A manual for lichenometry

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A MANUAL FOR LICHENOMETRY

by

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TABLE OF CONTENTS

1. INTRODUCTION

2. BASIS OF THE LICHENOMETRIC DATING METHOD
   A. Species and identification
   B. Parameter to be measured
   C. Sampling strategy
   D. Sampling area

3. SAMPLING AND RECORDING PROCEDURES
   A. Area/age determinations
   B. Comparison of large, multiple substrates
   C. Single, small, or critical substrates
   D. Additional recommendations
   E. Recording of data
   F. Summary

4. RELATIVE AND ABSOLUTE AGE DETERMINATIONS
   A. Relative age and correlation of substrates
   B. Absolute dating - generation and application of growth curves
      1. Direct approach
      2. Indirect approach
      3. Published information on lichen growth
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5. STATISTICAL TREATMENT
6. APPLICATIONS
7. PROBLEMS
8. SUMMARY
ACKNOWLEDGMENTS
ANNOTATED BIBLIOGRAPHY
REFERENCES
APPENDIX 1

AUTHORS' PREFACE

The format of this manual differs somewhat from that of other publications in the British Geomorphological Research Group Technical Bulletin series in that much of the text is devoted to a summary of published lichenometric methods. The reason for this is simple; there is no universally accepted lichenometric technique. Rather than advocate a single technique, we have chosen to discuss most published methods and to suggest those which we believe have the most potential. We recognize that some techniques which have been widely applied will receive short shrift, and that other, less well-known methods may appear to be overly emphasized. We hope, however, that the future application of the suggested methods will, if nothing else, help to relieve the confusion which currently afflicts lichenometry.
1. INTRODUCTION

The advantage of lichenometry over other methods of dating within the Holocene is that it can be applied at virtually all longitudes, latitudes, and altitudes. Over much of the earth, historical records prior to the last 100 years are fragmentary, radiocarbon dating is precluded by the lack of carbonaceous material associated with phenomena to be dated and by inherent problems in $^{14}$C dating within the last 500 years (Stuiver, 1978), and dendrochronology fails due to the lack of sufficiently long-lived trees. Lichenometry can be widely applied because of the ubiquitous distribution of lichens. Lichenometry is currently used to: 1) correlate substrates on the basis of lichen size or cover (relative dating and correlation), and 2) to date surfaces by converting lichen size to age via a lichen growth curve.

Lichenometry was probably first used in 1933 when Faegri (1933) mentioned the maximum sizes of lichen thalli of different species within recently deglaciated areas. However, the first paper dealing exclusively with lichenometry was not published until 1950. Roland Beschel of Innsbruck, Austria, published a paper entitled 'Flechten als Altersmaßstäbe rezenter Moränen' (Lichens as a measure of age of recent moraines) in which he formulated the concepts of lichenometry and discussed many of the problems. Beschel, now regarded as the 'Father of Lichenometry,' published copiously throughout the 1950's and 1960's until his untimely death in 1973. He did not, however, completely document his field techniques, and several variants of lichenometric measurements were developed throughout the world.

The aims of this Technical Bulletin are: 1) to describe the species of lichens commonly used, and the problems associated with their identification; 2) to present the basic assumptions upon which lichenometry is founded; 3) to examine the multiplicity of techniques by which lichenometric measurements have been made; 4) to discuss and recommend sampling procedures; 5) to comment on the establishment and use of growth curves; 6) to suggest applications for lichenometry; and 7) to stimulate further critical inquiry into the method of lichenometry.

2. BASIS OF THE LICHENOMETRIC DATING METHOD

Lichenometry is defined as the use of lichens to provide estimates of relative and absolute ages of the substrates on which they are found. The rationale for lichenometry is stated concisely by Beschel (1957):

'...growth (of lichens) proceeds in small steps, separated by fairly long pauses of passive existence. Annual increase is also subject to fluctuations.'
But in the case of the slow-growing high-mountain lichens, size variations after one year cannot be established with a millimetre-rule. Over fairly long periods, the yearly fluctuations tend to be smoothed out' (p 7-8).

It is this last assumption, that over a long period of time the growth of lichens can be approximated by a smooth curve, that forms the basis for lichenometry.

No portion of lichenometry has created as much argument as the sampling techniques. A reason for this is that Beschel did not completely describe his sampling procedure. Later workers were forced to invent their own technique, and most did. At the source of the uncertainty is the actual distribution of lichen thalli on a surface. Beschel (1957; p 7) states: 'Plotting of the number of individuals according to size-classes...yielded a very regular relationship. The number of individuals drops parabolically to zero, which, at the same time, indicates the maximum size.' It is this assumption of parabolic population distribution, with a finite maximum, which lies at the base of Beschel's view of lichenometry. Later workers have concluded that the size distribution of lichens on a surface is logarithmic. Matthews (1974, p 220) states that 'the largest lichen on the surface as a whole is unique - an extreme event,' and both Matthews (1974) and Mottershead and White (1972) suggest that the probability of finding a larger 'largest' lichen will increase with the area searched. The results of size/frequency measurements by Benedict (1967), Andersen and Solli (1971), and Lindsay (1973) indicate excellent fit of the data to logarithmic curves. No systematic study of the distribution of lichens on surfaces of different ages has yet been carried out, so no categorical statement on size distribution can be made. In the following discussion it will be assumed that the lichen size distribution on a surface is logarithmic.

Published lichenometric studies vary in four ways: 1) the lichen species used; 2) the parameter measured; 3) the sampling strategy; and 4) the nature of the sampling site. Each will be considered in turn.

2A. **Species and identification**

No portion of lichenometry has disturbed biologists more than problems of identification of the lichen species used for dating purposes. Not only is identification of lichens best accomplished under laboratory conditions, but some of the species used in the past 20 years as indicators of substrate age have since been reclassified. We feel, however, that, although it is important to collect voucher specimens in order to make species identification as accurate as possible, one can use lichenometric techniques without being able to personally identify all specimens in the field.
Of the 35+ species and subspecies of lichens which have been used in lichenometric studies (Table 1), the most commonly reported is the green/black *Rhizocarpon geographicum*. Whether this species is actually the most common, or whether some reports are the result of misidentification of other similar species, it appears to flourish in the polar/alpine environment. Because of the abundance of subspecific taxa or even of the possibility of misidentification, particularly in the field, this species is often reported as *R. geographicum* sensu lato ('in a broad sense'; Andrews and Webber, 1964) or *R. geographicum* agg. (Matthews, 1974) or *R. geographicum* coll. (Stork, 1963). This species is widely utilized because it is an early colonizer of fresh rock and grows slowly. As such, it allows the greatest range for dating, up to several thousand years in some alpine areas and perhaps 9000 in parts of the Arctic. *R. geographicum* is commonly identified on the basis of color, although color alone is not sufficient evidence on which to classify a lichen and voucher specimens must be collected. Color may vary on a regional basis, or in response to environment. Beschel (1965) notes that 'at a lichen factor (= growth rate in mm/100 yr) of 30 and above the thallus auroles of *R. geographicum* tend to touch and the rocks covered with this plant appear greenish-yellow. In areas with a lower lichen factor *R. geographicum* thalli appear dark because the greenish-yellow auroles rest widely scattered on the black hypothallus' (p 2).

