faegri and utilised by Beschel, and subsequently by many other workers in a wide range of settings. In its simplest form, lichenometry works well and can yield clear and meaningful results with very few intermediate steps or *a priori* assumptions. It is somewhat regrettable therefore that, in recent years, lichenometry has become removed from its humble origins and has started to lean too heavily on complex statistical approaches. It is particularly regrettable when these statistical approaches have not been shown to be appropriate to the lichenometric technique or to result in greater dating accuracy.

Existing lichenometric techniques

There are really only 4 different techniques in lichenometric dating:

1. The original approach of Beschel, often called the 'traditional approach' has been used to great effect many times since the 1950s. Beschel proposed that finding and measuring the largest lichen on a surface "growing under optimal environmental conditions" will result in the closest age-estimation (Beschel 1961: 1045). Consequently, this single largest lichen (LL) approach uses only the largest non-competing lichen of one species growing on an entire surface to derive a lichenometric age. The mean of the largest 5 lichens (5LL) on a surface was developed in the 1970s as a modification of the LL approach primarily to avoid

reliance on a single, potentially anomalous, lichen thallus. Others have chosen to use 10 or more 'largest lichens', however several studies have shown that neither accuracy nor precision is improved by measuring more than the 5 largest lichens on a surface (e.g. Matthews 1975, 1994; Innes 1984). Some workers have chosen to use the LL or 5LL technique within a representative sample area (from 25-500 m^2), when a whole-surface search is not practical. However, dating curves constructed using this fixed-area approach cannot be directly compared to those constructed using the LL on an entire surface, owing to the different sizes of the search areas (Innes 1983b, 1984). It is true that searching only part of a surface goes against the main assumption of the original LL technique, however as long as the same technique is used in the construction of the dating curve and for dating purposes the technique can be justified in most cases.

2. The fixed-area largest lichen (FALL) approach has been used, chiefly by Bull and co-workers, to ascertain the age and event history of diachronous surfaces. Essentially a development of the LL approach, this technique measures the single largest thallus of one species within a unit sample area. These sample areas, typically boulders, usually average ~1 m^2. The measurements from one surface (c. 100-500) are pooled to allow statistical treatment and age projections. It is important to state that the FALL technique was specifically designed to study rockfall and talus accumulations where the age of the deposit may not be uniform (McCarroll 1993; Bull *et al*. 1994). Unlike the previous approaches, this technique is based on the assumption that lichen populations have a normal distribution of thallus sizes, and that the mean thallus size increases with surface age. Using the FALL technique, Bull and Brandon (1998) recorded an accuracy of +/-10 years on rockfall deposits up to 500 years old in New Zealand.

3. The size-frequency approach (SF) was originally devised to identify multiple populations or anomalous, inherited or pre-existing, thalli growing on a single surface (Benedict 1967, 1985); but has since been used successfully as a relative and absolute dating technique (e.g. Caseldine 1991; Benedict 1999, 2009; Bradwell 2004; Bradwell *et al*. 2006). The SF approach has also been used to assess substrate stability, snow-kill frequency, lichen population structure and micro-environmental tolerance. It differs from the other techniques in that the operator records the long axis of <u>all</u> thalli of a single species growing within a representative sub-sample of the surface. Sample areas vary, but normally cover at least 25-50 m^2, and may include between 200 to

5000 thalli. For best results, sample sizes of 1000 or more lichens are recommended (Benedict 2009). Whilst on smaller surfaces, every lichen should be measured.

4. The lichen cover approach (LC) is based on the assumption that the percentage of a rock surface covered by a single species of lichen will increase with time. Estimates of lichen cover are not common in lichenometric dating studies, although several authors have reported success in constructing relative chronologies using this technique (e.g. Birkeland 1973; Locke *et al*. 1979; Grab *et al*. 2005). The LC technique is the most subjective of the 4 lichenometric dating approaches (Innes 1986a) and consequently is usually only used when the other 3 techniques are impractical. However, recent advances in digital image analysis may allow more quantitative lichen-cover studies to be performed (McCarthy and Zaniewski 2001).

