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Lichenometry

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ABSTRACT: Lichenometry has been widely used to date rock surfaces since it was developed by Roland Beschel in the 1950s. Two methods have been developed: first, the indirect method, which requires the availability of substrates of known ages and the measurement of lichens growing on them, from which a correlation is established between the size of the lichen and surface age; the second, is direct lichenometry, which requires the measurement of the growth rate of individual lichens in real time and construction of a growth curve. Both methods are reviewed here with reference to species, sampling and measurement techniques and dating-curve construction. Several different variants of the indirect approach are available. While the direct approach has always been regarded as based on sounder biological principles, there are greater practical limitations to surmount.

KEYWORDS: Lichens, chronology, environmental reconstruction, rock surfaces, Holocene.

Introduction

Lichenometry is one of a number of chronological tools used to estimate late-Holocene timescales accurately. It is particularly useful in arctic-alpine environments above the tree line where some crustose lichens grow very slowly, have great longevity (Armstrong, 2004), and where the lack of suitable organic material makes other dating techniques (e.g. dendrochronology and radiocarbon dating) less suitable or not possible.

Roland Beschel pioneered the use of lichens for dating surfaces. As part of his doctoral research completed in 1958 at the University of Innsbruck, he studied the ecology of lichens and measured diameters of lichens on dated tombstones in Austrian cemeteries, determining the growth rates of a number of fast-growing species. Beschel published a series of articles on the subject in the 1950s (Benedict, 2009).

Lichenometry has been used worldwide to date rock and boulder strewn surfaces. Bradwell and Armstrong (2007) identified a range of landforms that can be dated by lichenometry including river channels, flood deposits, lake shorelines, raised beaches, rock falls, debris flows and moraines. Other reviews include those of Locke *et al*. (1979), Innes (1985), Matthews (1994), Noller and Locke (2000), Benedict (2009) and Armstrong and Bradwell (2010).

The basic principle involved in using lichens for dating is that if the relationship between the size and age of lichens is known, then the age of a surface can be inferred from the size of the lichens present (Innes, 1985). However, a distinction is usually made between the differing methods of estimating the rate of lichen growth; the direct approach involves monitoring measurement of lichen growth rates, and the more commonly used approach of indirect lichenometry involves inferred growth rates from the sizes of lichens on surfaces of known age.

Species selection

The choice of lichen species used in dating is influenced by a sufficient abundance of individual specimens at the site (Mottershead, 1980). Armstrong and Bradwell (2010) produced a list of selected publications using 27 different species of crustose lichens in direct lichenometry. The most commonly used taxon is the slow growing, long lived, and widely distributed saxicolous (grows on rocks) crustose lichen *Rhizocarpon geographicum* (Loso & Doak, 2006). However, many published accounts that claim to use *Rhizocarpon geographicum* are actually using the larger grouping, *Rhizocarpon* subgenus *Rhizocarpon* (Matthews, 2005).

Measurement techniques

Measuring the growth of a lichen thallus needs to be quick, inexpensive and accurate in order for a large number of thalli to be measured (Armstrong, 1976). The two parameters commonly measured for crustose lichens are the area and the diameter, with the diameter of nearly circular thalli being the most common. In practice, the diameter of non-circular thalli may be defined as the long axis, the short axis or an average of the two. For example, Trenbirth and Matthews (2010) measured the long axis using Miltutoyo dial callipers (instrumental precision ± 0.05 mm) (Figure 1). Lichen diameters have also been measured by a ruler (Phillips, 1963; Bradwell & Armstrong, 2007), digital callipers (Lowell *et al.*, 2005; McCarthy, 2003), tracing the thalli outline (Miller & Andrews, 1972; Haworth *et al.*, 1986) and photography (Hooker & Brown, 1977; Proctor, 1983; Rogerson *et al.*, 1986; Bradwell, 2010). Indirect lichenometry usually measures to the nearest mm (with a ruler or steel tape) and does not require such high precision measurements as the direct method.