The other lichen species that have been used for lichenometry (Table 1) were chosen on the basis of abundance, longevity, and the presence of nearly circular thalli. In order to choose a species for study, it is necessary to examine the substrates and determine the most common lichens. If the substrates are young and closely spaced in age, then a fast growing species should be chosen. If the substrates are relatively old and widely distributed in age, then a slower growing species would be more desirable. If the substrates are old and were deposited close together in time, then not only must a slow-growing species be used, but a careful, controlled sampling technique must be followed in order to achieve sufficient resolution. It is suggested that measurements be made of several common species, in order to determine relative rates of growth and to increase the likelihood of applicability of a pre-established growth curve. As Beschel (1957, p 60) suggested, 'any crustaceous and foliaceous lichens will yield important data.'

Keys to the identification of common species of lichen are available for many areas (e.g., Duncan and James, 1970 - Great Britain; Hale, 1961, 1969 - United States). Many of these keys emphasize chemical methods for distinction between related and similar lichen species, but much of the identification can be accomplished with the aid of a hand lens alone. The best method for lichen identification will continue to be the collection, preferably multiple, of voucher specimens for laboratory identification by a qualified lichenologist. Good locational and broad habitat description should be made with each collection.
<table>
<thead>
<tr>
<th>Taxon</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Crustose</strong></td>
<td></td>
</tr>
<tr>
<td>Aspicillia caesiocinerea Ny1.</td>
<td>6, 7</td>
</tr>
<tr>
<td>Aspicillia cinerea (L.) Kbr.</td>
<td>6, 7, 8, 29, 41</td>
</tr>
<tr>
<td>Calopiaca cinericola (Hoe) Darb.</td>
<td>25</td>
</tr>
<tr>
<td>Diploschistes anactinus (Ny1.) Zahlbr.</td>
<td>10</td>
</tr>
<tr>
<td>Diploschistes scorpusus (L.) Norm.</td>
<td>7</td>
</tr>
<tr>
<td>Lecanora astrobrunnea (Ram.) Schaer.</td>
<td>5, 13, 17, 26, 30</td>
</tr>
<tr>
<td>Lecanora badia (Hoffm.) Ach.</td>
<td>7, 8</td>
</tr>
<tr>
<td>Lecanora polytropa (Hoffm.) Rabenh.</td>
<td>12</td>
</tr>
<tr>
<td>Lecanora thomsonii H. Magn.</td>
<td>4, 5, 17, 30</td>
</tr>
<tr>
<td>Lecidea lapidica Ach.</td>
<td>6, 7, 12, 13</td>
</tr>
<tr>
<td>Lecidea paschalis Zahl.</td>
<td>10</td>
</tr>
<tr>
<td>Lecidea promiscens Ny1.</td>
<td>6, 7, 8</td>
</tr>
<tr>
<td>Rhizocarpon alpicola Körb</td>
<td>6, 19, 24, 33</td>
</tr>
<tr>
<td>Rhizocarpon candidum Dodge</td>
<td>14, 15</td>
</tr>
<tr>
<td>Rhizocarpon geographicum (L.) DC.</td>
<td>1-8, 13, 14, 16, 17, 19, 20, 22-28, 30, 32-34, 36-41</td>
</tr>
<tr>
<td>Rhizocarpon jemtaandinicum Malme</td>
<td>2, 9, 23, 26</td>
</tr>
<tr>
<td>Rhizocarpon oreitae (Vain.) Zahlbr.</td>
<td>7, 39</td>
</tr>
<tr>
<td>Rhizocarpon superficile (Schaer.) Vain.</td>
<td>18</td>
</tr>
<tr>
<td>Rhizocarpon tinei (Tornab.) Run.</td>
<td>9, 10, 11, 12, 15, 29</td>
</tr>
<tr>
<td>Sporostania testudinea (Ach.) Mass.</td>
<td>6, 7, 9</td>
</tr>
<tr>
<td>Xanthoria elegans (Link.) Th.Fr.</td>
<td>7, 8, 10, 11, 12, 17, 35</td>
</tr>
<tr>
<td><strong>Foliose</strong></td>
<td></td>
</tr>
<tr>
<td>Alectoria minuscula Ny1.</td>
<td>2, 3, 23, 26, 31, 32</td>
</tr>
<tr>
<td>Alectoria pubescens (L.) Howe</td>
<td>11, 12</td>
</tr>
<tr>
<td>Physcia caesia (Hoffm.) Ny1.</td>
<td>7, 11, 12</td>
</tr>
<tr>
<td>Physcia dubia (Hoffm.) Lettau</td>
<td>7</td>
</tr>
<tr>
<td>Physcia picta (Swans.) Ny1.</td>
<td>10</td>
</tr>
<tr>
<td>Physcia teretiuscula (Ach.) Lyne</td>
<td>7, 8</td>
</tr>
<tr>
<td>Umbilicaria arctica Ny1.</td>
<td>12</td>
</tr>
<tr>
<td>Umbilicaria cylindrica (L.) Del.</td>
<td>6, 7, 27, 37, 39</td>
</tr>
<tr>
<td>Umbilicaria hyperborea (Ach.) Hoffm.</td>
<td>2, 11, 12</td>
</tr>
<tr>
<td>Umbilicaria proboesicidae (L.) Schrad.</td>
<td>2, 11, 12, 39</td>
</tr>
<tr>
<td>Umbilicaria torrefacta (Lightf.) Schrad.</td>
<td>2</td>
</tr>
<tr>
<td>Umbilicaria virginis Schaer.</td>
<td>11, 12</td>
</tr>
<tr>
<td>Usnea antarctica Du Rietz</td>
<td>25</td>
</tr>
</tbody>
</table>

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1. Andersen and Solld (1971)
2. Andrews and Webber (1964)
4. Benedict (1957)
5. Benedict (1968)
6. Beschel (1950a)
7. Beschel (1956)
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10. Beschel (1961b)
11. Beschel (1963)
12. Beschel and Weldick (1973)
13. Birkeland (1973)
15. Burrows and Lucas (1967)
16. Carrara and Andrews (1972)
17. Carrara and Andrews (1973)
Table 1. - continued

21 Follmann (1961) 32 G. H. Miller and Andrews (1972)
23 Harrison (1964) 34 Motterhead and White (1972)
24 Karlén and Denton (1976) 35 Osborn and Taylor (1975)
25 Lindsay (1973) 36 Rampton (1970)
27 Matthews (1973) 38 Scott (1974)
31 G. H. Miller (1973a)

28. Parameter to be measured

The variation in parameter measured is primarily a function of the lichen species under study and the purpose of the exercise. For foliose and fruticose species, the dry weight in mg is commonly determined (e.g., Lindsay, 1973). Most lichenometric studies, however, are concerned with the growth of crustose species on rock. Two parameters are commonly measured for crustose species, the area and the diameter (or the length of axes of elliptical shapes). Researchers determine the growth of a single thallus over a short time by measuring the area of the thallus, which is converted to the equivalent diameter of a circular thallus. Area measurements, however, are time-consuming, thus preclude the collection of a large sample.