All other lichenometric techniques are essentially modifications of one of these four methods. Most ‘new’ techniques merely use different statistical treatments of field data collected using one of the 4 techniques outlined above (i.e. LL/5LL, FALL, SF, LC). A powerful development of the LL technique was devised by Vanessa Winchester in the 1980s. She used multiple lichen species to derive several site-specific dating curves which, when used in combination, reduced uncertainty and improved accuracy (Winchester 1984). Using this multi-species approach, Winchester (1988) claimed precision of 1-2 years on stone monuments spanning the last 800 years in England. Surprisingly, few have adopted this technique to date recent glacial landforms – possibly owing to the lack of species diversity and the lack of control surfaces in many glacial environments.

Only the FALL approach makes assumptions about the size-frequency distribution of lichens on a surface. The SF approach measures, and therefore quantifies the precise size-frequency distribution of any given lichen population. The mathematical nature of the SF distribution on a specific surface, whether truncated log-normal, skewed, Poisson or otherwise, can only be determined from careful measurement of usually several hundred or more thalli. It is also worth stating that there is currently no consensus on the idealised nature of crustose lichen SF distributions (e.g. McCarthy 1999). However, in young developmental populations, typical of those on Little Ice Age moraines, where space restriction is not a factor, statistical normality will commonly apply (e.g. Innes 1983b, 1986b; Haines-Young 1988; McKinzey *et al.* 2004).

Recent statistical treatments of lichenometric data

Processing lichenometric data and deriving absolute calendar ages for publication, with confidence intervals or error bars, is highly dependent on 2 things: the strength and validity of the dating-curve calibration; and the statistical treatment of the measurement data. Varying either of these 2 factors will produce widely differing results. The GEV group claim to build on a detailed statistical treatment published by McCarroll (1993, 1994). However, this lichenometric approach was principally devised to investigate geomorphic activity in multi-event deposits. Rather than using the size-frequency approach, which is best suited for dating single-event surfaces, McCarroll chose to modify the largest lichen approach to examine the age-frequency of avalanche boulders. As McCarroll (1993: 529) states in his study aims: "it is not the frequency distribution of lichens of different size that is of interest, but the frequency distribution of boulders of different age". This study, and those of Bull and co-workers (1994, 1996, 1998) – who examined earthquake-generated rockfalls – have succeeded in using lichens to identify and date multi- and single-event deposits. But the GEV group go on to presume that all lichen-dating studies make the same assumptions made by McCarroll and Bull; whilst forgetting (or not recognising) that these authors were dealing with a specific modification of the lichenometric technique.

The GEV group criticise previous lichenometric techniques on the basis that "they assume that the largest lichens follow a Gaussian distribution" (Jomelli *et al.* 2007: 137). However this is a misconception, and their statement may be based on a misunderstanding. The largest lichen in any population is by definition an extreme, hence why the largest lichens are far less numerous in any population, as found in many previous studies. But the "extreme" nature of the largest thalli does not require the statistical complexity of Generalized Extreme Value theory to calculate a lichenometric dating curve (or simply an age-size function) based on largest lichens. A calibrated age-size *dating curve* is simply an empirical relationship between the largest thallus (or mean of the 5 largest), assumed to be the oldest, and the surface age of the feature, where the independent variable (x-axis) is time. There is no assumption of normal distribution in this procedure – Gaussian or otherwise. In its purest form, lichen dating curves can tell us, by interpolation, how old we should expect a certain-sized lichen to be. It is arguably this simplicity which has made the technique so useful to so many for so long.