A photographic technique for monitoring lichen growth is described by Benedict (2008). Photographs are taken over a period of time. Before digital photography the negatives were enlarged in the chemical darkroom and scanned at 600 ppi for use in Adobe Photoshop 6.0. The images were adjusted so that the millimetre scale included in each photograph was reproduced at the actual size. Original and repeat photographs were viewed side by side to ensure

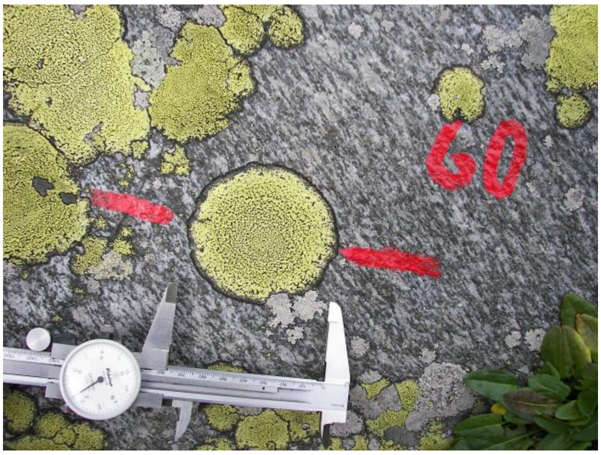

Figure 1. Rhizocarpon subgenus lichen with red paint lines marking the measured longest axis (Trenbirth & Matthews, 2010).

measurements were made in the same locations. Distances were measured in pixels. Bradwell (2010) adapted this method for a digital camera. The images were enlarged in an image analysis application (Adobe Photoshop 8.0) and accurately overlaid. Scale bars (Figure 2) were used to determine precise size. On-screen measurements were made to an accuracy of 0.01 mm.

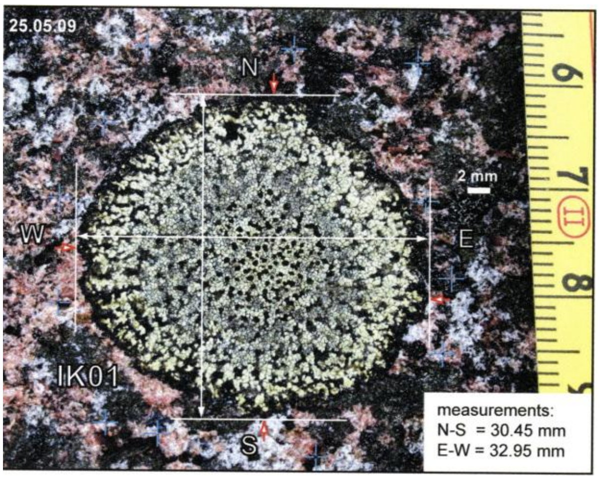

Figure 2. Measurement parameters used by Bradwell (2010), measured on screen in Adobe Photoshop.

The area of lichens can also be used to calculate lichen growth rates. Prior to the use of computer software for calculating area Rydzak (1961) traced the outlines of thalli on plastic sheets and then retraced these at a later date (Figure 3). The surface area of each thallus traced was measured using a planimeter; the procedure is repeated in the next period of measurement and the increment was calculated in mm^2. Miller (1973) found measuring the thallus area of *Alectoria minuscula* to have an accuracy of ±0.5 mm using the tracing method compared to an accuracy of ±0.01 mm using a photometric method. The latter can be inaccurate over short periods (Armstrong, 1976).

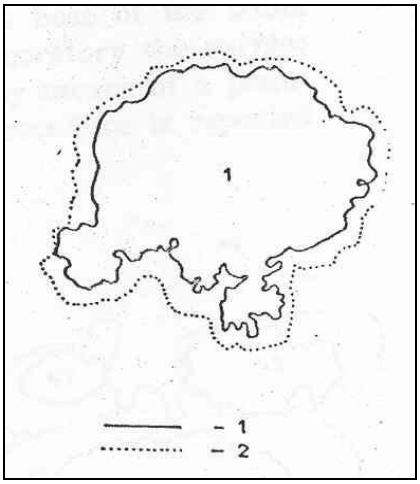

Figure 3. Change in the outline of a thallus of Lecanora saxicola Ach between 1957 (1) and 1960 (2) (Rydzak, 1961).