The most commonly used parameter for lichenometry is the diameter of nearly circular thalli. Both the longest and shortest diameter have been used in some studies. Beschel (1961, p 1045) states that 'any oblong patch should only be considered in its shorter diameter.' Similarly, Andrews and Webber (1964), Birke-land (1973), and Osborn and Taylor (1975) report the use of only the shortest diameter of the largest lichen thallus. In contrast, Burrows and Lucas (1967) and Matthews (1974) measured the longest axis, defined as the distance between the two points farthest apart on the thallus perimeter. W. Karlén, University of Stockholm (written comm., 1977) states that 'lichens can be slowed down in their expansion in one direction; there is no reason to believe they can be speeded up. Therefore, especially if the major interest is in the largest lichen on the deposit, it makes the most sense to measure the longest axis.' Our suggested procedure is shown in Figure 1 and consists of defining the diameter of the largest inscribed circle. This procedure holds to Beschel's (1961a) advice and reduces the likelihood of considering 2 coalescent thalli as a single thallus.

The accuracy with which the diameter is measured also varies. Matthews (1973) used calipers to determine diameters to ± 0.01 mm. Andrews and Webber (1964) measured to the nearest 0.5 mm, while other workers give measurements to the nearest 1 mm. In size-frequency studies, Andersen and Solld (1971), although not reporting the accuracy of measurement, give their data in 1 cm size
Figure 1. Suggested 'diameters' for measurement. The diameter of the largest circle (light line) to fit within the thallus under consideration (heavy line) can be visually estimated. For a nearly circular thallus the shortest diameter is the same as that of the largest inscribed circle.
classes. As the largest single lichen on a surface is seldom re-measurable to within 2 mm, it would appear that an accuracy of ± 1 mm should be sufficient for most uses.

Another index of the age of a substrate is the degree of lichen cover and the relative percentage of cover by faster growing foliose/fruticoselichens versus slower growing crustose lichens. This method has been used to delimit areas of recent snowkill and recolonization (Locke and Locke, 1977).

2C. Sampling strategy

The variation in parameter measured is minor compared to that in the sampling strategy. Common sampling methods include the single largest thallus, the mean of the largest from several subsites, and random sampling to determine the size/frequency distribution. An additional method, independent of the above methods, involves the measurement of the percentage cover, a function of both the number and the size of thalli present on a surface.

The rate of lichen growth is a function not only of the species under consideration, but of the macro- and micro-environment as well. Rock type, abrasion by wind and water, aspect (including sunlight, wind, temperature, and moisture), stability of the substrate, and length of the growing season may affect the rate of lichen growth (Benedict, 1967). In lichenometric studies it is necessary to maintain a consistent bias for comparable results; sampling strategies will be discussed below. Note that different species may show different responses to the same environmental change (Armstrong, 1976a), thus there is no 'optimal environment' that applies to all lichen species.

The rationale for measurement of the largest lichens on a surface is explained by Beschel (1961a, p 1045). He states that 'a consideration of the largest plants of one species as age indicators will simultaneously select the individual growing under optimal local conditions,' and that 'in the resulting mixture only the largest plants will be of an age equal to that of the exposed substratum.' These statements imply that the largest thallus is most representative of both the optimal micro-environment and the age of the substrate. Because of these assumptions, Beschel declared that 'no averaging can simplify the results' (1961, p 1047). Webber and Andrews (1973) concurred, and stated that 'any attempt to average even large thalli is illogical' (p 295). Benedict (1967, 1968), Andersen and Solild (1971), and Burrows (1973) also used only the largest lichen thallus to indicate the age of the deposit.

The major difficulty in using the single largest lichen on a surface as a dating criterion is that the largest single thallus may not belong to the same population as the majority of lichens on the surface. Although Benedict (1968) warned that exceptionally large thalli should be viewed with suspicion, no method of identifying them has yet been reported. Most large
thalli may have grown after deposition of a substrate but some
may have been transported in, e.g., by rockfall, or preserved
since before substrate deposition. It is impossible to dis-
tinguish these if only the single largest thallus is recorded.
The usual criterion for accepting the largest thallus is that
'a number of thallus diameters must fall close to that of the
maximum' (Denton and Karlén, 1977). To eliminate, or at least
lessen the effect of inclusion of an 'erratic' lichen, many
workers average the largest thalli observed in one sample or in
several subsamples on a deposit. This procedure was given
credence by Andersen and Sollid (1971, p 3) who incorrectly
averred that 'Beschel' (1950b) demonstrated that the average
diameter of the largest lichens on a moraine ridge is directly
proportional to the age of the ridge.' Prior to that time, how-
ever, the process of averaging the (generally 5) largest thalli
was commonly used, most notably by Stork (1963) and Reger and
Pövé (1969). At present, the most notable advocate of the averag-
ing technique is Matthews (1973, 1974, 1975, 1977). He states:

've use of the average size of the largest lichens is
not based on the same assumptions relating to lichen
age (as use of the single largest lichen). The assump-
tion in this case is that the longer a substrate has
been exposed the greater will be the average age of
the largest lichens growing on it... Use of averages...
is therefore unexceptionable as a tool for prediction
of surface age and use of single largest lichens can
be viewed as a limiting case of a large number of
possible alternatives.'

Studies by Matthews (1974) indicate that averaging yields accur-
ate ages, in most cases with greater statistical significance
than the single largest thallus. The number of largest thalli
to be averaged is arbitrary, but five is most commonly used.

Another technique which has been used to determine the age
of a deposit is that of size/frequency measurement. Such tech-
niques have been dismissed as too time-consuming (e.g., Matthews,
1974), but have been used to advantage by Benedict (1967),
Andersen and Sollid (1971), and Lindsay (1973). The prime advan-
tage of determining the size/frequency distribution of a species
is that anomalous thalli can be excluded. Reported distribution
of lichen size usually fit logarithmic curves at very high levels
of confidence, so that extreme outlying thalli can be identified
and ignored. Size/frequency sampling has also been used to
identify periods of substrate instability (e.g., Benedict, 1967).
As asserted by Andrews and Webber (1974, p 66), if the need is
for 'methods to recognize the presence of two distinct populations
of lichen sizes...this aim can be realized through plotting of
size/frequency data.' Dating on the basis of size/frequency
studies has been accomplished on the basis of the largest ob-
served thallus which fits the distribution, rather than the
largest thallus predicted by the distribution. No dating criter-
ion has been established for size/frequency measurements, but a
predicted lichen diameter, such as the 1-in-1000 thallus, is a
logical choice. One problem with size/frequency measurements is

our emphasis
that the difficulty of measuring very small thalli is considerable, thus both Benedict (1967) and Lindsay (1973) report fewer 1 mm thalli than would be predicted by a logarithmic distribution. Andersen and Sollid (1971) eliminated this problem by recording only those thalli larger than 10 mm.

Each of the preceding methods has as its end the determination of a 'maximum' lichen size on the deposit under study, and, as such, should yield comparable values. A semi-independent method by which lichenometric ages have been derived is that of percent of lichen cover (Orwin, 1970; Carrara and Andrews, 1973; Birkeland, 1973; C.D. Miller, 1973). This method requires estimation of the lichen cover on individual boulders, rather than exact measurements. The number of boulders used has varied from 50 (Birkeland, 1973) to 250 (Carrara and Andrews, 1973), and has included as a variant the estimation of percentage cover on all boulders within a certain area (ca. 60 m², C.D. Miller, 1973). Both the average cover and the maximum cover for a single rock may be used, with Birkeland (1973) suggesting that the maximum lichen cover on a single rock is usually about 1.5 times that of the average for 50 boulders.