The presentation of lichenometric dates has yet to be standardised, particularly regarding the calculation of confidence intervals. The GEV group claim (e.g. Cooley *et al.* 2006; Jomelli *et al.* 2007) that this as an inherent weakness in existing lichenometric approaches, and they attempt to devalue previous work which does not present the associated mathematical uncertainties. Jomelli *et al*. (2007: 140) criticize those studies which derive confidence intervals that "lack a mathematical foundation". Instead they propose the use of their highly complex statistical approach (a Bayesian treatment of Generalized Extreme Value theory) in the perceived pursuit of greater precision and to calculate stronger mathematical confidence intervals (Cooley *et al.* 2006; Naveau *et al.* 2006; Jomelli *et al.* 2007). They fail to recognise that uncertainties have been expressed quite succinctly and precisely in many 'traditional' lichenometric studies (e.g. see Table 1). For dating curves constructed using the LL or 5LL, 2 standard deviations are preferred (95% confidence limits). The interpolated ages can be presented with the associated standard error, derived in the normal way, using (a) the lichen diameter, (b) the relevant calibration points, and (c) the value of the curve fitted through the calibration points at the relevant intersection. Any calibrated-age dating technique, such as lichenometry, will always be subject to the precision uncertainties of the field measurements combined with the construction of the calibration curve. These can be expressed and, in many cases, are incorporated into the derived lichenometric ages. If a new technique to derive mathematical uncertainty implies greater confidence than the original data warrants, regardless of its complexity, the technique risks serving no purpose. This is surely a major criticism of the new methodology proposed by the GEV group.

The SF technique makes use of a simple class-size statistical treatment in order to firstly determine the composition of the lichen population, whether it is unimodal or not, and secondly uses linear regression to determine the age of the population measured against a SF distribution 'calibration curve'. This technique has had considerable success both as a relative and an absolute dating technique, and is more statistically robust than the LL or 5LL techniques because of the large number of measurements which make up a single age-determination (Benedict 1985, 1999, 2009; Locke *et al.* 1979; Innes 1983b, 1986b; Caseldine 1991; Cook-Talbot 1991; Bradwell 2004; Bradwell *et al.* 2006). It is not dependent on assumptions of statistical normality within lichen populations, although several studies have shown skewed normal distributions to be typical on young surfaces (e.g. Innes 1986b; Haines Young 1988; Bradwell 2004; McKinzey *et al.* 2004). The SF approach is the least criticised by the GEV group in their assessment study of lichenometric dating techniques (Jomelli *et al.* 2007). However, they fail to see any advantages of the SF approach over their newly proposed GEV technique; and in conclusion Jomelli *et al.* (2007) omit the SF approach as a valid alternative to their own more statistically complex, and somewhat confusing, Bayesian GEV approach. The reason for this omission is not altogether clear, however it may be due to the construction of their experiment and a misunderstanding of the SF technique. Jomelli *et al.* (2007) could not perform the SF technique in one of their two test areas because they chose tombstones with small surface areas (typically <2 m^2). In the second test area, glacier forelands in the Bolivian Andes (Rabatel *et al.* 2006), the SF measurement data appear to have been collected unconventionally – possibly erroneously. Jomelli *et al.* (2007: 137) state that they measured at least 300 lichens "randomly selected" within a fixed area of 50 m^2 – "1 lichen per block". This is not the normal SF approach – which measures **all** thalli within a fixed area – and therefore their results cannot be compared with the conventional SF approach used by others (e.g. Benedict 1985, 1999, 2009; Innes 1983b, 1986b; Bradwell 2004). This confused methodology, a mix of the SF and FALL techniques, may explain the apparent success of the GEV approach, as tested by Jomelli *et al.* (2007), over other more traditional lichenometric techniques such as the SF approach. Failure to recognise this flaw, along with the propagation of other false assumptions previously mentioned, seriously compromises the assessment study of Jomelli *et al.* (2007). Consequently, advocation and adoption of the GEV method as the "most reliable" lichenometric dating technique (Jomelli *et al.* 2007: 131) is probably unjustified.