Sampling techniques

The majority of workers attempting to date a substrate use the largest thalli, which has resulted in many debates about the sampling strategy. There is a need to recognise abnormal thalli sizes as there are a number of factors affecting the relationship between the largest lichen and those that are slightly smaller. These include: age of substrate; chemical composition of the substrate; lichen population dynamics; microenvironment; lichen species; presence of anomalously old thalli; and area of the substrate searched (Innes, 1983b). Matthews (1994) pointed out that the use of a large surface area is likely to produce more realistic results as lichen sizes vary over a moraine surface of a single age. To avoid the problem of abnormally large thalli, Calkin and Ellis (1980) discounted any thalli 20% larger than the next largest. Maizels and Petch (1985) proposed the use of the mean of the 100 largest lichen thalli from 100 m^2 quadrats. Although this is more time consuming, it has the advantage that it is likely to cancel out any extreme values representing localised conditions promoting excessive growth. Locke *et al.* (1979) recommended using a search area of 400 m^2, measurement of the ten largest thalli, and the mean of the five largest thalli (including the largest). This method provides a compromise approach in which the effect of extreme measurements may be reduced.

Indirect lichenometry

This requires the recognition of substrates of different known ages and the measurement of lichens growing on them (Mottershead, 1980). A correlation is established between the size of the lichen and the surface age, based on lichen measurements from surfaces of known age (Matthews, 1994). Substrates of known age (control points) that have been used in indirect lichenometry include: anthropogenic surfaces, such as gravestones (Innes, 1983a); stone walls (Benedict, 1967); mine spoil heaps (Karlén, 1973); abandoned farmsteads (Caseldine, 1983); a whaling monument (Werner, 1990); and natural surfaces dated by tree rings and varves (Noller & Locke, 2000). Historical documents can also be used to date surfaces (Anderson & Solid, 1971). A growth curve is then constructed from the lichen sizes from surfaces of known age. A selection of growth rates from different regions is shown in Figure 4.

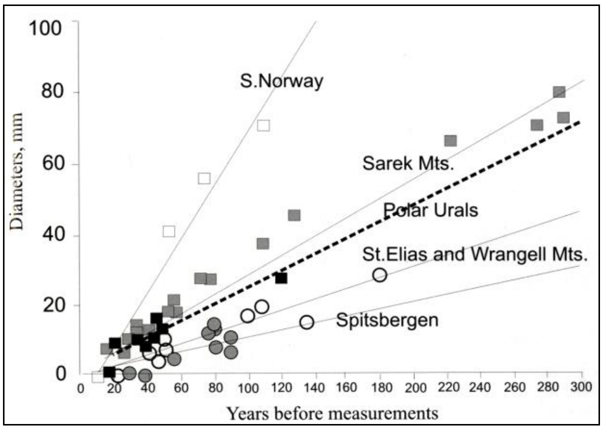

Figure 4. Rhizocarpon subgenus Rhizocarpon growth rates in several subpolar regions (Solomina et al., 2010): Spitsbergen (grey circles) (Werner, 1990); St. Elias and Wrangell Mts, southern Alaska (open circles) (Denton & Karlén, 1973); Sarek Mountains (grey squares) (Karlén & Denton, 1975); Southern Norway (open squares) (Bickerton & Matthews, 1992); Polar Urals (black Squares) (Solomina et al., 2010).

It is essential that the sampling design used to derive the control points for the growth curve is the same as that used on the surfaces of unknown age (Innes, 1985).

There have been numerous studies using the indirect approach to lichenometry, involving numerous different methods adapted to local conditions. This makes it impossible to recommend a standard technique.

One method frequently used is to take the largest lichen or the mean measurements of lichen diameters or the radius. Hughes (2007) measured *Aspicilia calcarea* agg. lichens in Montenegro to date recent behaviour of the Debeli Namet glacier. The mean of the five largest lichens from a total sample size of 30 lichens measured at random from 50 gravestones and monuments was used to construct the lichen age/size relationship (Figure 5). The mean diameter of the five largest lichens from a random sample of 30 lichens was then calculated for each sediment ridge to compare with the size/age relationship established from the gravestones and monuments to determine the approximate age of the landform.