2D. Sampling area

Within each of the measurement strategies there is variation in the size of the sample or sampling area. It was Beschel's contention that there is a parabolic distribution of lichen sizes on any young deposit, and that the largest lichen in any species can be found by examining as little as 50 m of moraine crest. He implies, moreover, that there are many thalli of maximal size on a moraine crest more than 50 m long. 'The longer the moraine, the greater, naturally, is the probability of finding maximal-sized lichen. of several species. If one considers only one lichen species, then the probability increases with the frequency of the species' (Beschel, 1956, p 6-7). Later, however, Beschel (1961a, p 1047) stated 'the rock surface to be studied should at least be of the order of 100 square meters,' and he also advocated quadrat sampling. In apparent conformity with these instructions, Stork (1963) examined five separate squares of 5 x 5 m (125 m²), Andrews and Webber (1964) measured thalli in eight squares of 8 x 8 m (64 m²) and stations of 10 m radius (314 m²), C.D. Miller (1973) used stations of 9.2 m diameter (66 m²), and Matthews (1973, 1974) examined strips of moraine crest 50 x 8 m (400 m²) and 25 x 8 m (200 m²). Results from each of these lichen stations were treated either as a single maximum or averaged.

A variant of the fixed area search is the selective or random walk method. Those researchers who apparently believe that a logarithmic model of lichen population distribution is accurate have tended to agree with Andrews and Webber (1974, p 66) that 'if the research is aimed at dating of a particular till unit, then a search of the entire deposit for maximum thalli is best.' Such searches have been undertaken in various studies, both as a fixed time search for the largest thallus and as an exhaustive
search. Rampton (1970) speaks of a 15-20 minute search, Birke-
land (1973) a search of 30 minutes, Burrows (1973) states that
'tall likely boulders were examined for lichens' (p 858), and,
as an extreme case, Benedict (1968), Denton and Karlén (1973,
1977) and Karlén and Denton (1976) speak of repeatedly cross-
crossing the surface of each feature in search of the single
largest lichen thallus. It must be stressed that the results of
an exhaustive search should not be expected to be directly com-
parable to those of the lichen station method, and should not be
applied to the same growth curve, as Denton and Karlén (1973,
p 348) state that 'an area in excess of 500 m² often was neces-
ary to locate the largest thallus on the map unit,' and that
areas as large as 50,000 m² were searched in this manner.

A less common sampling procedure is the use of a transect. Orwin
(1970) measured lichens across a transect with points at 2
foot (small rocks) or 10 foot (large rocks) intervals. At each
point, species diversity and percentage lichen cover was deter-
mined, until a total of 50 or 100 points was examined. Similarly,
C.W.Locke and W.W. Locke, University of Colorado (unpubl.)
measured all thalli in a transect 2m wide across a zone of
recently contracted snowbank cover. Although the number of thalli
measured in such a study is small, both the size distribution and
the amount of rock surface colonized by lichens show distinct
changes. A transect method can be of great help in specific
cases, but is not generally applied for dating.

In summary, published techniques vary in terms of parameter
measured, sampling strategy, and sampling site or area. Most
serious is the problem that many researchers do not document
their techniques, or cite contradictory references, such as
Beschel (1961a), Andrews and Webber (1964), and Benedict (1967).

3. SAMPLING AND RECORDING PROCEDURES

There is as yet no agreement on an optimal lichenometric
technique. The techniques we suggest are those which have the
most potential for both accuracy and precision; as more informa-
tion on lichen populations, distribution, and growth rates be-
comes available, revised techniques may be necessary. Our sug-
tested techniques vary with the purpose of the study. For all tech-
niques we recommend the measurement of only the smallest diameter
(the diameter of the largest inscribed circle) of thalli which
are approximately circular.

3A. Area/age determinations

Some studies (e.g., Andrews and Webber, 1964) have as a goal
the determination of variations in age across a surface. Such
surfaces could include glacier forelands, talus slopes, rock
glaciers, or former high lake levels. In situations where no
deposits remain to mark the borders of different temporal units,
sampling of small sites scattered across the area will yield the
most data. Where large-scale airphotos or maps are available a sampling grid will allow easy data manipulation. The size of the grid will be a function of the individual study. If some degree of latitude in site placement is desired to permit avoidance of local anomalous areas, such as snowbanks, or where only poor location control is available, a uniform, nonregular (Davis, 1973, p 303) distribution of points may be preferred.

Because the aim is to 'map' an area a dense sampling of small sites will give the best results. We suggest that the sites be squares of 5 m (25 m²). The small sample area should ensure a high sampling density - the most important criterion in studies of this type. Within each site ca. 10 of the largest thalli should be recorded and the mean of the 5 largest used to represent the site. It would be informative to report the largest thallus within each site, to test the variability between these two criteria. The application of this method should permit accurate subdivision of an area on the basis of lichen size, particularly when used in conjunction with appropriate statistical techniques, such as trend surface analysis. Methods for dating and correlation of temporal units are described below.

38. Comparison of large, multiple substrates

Where an area has been divided into temporal units on the basis of lichen diameter (above) or morphology (e.g., Matthews, 1974), larger samples than those above should be used. The use of larger samples will reduce variability due to microenvironmental and topographic effects. Of two possible variants: a fixed-area technique may be susceptible to the absolute density of lichen cover and a fixed-time technique will be affected by the style and speed of various workers. Because variation in lichen density can be estimated using measurements of percent cover (below), we advocate the measurement of the largest lichen thallus within a fixed-area. The use of a fixed-area rather than a search of the entire substrate should increase the probability of achieving comparable results. We suggest that a fixed-area of 400 m² be searched, that ca. 10 large thalli be recorded and the mean of the 5 largest (and the maximum) be reported. The shape of the sampling area will be a function of the shape of the deposit. To assess the variability of lichen sizes a minimum of 3 sites should be examined on each substrate where the area of the unit permits.

The location of sampling sites on a substrate will reflect the purpose of the study. For correlation and dating, the most representative locations (largest area, most stable) should be chosen to facilitate comparison. On ice-cored moraines the crest is probably optimal; on push moraines or analogous features the proximal slope is preferable. Areas of environmental stress (ivation hollows, flood plains) should be avoided.
3C. Single, small, or critical substrates

When the aim of a study is an accurate determination of substrate age the lichen population, rather than a small sample of individuals, should be examined. Such studies may indicate the effects of climatic change, substrate disturbance, lichen senility, and competition, and may be accomplished by size/frequency measurements. We recommend that a minimum of 1000 thalli, each > 1 mm or > 10% of the diameter of the maximum thallus, whichever is greater, be recorded.

Linear regression techniques (below) can be applied to the data to: 1) identify and discard anomalous thalli; 2) determine the 1-in-1000 thallus diameter, by which the deposit may be characterized; and 3) reveal evidence of irregular growth patterns. The precision of the 1-in-1000 thallus diameter will be a function of the lichen distribution and the sample size. If the substrates is very small and a sample < 1000 must be used the precision will decrease accordingly, although a prediction of the 1-in-1000 thallus will still be possible. To test the accuracy of these measurements we urge that at least 2 sites per substrate be sampled.