The complex statistical treatment proposed by Orwin *et al.* (2008) is not a dating method, but a technique which helps to identify lichen-colonized surfaces with similar histories. Orwin *et al.* (2008) propose the use of the U^2 statistic (Watson, 1961) to quantify the closeness of fit between any two lichen size-frequency distributions. The U^2 function has been used by statisticians for over 4 decades, but never before applied to lichenometry. Orwin *et al*'s methodology is built around and based on the SF approach, and in fact uses the same dataset as the lichenometric study conducted by McKinzey *et al.* (2004).

The U^2 technique may prove useful when examining lichen populations on multi-event surfaces. However, it is statistically cumbersome involving numerous steps, (observation ranking, cluster analysis and similarity matrices) whilst seeming to offer little in return. In many of the lichen populations from SE Iceland (Orwin *et al.* 2008; Fig. 3) visual inspection and simple statistics (i.e. mode, falling limb gradient or central tendency) easily describe their similarity or difference. Hence, the use of the U^2 statistic to distinguish between unimodal populations with markedly different SF gradients seems unnecessary and overcomplicated (e.g. HJ8708 & HJ8704 in Orwin *et al.* 2008; Fig. 3). The technique's ability to distinguish between complex or polymodal populations does represent a methodological advance. However, simple visual inspection can again prevent the inclusion of composite or polymodal populations in SF dating studies. This is important as older polymodal lichen populations cannot be dated with SF *age-gradient* curves (sensu Bradwell 2004) as they usually contain inherited thalli or multiple natality and mortality events (Innes 1983b, 1986b; McCarthy 1999). Simply stated, the use of complex U^2 statistics merely groups lichen populations with similar size-frequency distributions; it cannot decode moraine chronologies or the associated environmental conditions in any more detail than the lichen SF data itself. The use of this technique in "augmenting lichenometric surface dating" is suggested by Orwin *et al.* (2008: 151). However, it may offer little in uncomplicated, recessional moraine sequences; and it remains to be seen how the complex U^2 statistics once generated can be applied to extract environmental information.

Some ecological uncertainties

Philosophically, it is hard to defend the use of high precision, highly complex statistics (such as those proposed by the GEV group) to solve what is essentially a simple problem: How can the size of lichens growing on a surface best inform us of its age? Owing to the nature of the subject matter, uncertainty will always be high and hence dating precision will, in reality, always be low. Numerous ecological factors, central to the establishment and growth of the lichen thallus, determine this statement. A review of these factors, although probably timely, is far beyond the scope of this short article. However, it goes without saying that environmental conditions can vary greatly from site to site and even within sites. This can lead to problems when trying to calibrate or standardise field procedures, for instance when constructing a lichenometric dating curve. Uncertainties still surround the different growth rate of non-competing crustose lichens on surfaces with different aspect, slope angle, lithology, macro- and microclimate. Some of these topics remain largely unstudied, or are still being explored (e.g. Armstrong 1993, 2002, 2006, etc.). When combined with added uncertainties surrounding competition between thalli and between species (Armstrong and Welch 2007); differences in fungal (hypothallus) growth relative to algal (areolae) growth (Armstrong and Bradwell 2001); the impact and timing of mortality events (Loso and Doak 2006); and the importance of biological niches within certain environments (McCarthy 1999) – the range of factors likely to influence the growth rates of lichens becomes far greater. Even the exact nature of the growth curve in the most commonly used species in lichenometric dating (*R. geographicum*), although found to be non-linear over time, is still debated and in need of further study (cf. Proctor 1983; Matthews 1994; Bradwell and Armstrong 2007). Careful research has shown that lichen growth is strongly controlled by moisture availability (Armstrong 1976, 2006; Benedict 1990). As a consequence, micro-environmental factors such as slope inclination (horizontal or vertical), surface orientation (to prevailing winds), surface texture and lithology may play an equally important role in determining growth rates alongside regional climatic conditions. Until the time when these key growth rate factors have been fully examined, and preferably quantified, in-built uncertainty will always surround the derivation of lichenometric dates even when local dating curves are used and field-measurement errors are minimised.