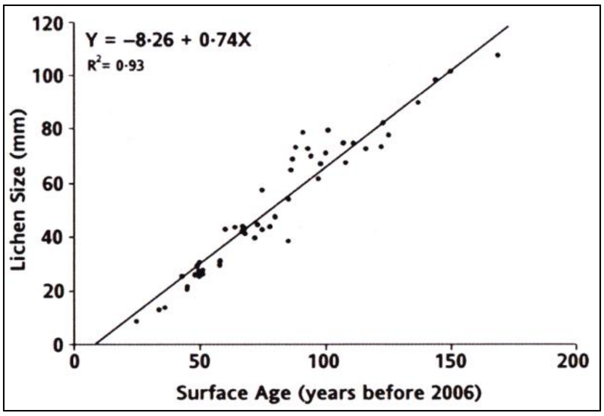

Figure 5. Regression of surface age against the mean size of the five largest lichen thalli (50 samples) obtained by measuring lichens on monuments and gravestones of known age (Hughes, 2007).

Cook-Talbot (1991) calculated the mean diameters of the 5, 10 and 50 largest lichens on clasts in stone circle borders and centres in Norway as part of an investigation into palaeoenvironmental reconstruction in an alpine periglacial environment.

The largest lichen method was used by O'Neal and Schoenenberger (2003) to produce a *Rhizocarpon geographicum* growth curve for the Cascade Range of Washington and northern Oregon, USA. The largest lichen was identified on each man-made structure and each moraine for 22 sites. The maximum diameters of individual lichens with circular or nearly circular thalli were measured on boulders with surface area > 0.3 m^2 or on rock walls. For the man-made structures the largest lichens on individual blocks were measured. These structures were selected through the altitudinal range of the glacier moraines to ensure no bias between the setting and the altitude.

The accuracy of such methods is difficult to estimate. Matthews (2005) compared the lichenometric dates based on indirect lichenometry (using the mean of the five largest lichens) to the control points of known age. The surfaces, which were about 50 years old, had an accuracy of ±6 years whereas surfaces about 230 years old had an accuracy of ±35 years.

One indirect technique uses size-frequency distributions. Benedict (1967) was the first to use this approach when dating a native Indian wall in the Colorado Front Range. This method has been adopted by several studies including: Andersen and Sollid (1971), Innes (1983b), Cook-Talbot (1991), Bradwell (2004), McKinzey *et al*. (2004), Bradwell *et al.* (2006), Golledge *et al.* (2010) and Roberts *et al.* (2010). In South Georgia, Roberts *et al.* (2010) measured the diameters of 872 lichens on boulders on five moraines. These lichens were analysed using the size-frequency method. The lichens were measured in pre-defined areas of approximately equal dimensions. Size-frequency analysis of the data was then used to determine whether using the largest five or the largest ten lichens could be used for dating. The lichen population size-frequency data were plotted as histograms, Q-Q plots (which are quantile probability plots showing all data and illustrating where each data point deviates from the theoretical normal distribution) and also plotted using a class size of 3 mm expressed as $\log_{10}$ percentage frequency against diameter size (Figure 6).