3D. Additional recommendations

As mentioned above, percent lichen cover is measured independently of the lichen diameters, thus may provide a useful, semi-independent source of data. We have provided a series of charts for the estimation of percent cover (Appendix A); we suggest that the maximum cover on any surface on each of 50 boulders be determined using the charts, and that the mean again be reported as a characteristic of the substrate. Such measurements would ordinarily be made within a site used for size/frequency and/or mean of 5 largest thalli measurements. Where possible the contribution of different species or colors of thalli to the total percent cover should be indicated (e.g., black/green = 3/1).

Measurement of similar parameters for different lichen species will provide more usable information, both for your study and those in the future. Where possible, measure all common lichen species with circular habits. Similarly, the determination of multiple parameters for a single species may facilitate correlation, thus the application of fixed-area, size/frequency, and percent cover measurements to a single substrate is highly encouraged.

3E. Recording of data

A 2-person party is most efficient for lichenometry, with one person measuring the thalli and calling out species and diameters and the other recording the information. Measurement can be accomplished with flexible plastic rulers; if greater precision than ± 1 mm is desired, calipers may be used. The data should be recorded permanently; high-quality paper and medium-soft lead pencils or indelible ink are essential.
A 2-person party can record about 1000 thalli per hour in size/frequency studies, whereas measurement of the largest thalli in 400 m² plots should require no more than 15 minutes. Smaller sample sites will require proportionally less time, but more must be examined to produce meaningful data. In any case an absolute minimum of 2 person-hours should be applied to any substrate. For greater efficiency fixed-area sites can be marked with premeasured flagging.

One aim of all scientific inquiry is that of data reproducibility. To obtain such data from lichenometric studies the procedures (above) must be comparable and the sampling area should also be comparable. To this end, detailed sampling sites should be marked with cairns or other symbols, photographed, and indicated clearly on published large-scale maps. If thalli are identified as anomalous their approximate locations should also be indicated in case of re-examination of the substrate by later workers.

3F. Summary

We have advocated 3 procedures for lichenometry under different conditions, plus the use of percent lichen cover as a semi-independent variable. The use of these techniques for correlation and dating is discussed below. The most critical items to emphasize are that 1) the diameter measured be that of the smallest inscribed circle, 2) that fixed-area searches are preferred to fixed-time or exhaustive ones, 3) that the mean of the 5 largest thalli should be less variable than the single maximum, and 4) that the application of multiple methods, where time permits, is to be preferred to the use of only a single method. Establishment of lichen stations for growth studies is discussed in section 4.

4. RELATIVE AND ABSOLUTE AGE DETERMINATIONS

Once the lichen data have been collected the next step is to apply the results to problems of regional correlation and 'absolute' dating. The applications require a series of techniques and approaches which are discussed below.

4A. Relative age and correlation of substrates

Within a restricted area, the raw data from field studies can be used for correlation and relative dating. Any or all of the suggested techniques should permit the determination of relative ages. The accuracy with which correlation can be undertaken is a function of the technique applied, the climatic diversity within the region, and the intrinsic variability of vegetative growth.

In order to estimate the error involved in relative dating, it is necessary to evaluate the internal consistency of the data.
Table 2. Relative Growth Rates of Some Species Used in Lichenometry

<table>
<thead>
<tr>
<th>Species</th>
<th>Species</th>
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<tbody>
<tr>
<td>Rhizocarpon geographicum</td>
<td>Rhizocarpon oreites</td>
</tr>
<tr>
<td>Rhizocarpon geographicum</td>
<td>Sporastatia testudinea</td>
</tr>
<tr>
<td>Rhizocarpon geographicum</td>
<td>Aspicilia cinerea</td>
</tr>
<tr>
<td>Rhizocarpon geographicum</td>
<td>Aspicilia caesiocinerea</td>
</tr>
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<td>Rhizocarpon geographicum</td>
<td>Diplomyclites scrobipulchrae</td>
</tr>
<tr>
<td>Rhizocarpon geographicum</td>
<td>Lecidea lapicida</td>
</tr>
<tr>
<td>Rhizocarpon geographicum</td>
<td>Lecidea promiscens</td>
</tr>
<tr>
<td>Rhizocarpon geographicum</td>
<td>Alectoria minuscule</td>
</tr>
<tr>
<td>Rhizocarpon geographicum</td>
<td>Rhizocarpon jemtlanticum</td>
</tr>
<tr>
<td>Rhizocarpon geographicum</td>
<td>Alectoria minuscule</td>
</tr>
<tr>
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<td>Alectoria minuscule</td>
</tr>
<tr>
<td>Rhizocarpon geographicum</td>
<td>Alectoria minuscule</td>
</tr>
<tr>
<td>Rhizocarpon geographicum</td>
<td>Lecanora thomsonii</td>
</tr>
<tr>
<td>Rhizocarpon geographicum</td>
<td>Lecidea atrobrunnea</td>
</tr>
</tbody>
</table>

If more than one lichen species is measured, particularly using fixed-area measurements, then the ratio of lichen sizes can be used to determine if any of the measured values are anomalous. The data for the two species to be compared should be plotted as in Figure 2. If two species with widely differing growth rates are under consideration, the data may show considerable scatter. Such variation may result from inaccuracy of measurement of the smaller thalli of the slower growing species, the onset of senescence in the faster growing species, and the variation in the timing of the great and linear periods of growth (below) between the two species. If the scatter resulting from the very young and very old thalli is ignored, the resulting distribution should be approximately normal (Figure 3), and the mean value and standard deviation can be used to check individual sites for consistency. Results from some such studies (Table 2) suggest that the ratios of thallus diameter between most species are consistent on an interregional scale. Consideration of the interspecific ratios can also be used to determine absolute growth rates once the growth rate of one of the species is known (below).

Where detailed sampling of the lichen size distribution on a substrate has been undertaken, the distribution of maximum thalli or percentage cover can be contoured. Such contours, or isophytes (lines of equal growth; Andrews and Webber, 1964) can be used to indicate such geomorphic processes as the manner of retreat of glaciers (Figure 4, redrawn from Andrews and Webber, 1964), accretion and movement of rock glaciers (C.D. Miller, 1973), or soil movement due to frost processes on a stone-banked...
<table>
<thead>
<tr>
<th>Locality</th>
<th>Ratio</th>
<th>SD</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austrian Alps</td>
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<td></td>
<td>Besche, 1956</td>
</tr>
<tr>
<td>Austrian Alps</td>
<td>1:0.8-2.0</td>
<td></td>
<td>Besche, 1956</td>
</tr>
<tr>
<td>Austrian Alps</td>
<td>1:1.5-2.5</td>
<td></td>
<td>Besche, 1956</td>
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<td></td>
<td>Besche, 1956</td>
</tr>
<tr>
<td>Austrian Alps</td>
<td>1:2.0-3.0</td>
<td></td>
<td>Besche, 1956</td>
</tr>
<tr>
<td>Austrian Alps</td>
<td>1:2.5-3.5</td>
<td></td>
<td>Besche, 1956</td>
</tr>
<tr>
<td>Austrian Alps</td>
<td>1:2.5-4.0</td>
<td></td>
<td>Besche, 1956</td>
</tr>
<tr>
<td>Baffin Island</td>
<td>1:7.0</td>
<td>2.8</td>
<td>Andrews and Webber, 1964</td>
</tr>
<tr>
<td>Baffin Island</td>
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<td>1.06</td>
<td>Andrews and Webber, 1964</td>
</tr>
<tr>
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<td>1.01</td>
<td>Andrews and Webber, 1964</td>
</tr>
<tr>
<td>Baffin Island</td>
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<td>Andrews and Webber, 1964</td>
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<td></td>
<td>Harrison, 1964</td>
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<td>Baffin Island</td>
<td>1:6.9</td>
<td></td>
<td>Harrison, 1964</td>
</tr>
<tr>
<td>Baffin Island</td>
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<td>0.60</td>
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</tr>
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<td>1:5.35</td>
<td>1.40</td>
<td>Løken and Andrews, 1966</td>
</tr>
<tr>
<td>Baffin Island</td>
<td>1:7.9</td>
<td></td>
<td>Miller and Andrews, 1972</td>
</tr>
<tr>
<td>Colorado</td>
<td>1:2.43</td>
<td></td>
<td>C.D. Miller, 1973</td>
</tr>
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<td>Colorado</td>
<td>1:2.20</td>
<td></td>
<td>C.D. Miller, 1973</td>
</tr>
</tbody>
</table>