Summary

This article attempts to dispel some of the current myths surrounding the statistical treatment of lichenometric data. Recent studies using complex statistics – most notably by the GEV group – are attempting to overcomplicate what is a simple scientific technique. Many workers have successfully dated old surfaces using traditional lichenometric methods (see Table 1). In the North Atlantic region, the technique has enjoyed over 50 years of success and in this time has received several modifications and tweaks since the first studies by Roland Beschel. Importantly though, the long-established practice of comparing lichen sizes in the field with a carefully calibrated dating curve has proven effective for many workers in many countries over many years. So is it really time to adopt a new, considerably more complex, considerably less transparent technique, when the old one has not been found wanting? For this reason, advocation of highly complex statistical techniques, such as the GEV approach, in pursuit of greater reliability or improved accuracy – over and above existing lichenometric techniques – seems premature and probably unjustified. These novel uses of statistics, whether to examine lichen populations growing on "similar historied surfaces" (Orwin *et al.* 2008), or to model uncertainties within idealised distributions (Naveau *et al.* 2007), leave the average potential user baffled by their complexity and inapplicability. Clearly, a good scientific technique is one which is only as complex as the subject matter warrants. In the case of lichenometry – a simple, user-friendly, field technique – the use of complex statistics is hard to support (e.g. Cooley *et al.* 2006; Naveau *et al.* 2007; Jomelli *et al.* 2007; Orwin *et al.* 2008) – particularly given the natural complexity and variability inherent within the lichen growing environment.

Whilst uncertainty still surrounds fundamental questions regarding lichen ecology, lichenometric dating will never be an exact science. In the meantime, any attempt to make it so should be viewed with caution and healthy scepticism. The lichen-dating community still awaits consensus on key questions relating to: the exact shape of the lichen growth curve; the typical size-frequency distribution for populations of different age; the effects of species competition; and the effects of temperature, precipitation and seasonality changes on lichen growth rates over many years. Lastly, on a more philosophical note (and maybe a suitable subtitle for this article), all this begs the question: can statistical complexity in pursuit of high precision ever be scientifically justified in a poorly understood 'geobotanical' dating technique?

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Table 1. A cross-section of lichenometric dating studies conducted in northern Europe since 1980.