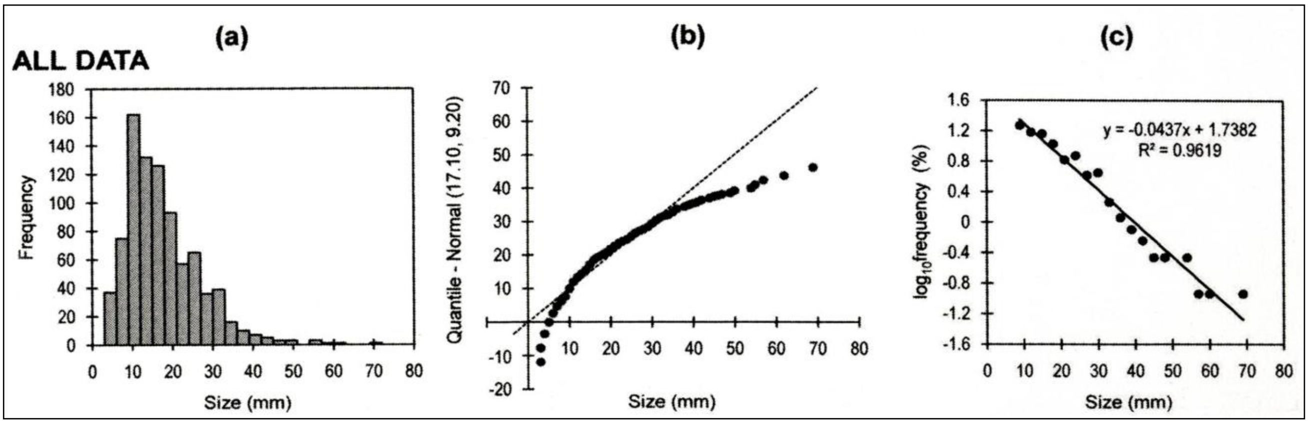

Figure 6. Lichen size data for all data shown as: (a) histograms plotted with a class size of 3mm; (b) Q-Q plots; (c) lichen population size-frequency data plotted using a class size of 3 mm expressed as log_{10} percentage frequency against diameter size (Roberts et al., 2010).

The results showed a notable increase in lichen size with increased distance from the cirque headwall. In the absence of an age-size curve for South Georgia the largest lichen, size-frequency method and long-term growth rates established on the nearest Antarctic localities were used to establish lichen growth-rate ranges, and likely age ranges for the moraines.

Percentage cover measurements of lichens is another indirect lichenometry technique. The premise is that the total surface area of a rock covered by one or more species of lichen increases through time. The deposit with a greater lichen cover than another has been taken as being older. Innes (1986) concluded from studying two glacier forelands in Norway that this technique is subjective as the results obtained by different observers are not reproducible. Substantial variations in cover were found on the moraines and this method appears to be more sensitive to environmental variations. The technique appears to be unreliable but has considerable potential for the dating of smaller boulders or surfaces that cannot be dated by conventional lichenometric techniques. Several studies have used this technique including Carroll (1974) who used the percentage of lichen cover as one relative dating technique to date Quaternary deposits in Arikaree Cirque, Colorado.

McCarroll (1993) proposed a new technique for using lichenometry on surfaces comprising material deposited at different times, as traditional techniques are used for surfaces deposited in a single event. This approach uses simulation-modelling in an attempt to translate the lichen-size frequency distributions obtained from diachronous surfaces into the age-frequency of surface boulders. A record of snow avalanche activity was obtained from using this approach in western Norway (McCarroll, 1993, 1994, 1995; McCarroll *et al*., 1995) and rock fall activity (McCarroll, 1994; McCarroll *et al.*, 1998).

A new statistical model for lichenometry has been developed using the generalized extreme value (GEV) distribution, building a Bayesian hierarchical value model (Cooley *et al*., 2006). It uses the largest lichen measurements and applies statistical theory of extreme values. It offers several advantages, including: accounting for the uncertainty associated with the estimates of moraine ages; accommodating any growth curve function; and allowing for spatial variation in lichen growth. Further studies on this method include Jomelli *et al*. (2007, 2008), Naveau *et al*. (2007), Rabatel *et al*. (2008) and Chenet *at al*. (2010). Although the GEV is computationally intensive (Bradwell, 2009), it appears to enables a better quantification of uncertainty (Jomelli *et al*., 2010).

A selection of recent applications, locations and different indirect lichenometric techniques is shown in Table 1. Different methods have been used depending on the availability of lichens and the terrain on which they are growing.

Table 1. Aspects of selected indirect lichenometric dating studies: location, area surveyed, area searched, method used, lichen size range and the authors.