terrace (Benedict, 1970). Generation of isophyses has wide applicability over small areas that can be intensively studied, such as those mentioned above, plus scree slopes, boulder fields, outwash plains, and trimlines.

Where large numbers of discrete events have been dated by lichenometry, the number of events associated with a given lichen cover or size can be plotted as a frequency histogram (Figure 5). At the present, this method has been applied only to glacial

and mass movement chronologies (Benedict, 1968; G.H. Miller, 1973b; Denton and Karlén, 1973), but it has the potential for correlation of any sequence of discrete events, such as lava or debris flows or episodes of cryoturbation.

Variations in percentage lichen cover can only be determined quantitatively in the field. Qualitative examination of airphoto imagery can, however, reveal large areas with a distinctive light tone indicative of immature lichen cover (Figure 6). On central Baffin Island, examination of such areas in the field indicated that the former mature lichen cover had been killed under enlarged snowbanks during the Little Ice Age (1000-350 yr BP). The ease of identification of such areas on both airphotos and satellite (LANDSAT) imagery allowed calculation of the extension of ice cover across Baffin Island at that time (Locke and Locke, 1977). Similar tonal contrasts have been noted on alluvial fans, scree slopes, and rock glaciers, and suggest that the mapping of such areas would provide a feasible method of extending detailed field mapping over a larger area.
Figure 2. Sample-frequency graphs showing ratios of lichen diameters
(R. geographicum: R. jemtlandicum and R. geographicum:Alectoria
minuscula) to maximum R. geographicum diameter. Note that the
greatest variation is evident when dealing with very small
(<10 mm) R. geographicum thalli, most probably due to sampling
difficulties. (From Løken and Andrews, 1966.)
Figure 3. Histograms of frequency distribution of lichen ratios (R. geographicum > 10 mm) and fitted normal curves. The agreement of the observed ratios to a normal distribution suggests that the ratios may be used for establishment of a relative dating curve. The broad spread in the R. geographicum/A. minuscula ratios suggests that the ratio changes with time; this is corroborated by the results of Figure 2. Care should be used in the use of such data.
Figure 4. Isophyses of Alectorina miniscalca surrounding the Lewis Glacier, an outlet of the Barnes Ice Cap, Baffin Island, N.W.T., Canada. By application of a separately derived growth curve, the isophyses indicate times of deglaciation due to the retreat of the glacier. (From Andrews and Webber, 1964.)
Figure 5. Histograms from three studies showing moraine frequency versus thallus diameter of *K. geographicum*. Within a restricted area, these diagrams indicate a relative stratigraphy. The lack of general agreement between regions may be a function of a difference in growth rate, a difference in glacial history, or both.
Figure 6. Airphoto (Canadian Government A17044-36-37) showing lichen-free areas west of the Barnes Ice Cap, Baffin Island, N.W.T., Canada. In order of decreasing reflectivity, the photo shows 1) ice on Rimrock Lake (center), 2) areas in which modern snowbanks often occur, and lichen cover is nonexistent (right and bottom), 3) broad plateaus with minimal lichen cover, believed to have been occupied by unpermanent snowfields during the Little Ice Age (ca. 100-350 yr BP) (left), 4) a trimline around Rimrock Lake (best preserved at lower right) indicating moderate lichen cover found since ca. 1200 yr BP, and 5) mature lichen cover on the remainder of the landscape.
None of the above methods permits the generation of an
absolute chronology. They all do, however, permit detailed relative
age assessments using only field data. These methods should
only be used within a limited area, unless other studies have
produced consistent growth rates over a larger area. It remains
for the determination of curves of lichen size versus absolute
age to prove that relative techniques are valid across large
areas or to permit the determination of absolute chronologies.

4B. Absolute dating - generation and application of growth
curves

Within a restricted area, relative dating by means of
lichenometry can easily be accomplished assuming measuring tech-
niques are applied consistently. 'Absolute' dating, however, re-
quires detailed knowledge of the rate of growth of a given lichen
species, in a (possibly) changing environment, over an unknown
length of time. Such knowledge can be gained in two ways: through
multiple precise measurements of the same lichen thallus over
time ('direct'), or by determining the distribution of lichen
sizes on substrates of known age ('indirect').

4B.1. Direct approach

The direct determination of lichen growth rates has been
undertaken by lichenologists for many years (e.g., Hale, 1959;
Phillips, 1969). More recently, the technique of photogrammetric
determination, as opposed to the tracing method of Hale, has
been discussed by Fayer (1973), G.H. Miller (1973a), and Hooker
and Brown (1977). Miller (1973a) used precisely machined metal
squares to photographically compare thalli over one to several
years. The method is as follows:

1) An area of study, such as a boulder or a series of
boulders, is chosen so that it is in the center of
the field area to which the curve is to be applied,
contains a number of lichen thalli of the same species
but varying sizes, has known environmental parameters,
and offers easy access.

2) A machined square of known area is placed within or
immediately adjacent to each thallus (Figure 7) and
the thallus is photographed with a 35 mm camera held
perpendicular to the thallus. The simplest method for
determining perpendicularity is that of Hooker and
Brown (1977, p 66), who noted that 'using large lens
apertures...perpendicular orientation may almost be
defined as that position where all the thallus circum-
ference is in focus.'

3) After development of the film, enlarged prints can be
made of the thallus, which can then be planimetered to
yield an area. The area of the square can also be
planimetered, and, because the area of the square is
known, a correction factor for both the enlargement and
the distortion of the paper can be determined. More
sophisticated corrections, including that for parallax

23
Figure 7. A recommended method for photographic recording of lichen thalli for determination studies of growth rate. The aluminium metal square (1 x 1 cm) is machined to strict tolerances. The neighboring lichen is Usnea thomsonii, a lichen which has been used frequently in the central Rocky Mountains of Colorado as an indicator of the age of late Neoglacial deposits.

on a non-horizontal surface, can be found in Hooker and Brown (1977). The computed area can be transferred into a theoretical diameter, assuming a circular thallus.

4) The process should be repeated at appropriate intervals, depending on the growth rate of the species in question. At least three growing seasons are recommended to average out anomalous summers. Details of the procedure are given by G.H. Miller (1973a).