author(s)	date[1] (AD)	location	lichen species[2]	technique[3]	lichen dimension	no. of lichens recorded[4]	survey area[5] (m^2)	calibration surfaces[6]	uncertainty expressed
Rapp and Nyberg	1981	Abisko Mtns, Sweden	*R. geographicum* agg.	LL	long axis	1	variable	ex. curve	no
Innes	1983	Scottish Highlands	*R.* section *Rhizocarpon*	LL	long axis	1	entire	gravestones	no
Gordon and Sharp	1983	Breiðamerkurjökull and	*R. geographicum* agg.	5LL	short axis	5	1500	moraines	yes
		Skálafellsjökull, Iceland	*R. geographicum* agg.	5LL	long axis	5	150	moraines	yes
Anda *et al.*	1985	Jan Mayen	*R. geographicum*	LL	long axis	1	entire	moraines	no
Thompson and Jones	1986	Öræfi, SE Iceland	*R. geographicum* agg.	5LL	short axis	5	entire	moraines	yes
Broadbent and Bergqvist	1986	Bothnia coast, Sweden	*Rhizocarpon* subgenus	LL, SF	long axis	203	entire	raised beaches	yes
Andre	1986	NW Spitsbergen	*R. subgen. Rhizocarpon*	LL	long axis	1	variable	n/a	n/a[7]
Winchester	1988	Cumbria, England	*R. geographicum* subsp.	LL	long axis	1	entire	gravestones	no
Ballantyne	1990	Lyngshalvoya, Norway	*Rhizocarpon* subgenus	5LL, SF	long axis	100-400	variable	gravestones	no
Kugelmann	1991	Skiðadalur, Iceland	*R. geographicum* agg.	LL	long axis	1	entire	gravestones	yes
Cook-Talbot	1991	Jotunheimen, Norway	*R. geographicum* agg.	5LL, SF	long axis	300	variable	ex. curve	no
Jonasson *et al*.	1991	High Tatra Mtns, Poland	*R. geographicum*						
Caseldine	1991	Tröllaskagi, Iceland	*R. geographicum* s.l.	SF	long axis	1000	variable	debris flows	n/a[7]
Macklin *et al*.	1992	North Pennines, England	*R. geographicum* and *Huilia tubercolosa*	3LL	long axis	3	variable	gravestones, bridges	no
Bickerton and Matthews	1993	Jostedalsbreen, Norway	*Rhizocarpon* subgenus	LL, 5LL	long axis	5	c. 430	ex. curve	yes
McCarroll	1993	Jostedalen, W Norway	*R. geographicum* agg.	FALL	long axis	100	<2	ex. curve	yes
Evans *et al*.	1994	Sandane, W Norway	*R.* section *Rhizocarpon*	5LL	long axis	5	20	ex. curve	no
Gudmundsson	1998	Eiriksjökull, Iceland	*R. geographicum*	5LL	short axis	5	entire	ex.curve	no
Evans *et al.*	1999	Vatnajökull, Iceland	*R. geographicum* s.l.	5LL	long axis	5	entire	m, sh, br, g	no
McCarroll *et al*.	2001	Hurrungane, W Norway	genus *Rhizocarpon*	FALL	long axes	100	<2	ex. curve	yes
Kirkbride and Dugmore	2001	Eyjafjallajökull, Iceland	*R. geographicum*	LL, 5LL, SF	long axis	>250	50-100	m, fd	no
Winchester and Chaujar	2002	North Wales	*R. geographicum* subsp.	SF	long axis	100-500	variable	gravestones	no
Winkler *et al.*	2003	Breheimen, Norway	*Rhizocarpon* subgenus	LL, 5LL	long axis	5	variable	ex. curve	no
Bradwell	2004	SE Iceland	*R.* section *Rhizocarpon*	LL, SF	long axis	>250	30-100	m, rf, lf, fd	no
Matthews	2005	Jotunheimen, Norway	*Rhizocarpon* subgenus	LL, 5LL	long axis	5	200	moraines	no
Bakke *et al.*	2005	Lyngen, Norway	*R. geographicum*	5LL	long axis	5	30	ex. curve	no
Bradwell	2006	Lambatungnajökull, Iceland	*R.* section *Rhizocarpon*	LL, SF	long axis	>250	30-100	m, rf, lf, fd	yes
Principato	2008	Vestfirdir, Iceland	*R. geographicum*	5LL	mean diameter	5	entire	ex. curve	no

Notes

1 – year of publication, not necessarily year of lichenometric survey.
2 – species, or taxonomic classification, as stated in publication.
3 – principal dating technique(s) used: LL (largest lichen); 3LL (3 largest lichens); 5LL (5 largest lichens); FALL (fixed-area largest lichen); SF (size-frequency distribution); see text for more details on different techniques.
4 – total number of lichens measured per surface in order to derive numerical age (1 = only largest-lichen used)
5 – average search area of lichenometric survey per surface, where stated. 'Entire' indicates the whole surface was searched. For FALL surveys, search areas are not recorded; a nominal value of <2 m^2 has been ascribed.
6 – surfaces used in calibration of dating curve, where applicable: moraines (m), gravestones (g), bridge (br), shoreline (sh), flood deposit (fd), rockfall (rf), lava flow (lf); ex.curve = existing (published) curve or modification of existing curve used to derive ages.
7 – relative ages only; uncertainty not applicable.