Location .	Area surveyed	Search area	Method	Lichen size range	Author
Bolivian Andes	15 glacier forelands	Blocks, 2678 lichens	Largest lichen	9-41 mm	Rabatel *et al.* (2008)
Patagonian Andes	6 glacier forelands	Entire surface each moraine	Largest lichen Size-frequency	0.6-13.5 cm (largest lichen)	Garibotti & Villalba (2009)
Montenegro	5 cirques	Sites 25 m long, 10 m wide	Mean 5 largest	67.5-142.3 mm	Hughes (2010)
Vancouver Island, Canada	2 glacier forelands		Largest lichen Mean 5 largest	33.2-97.4 mm (largest lichen)	Lewis & Smith (2004)
Iceland	Glacier forelands	30 m^2/ site	Largest lichen Size-frequency	19-95 mm (largest lichen)	Bradwell (2004)
Norway	16 glacier forelands	25x8 m/site	Largest lichen Mean 5 largest	14-158 mm (largest lichen)	Matthews (2005)
Cascade Range, USA	Glacier forelands		Largest lichen	11.8-50 mm	O'Neal & Schoenenberger (2003)
New Zealand	Glacier forelands	Sample areas 10 to 100 m^2	Largest lichen Mean 5 largest Mean 10 largest 98% quantile		Lowell *et al*. (2005)
Iceland	Rock Glacier	Entire surface	Size-frequency	<5 to 80 mm (size class)	Hamilton & Whalley (1995)
Austria	Talus slope	300 boulders	Mean 5 largest % cover	5.1-27.9 mm (mean 5 largest)	Sass (2010)
Norway	Talus slope	100 boulders, 25 sites	Largest lichen Size-frequency	16.6-37.2 mm	McCarroll *et al.* (2001)
Antarctic	Former snow -patch areas	13 sites	Size-frequency		Golledge *et al*. (2010)
Poland	Debris flow		Largest lichen		Jonasson *et al*. (1991)
Iceland	Proglacial river terrace	Entire surface of each terrace	Mean 5 largest	14.3-67.4 mm	Thompson & Jones (1986)
Sweden	Raised beaches	All rocks and surfaces	Largest lichen	19-358 mm	Broadbent & Bergqvist (1986)
Norway	Lake shoreline	25 m sections, 6 sites	Mean 5 largest	59-310 m	Matthews *et al*. (1986)
Lake District, England	Flood event	All deposit measured	Mean 5 largest		Johnson & Warburton (2002)
France	Flood event, 4 rivers	Blocks in riverbeds	Mean 5 largest Size-frequency	0.1-81 mm	Gob *et al*. (2010)
Cumbria, England	Valley floor development	7 zones	Largest lichen	4->95 mm	Harvey *et al*. (1984)
Australia	Archaeological structures		Largest lichen	5.7-74.4 mm	Müller (2005)
Central Asia, USSR	Seismic dislocations		Statistical model		Smirnova & Nikonov (1990)
New Zealand	Earthquake blocks, rockfall event		Largest lichen	0.2-1m	Bull & Brandon (1998)

Direct lichenometry

Observations of individual lichens at repeated intervals over time are required for the direct approach. Several years of measurement are needed to assess the growth rate. A growth curve is constructed from the growth measurements of lichens of varying size.

Relatively few studies have adopted the direct approach, largely because of practical difficulties associated with the slow-growing crustose lichens that are most commonly used for dating purposes. Bradwell and Armstrong (2007) reviewed 13 studies (including their own) that used the direct approach for the *Rhizocarpon* subgenus (Hausmann 1948; Ten Brink 1973; Hooker 1980; Armstrong 1983, 2005; Proctor 1983; Rogerson *et al.* 1986; Haworth *et al.* 1986; Matthews 1994; Winchester and Chaujar 2002; McCarthy 2003; Sancho and Pintado 2004). These studies showed considerable variability in the estimated mean annual diameter growth rates ranging from 0.08 to 1.47 mm/yr. The number of years over which the measurements were made ranged from 1.5 to 12 years, with only two records > 6 years. Furthermore, the majority of sample sizes have been small at single sites. This has resulted in little information on temporal variability and the effects of habitat variation.

A recent exception is the study of Trenbirth and Matthews (2010) who monitored diameter measurements over 25 years for 2,795 individuals of the *Rhizocarpon subgenus* at 47 sites on 18 glacier forelands in southern Norway. Individual lichens were selected with well-defined orbicular thalli, free of competition from other lichens and located on stable boulders or, in a few cases, on bedrock. Red marker lines were painted on the adjacent rock (Figure 1), to indicate the position of the measured long axis of each thallus, and an identification number was painted close to the lichen. The long axis was then measured using Miltutoyo dial callipers (instrumental precision ± 0.05 mm). The mean annual growth rate for the 47 sites ranged from 0.43 mm/yr to 0.87 mm/yr. The main between-site pattern in these data related to surface age, with the growth rate declining with increasing surface age.