The direct determination of the growth rate of a lichen species is a long-term procedure. When such studies are initiated, cairns should be erected to mark the site, and a detailed map should be drawn to lead later investigators to the site. It is expected that many direct rate determination projects will not be completed by one individual. The results, therefore, should be kept available should other workers wish to repopograph the sites. The Institute of Arctic and Alpine Research, University of
Colorado, Boulder, Colorado 80309, has offered itself as a repository for information concerning lichen growth, including photographs.

Use of a directly derived lichen growth curve involves two major sources of possible error: the time required for colonization, and the variation in the growth rate with time and environmental change. The time needed for colonization varies with species and locality, from ca. 10 years for Alectorion minuscula in the Arctic (Andrews and Wehner, 1964) and for Rhizocarpon geographicum in the Yukon Territory (Rampton, 1970), to ca. 50 years for R. geographicum in the Arctic (Miller and Andrews, 1972). In addition, 'a basic assumption of lichenometry as an indication of time since deglaciation is that the substrate is devoid of all living lichens immediately after deglaciation' (Andrews and Wehner, 1964, p 85). Matthews (1973, p 309), however, in a study of lichen distribution on medial and terminal moraines, found lichens may survive deposition. Matthews (1973) suggested contamination equivalent to about 25 years growth on the basis of this preservation.

Application of a directly determined growth curve to field data also requires the assumption that the largest thalli observed has grown at the computed average rate determined by a direct measurement. Because the largest thalli observed in the field probably occupy a favorable microenvironment, they may have grown at a higher average growth rate than that determined directly, thus the estimate of age should be a maximum. Second, the derivation of a direct growth curve usually occurs over a sufficiently short time span as to represent a constant climate (assuming that it allows sufficient time for random variations to average out), but the lichen thalli measured on a substrate to be dated may have resulted from the effects of several climatic changes.

Despite these difficulties, growth curves derived from direct measurements have been shown to be approximately equivalent to those determined indirectly (G.L. Miller, 1973a). In addition, if direct measurements indicate that the lichen growth within a field area is similar to that within a nearby area for which an indirectly determined curve is available, it lends credence to the extension of the indirect curve outside the area in which it was defined (Andrews and Barnett, 1979).

482. Indirect approach

The indirect method of growth curve determination – the 'method of the dated substrate' of Beschel (1955) – relies on alternative absolute dating methods to determine the age of a substrate, which is then characterized with a lichen diameter by one or more of the methods listed above. As originally applied in Europe by Beschel and others, the most commonly used dating criteria were historical records of glacier advance and retreat. Historical records have the advantage of accuracy to within 1 to 5 years, but are seriously limited in their scope, both
areally and temporally. In less travelled areas of Europe, where little attention was paid to glacier fluctuations, Karlén and Denton (1976) used lichen growth on man-made substrates, such as mine tips and buildings, to derive portions of a growth curve. Again, the distribution of such substrates is limited in spatial and temporal distribution. The small size of such substrates may also lead to error (below).

Well-documented lichen growth curves are those of Benedict (1967) and Andrews and Barnett (1979). Major control on the younger part of these curves was provided by historically dated substrates. Benedict also examined cairns, placed on mountains as triangulation stations. Such small substrates should be used only as indicators of the minimum largest thallus to be expected for a given age, as their surface area is not sufficient to permit direct comparison with larger substrates. If as many as 100 thalli are present, a size/frequency approach might be viable.

Another variation of the historical records method is provided by examination of gravestones. Miller and Andrews (1972) and Carrara and Andrews (1973) used growth curves partly derived on this basis. A number of stones emplaced in the same year may provide a relatively large substrate. Problems with this method include the variation in the type of stone used and the practice of polishing the stones, which inhibits colonization. Lichen sizes measured in such a study must be assumed to be minima, but a sufficiently large number of minimum thalli may define a curve (Figure 8).

In areas such as Alaska and the northwestern United States, where glacier margins are or have been forested, dendrochronology has been used to determine the age of young moraines (e.g., C.D. Miller, 1969; Rampton, 1970; Denton and Karlén, 1977). This method has restrictions similar to those of lichenometry - the time before colonization is unknown, and the age of the largest trees assumed to represent the age of the moraine, but is actually a minimum estimate. In addition, preservation of forest cover on stagnant ice is well-documented, and it is more difficult to collect a large enough sample for statistical purposes for dendrochronology than it is for lichenometry.

Most commonly, the critical older portions of lichen growth curves are based upon $^{14}$C dates. The limitations of such dates must be clearly understood. First, they are generally limiting dates, rather than actually describing the event (usually deglaciation) attested to by the lichen cover. They may represent lower limits, as in basal dates from ponds within glacier boundaries, or upper limits, if derived from organic material incorporated within the moraine. Second, they are determined as $^{14}$C dates BP, and must be understood as distinctly different from calendar years, that is, $^{14}$C ages and calendar years are not in 1:1 correspondence (Stuiver and Suess, 1966). For this reason, most lichenometric dates older than about 400 years, depending on the area, should be reported as approximately equivalent to $^{14}$C years. Third, $^{14}$C dates in the range 100-400 BP are ambiguous
Figure 8. Maximum thallus diameter \( (R. \text{ geographicum}) \) as a function of the age of tombstones in the Silverton, Colorado, cemetery. Because pre-existing thalli can be ruled out, the largest thallus in a given age class should be indicative of the maximum rate of growth. The apparent sinusoidal curve derived here may be the result of environmental variation, or, more likely, of insufficient sampling in some age groups. The straight line is the presumed linear variation in maximum thallus diameter as a function of age. Note also the possible substrate effects. (From Carrara and Andrews, 1975.)
(Stuiver, 1978). Fourth, most curves are based on relatively few dates, with the remaining portion of the curve interpolated or extrapolated. Such a procedure assumes the effect of environmental (climatic) change to be negligible over spans of time up to or greater than 1000 years. This assumption may be accurate, but has not yet been proven, and some evidence has been put forward to the contrary (Curry, 1969).

In order for a previously derived growth curve to be applicable to new field data, two restrictions must be met. First, the growth curve must be representative of the actual growth rate within the new area. This can best be established by at least one indirect date on a substrate within the new field area, preferably within the older part of the curve, which conforms to the previously derived curve. Alternatively, direct growth measurements which indicate a similar rate of growth can be substituted. Second, the technique used to measure the lichens in the establishment of the growth curve must be the same as or directly comparable to that used in the new field area. This second restriction is commonly flouted, and may account for some of the variation reported in the timing of Holocene glacial events. We urge that both size/frequency and fixed-area sampling be accomplished on indirectly dated substrates so as to generate growth curves for both methods.