Lichen growth curves (age-calibration curves), which relate lichen size to lichen age, were constructed for three sites using the method of Armstrong (1976) with initial 5.0-mm lichen-size classes (Figure 7). Wider class intervals were used for lichen sizes above about 100 mm and also for lichens <10 mm diameter at one of the sites (Styggedalsbreen) because of the small number of lichens. Growth rate at the

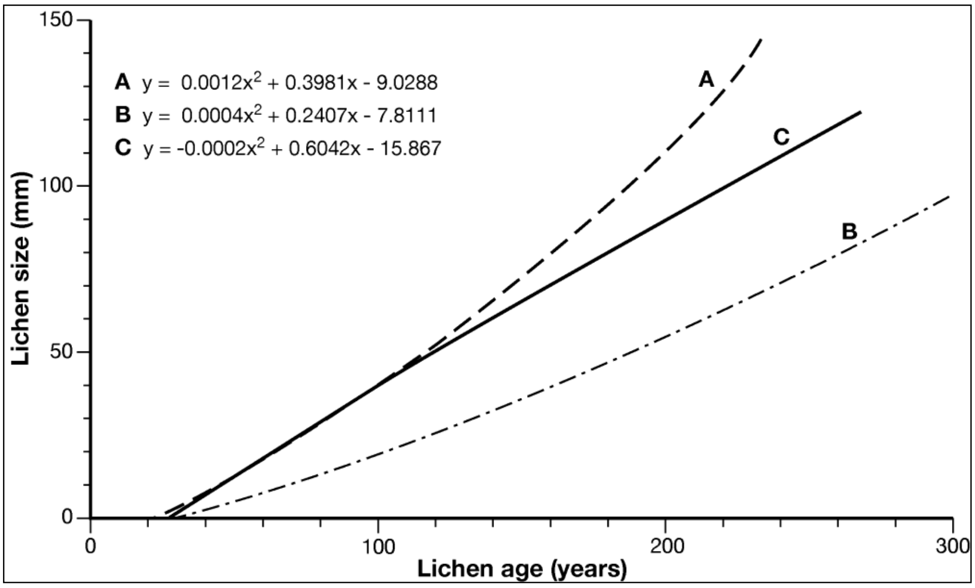

Figure 7. Growth curves constructed for direct measurements: (A) Storbreen AD1750 high altitude site; (B) Styggedalsbreen AD1750 site; and (C) Nigardsbreen AD1750 site (Trenbirth & Matthews, 2010).

midpoint of each size class was calculated from the data. The time taken for each 5.0-mm growth increment, estimated from the annual growth rate within each size class, was plotted against the size-class mid-point. Second-order polynomial curves were fitted to these mid-point values to represent the generalised growth curve. A lag-time of 15 years was assumed on the basis of previous indirect lichenometric dating in southern Norway. The growth curves (Figure 7) reflect the widely differing growth rates measured at the three sites.

Advantages and limitations

Indirect lichenometry requires surfaces of known age. Therefore indirect lichenometry cannot be employed in areas where there are no surfaces of known age (Smirnova & Nikonov, 1990). Jochimsen (1973) criticised lichenometry as numerous potential sources of error arise from ecological factors. Noller and Locke (2000) drew attention to one of the unresolved dilemmas of lichenometry, namely lichen thallus sensitivity to climate. Growth curves that have been developed for one region will not necessarily be applicable elsewhere as environmental factors make them area-specific (Walker, 2005).

Benedict (1990) suggested that growth curves derived from direct monitoring of annual growth of individual lichens were likely to be unrepresentative due to current climate being atypically warm with no indication of imminent cooling. This should affect dating of Little Ice Age moraines that have experienced mean temperatures substantially cooler than present. Matthews (1994) and Trenbirth and Matthews (2010) concluded that direct measurements produce extremely variable growth rates for the slow-growing species of lichens used for dating purposes. This point combined with the small number of thalli measured over relatively few years leads to an inability to determine accurately the form of the lichen growth curve. Some direct studies have therefore produced results that conflict with indirect studies at the same location.

Conclusion

Lichenometry is an inexpensive and widely applicable tool for estimating surface ages. Its application is straightforward and does not require the user to undergo intensive training or use sophisticated instruments. It has the ability to date surfaces during the last 500 years a period when radiocarbon dating is least efficient (Armstrong, 2004). A major advantage is the ubiquitous presence of lichens on many rocky substrates (Noller & Locke, 2000). Lichenometry is a useful proxy dating method and has been successfully used on its own or in combination with other dating methods (e.g. Solomina and Calkin, 2003).

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