483. Published information on lichen growth

In 1955 (p 68), Beschel stated that 'the growth rate is directly proportional to the duration of active life in the year, and inversely proportional to the maximum age (of the species).'. Thus lichens grow most slowly in cold, dry climates, and the longer lived species grow most slowly. These basic conclusions have since been expanded upon, but the exact controls on lichen growth, and the response of an individual thallus to changes in these controls, are still unknown. In 1961, Beschel discussed the form and the mechanism of growth curves, which he concluded consisted of a relatively short colonization and slow growth period, a period of rapid growth (termed the 'great period'; Beschel, 1950), and a long period of approximately linear growth. In the case of R. geographicum the great period may last for 200 to 400 years, whereas the linear period may extend over 9000 years in favorable circumstances (Andrews and Barnett, 1979). The ratio of lichen growth during the great period to that of the linear phase is between 3:1 and 7:1 (Webber and Andrews, 1973, Table 2). Armstrong (1976) and Hale (1973) came to similar conclusions for both crustose and foliose species. Webber and Andrews (1973, p 299) comment that 'we give the great period rate as if it were always linear; in many cases careful control may well show it to be exponential as one would expect of the traditional biological growth curve.' The shape of the growth curve is critical to the maximum age limit of lichenometry, which Beschel (1958a) thought to be approximately 4500 years and Miller and Andrews (1972) suggested as 7-8000 years. Further search has yielded a thallus of R. geographicum on Baffin Island of 280 mm diameter, which is equivalent to about 9000 years at published
growth rates (Andrews and Barnett, 1979). Denton and Karlén (1973) report a thallus of *R. alpicola* from Sweden with a diameter of 480 mm. If the linear rate which the authors have determined for the area is extrapolated to that size, this thallus would also date from ca. 9000 yr BP, a date which agrees well with other evidence as to the time of deglaciation of the area.

Rates of growth for several lichen species as determined by different authors are summarized in Table 3. The lichen factor, by which rates of lichen growth have commonly been defined, is given by Beschel (1956) as the diameter of 100 year old lichen. Because rates change greatly with time, however, they are now more commonly given in terms of change in diameter in mm/100 yr. It is interesting to note that, although the growth of one species (*R. geographicum*) is reported to vary widely with local climate (Ten Brink, 1973), it is relatively consistent in many of the arctic and alpine areas in which it has been used as a dating criterion. Thus, growth curves from Colorado, Alaska, Lapland, and Baffin Island are essentially similar. Such constancy in growth rates cannot be assumed, however, and must be proven anew for each new field area.

Platt and Amsler (1955), in studies of foliose lichen growth on trees, suggest that the time of establishment of intermediate-sized specimens may be ascertained by applying to them a growth curve defined from the size of the largest specimen. Although this procedure may be correct, it has not been proven that all thalli of the same species grow at the same rate, leaving time of colonization as the only operative variable. Intuitively, it appears unlikely that this is the case, thus lichen growth curves should be applied only to the thalli size by which they were derived; the largest in a given sample size, area, or time on a deposit.

5. STATISTICAL TREATMENT

Rigorous statistical treatment of operator variation in lichen measurements has not been attempted to any great extent. Similarly the possible errors introduced by sampling only maximum lichen thalli or an average of maximum thalli has only been examined in any detail by Matthews (1973, 1974, 1975, and 1977) using historically dated moraine sequences in Norway. In those papers, Matthews showed that most approaches gave reasonable results. However, most applications of lichenometrical techniques in North America and in many parts of Scandinavia take place via the application of an indirectly dated growth curve. These curves frequently span the interval between 2000 and 9000 BP and are based on between 2 and 8 $^14$C dated controlled sites. Rigorous statistical analysis of the errors of precision and accuracy of the lichenometric dates using such curves has not been attempted, and indeed it is difficult to judge how this could be done. Recourse is, therefore, made via two approaches: 1) lichenometrically dated moraines are presented as frequency diagrams (Figure 5)
<table>
<thead>
<tr>
<th>Lichen Factor</th>
<th>Great Period</th>
<th>Location</th>
<th>Author</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>6</td>
<td>Beschel</td>
<td>Continental climate; Beschel refers to this as a possible, valueless, growth curve based on several indirect means. For B. supraneous, not used in this manner.</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>Greenland, W. Greenland, central Baffin Island</td>
<td>Ten Brink, 1973</td>
<td>Growth curve based on several indirect means.</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>Southern Barnes Ice Cap, central Baffin Island</td>
<td>Beschel, 1957</td>
<td>Growth curve based on several indirect means.</td>
</tr>
<tr>
<td>5</td>
<td>10(100); 3(3,000)</td>
<td>Front Range, Colorado</td>
<td>Benedict, 1967</td>
<td>Growth curve based on several indirect means.</td>
</tr>
<tr>
<td>6</td>
<td>15(300); 3(9,500)</td>
<td>Cumberland Peninsula, eastern Baffin Island</td>
<td>Miller, 67-68 and Andrews, 1972</td>
<td>Growth curve based on several indirect means.</td>
</tr>
<tr>
<td>7</td>
<td>14(300); 4(4,000)</td>
<td>Axel Heiberg Island, M.K.I.</td>
<td>Beschel, 1953a</td>
<td>Growth curve based on several indirect means.</td>
</tr>
<tr>
<td>8</td>
<td>15(150)</td>
<td>Disko Island, Greenland</td>
<td>Beschel, 1953b</td>
<td>Growth curve based on several indirect means.</td>
</tr>
<tr>
<td>9</td>
<td>16(130)</td>
<td>Signy Island, Antarctica</td>
<td>Lindsay, 1973</td>
<td>Growth curve based on several indirect means.</td>
</tr>
<tr>
<td>10</td>
<td>16(140)</td>
<td>Upernavik, West Greenland</td>
<td>Gibbs, 1970</td>
<td>Growth curve based on several indirect means.</td>
</tr>
<tr>
<td>11</td>
<td>17(300)</td>
<td>Scoresby Sund, West Greenland</td>
<td>Ten Brink, 1973</td>
<td>Growth curve based on several indirect means.</td>
</tr>
<tr>
<td>12</td>
<td>17(2,800)</td>
<td>St. Elias and Wrangel mountains, Alaska</td>
<td>Denton and Karl, 1973</td>
<td>Growth curve based on several indirect means.</td>
</tr>
<tr>
<td>Year</td>
<td>Location</td>
<td>Peak Elevation</td>
<td>Notes</td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>-------------------</td>
<td>----------------</td>
<td>---------------</td>
<td></td>
</tr>
<tr>
<td>1969</td>
<td>White, 1972</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1970</td>
<td>Matthesen and Bessertoppen, Aust-Agder</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1971</td>
<td>Jotunheimen, South Norway</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1972</td>
<td>Turtagrundt, South Norway</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1973</td>
<td>Central Alaska Range</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1974</td>
<td>Skaftafell, Aust-Skaftafellssysla</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1975</td>
<td>Zermatt, Switzerland</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1976</td>
<td>North Cascades, Washington</td>
<td></td>
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<td>1977</td>
<td>North Cascades, Washington</td>
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<td>1979</td>
<td>North Cascades, Washington</td>
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<td></td>
</tr>
</tbody>
</table>

Note: The dates in parentheses indicate years of the most recent ice retreats. The ages are rounded to nearest 100 years old.
to see if there is some grouping of the moraine ages, which could be tested using nonparametric statistics; and 2) Miller and Andrews (1972) suggested that the probable error or a lichenometrically derived date increases as a non-linear function of maximum thallus size. Although it is obviously possible to statistically define the relationship between thallus size and \(^{14}C\) age from curves such as those derived by Denton and Karlén (1973a) or Andrews and Barnett (1979), the limited number of control points would make estimates based on the standard error of estimate (Syx) very large and this would be even more so for the ends of the 'growth curve' if a 95\% confidence limit method was developed. (NB. 95\% confidence limits on \(Y\) - the estimate of age - are not parallel to the regression line. Because of the assumptions of a 'normal' population these limits are smallest in the vicinity of the means of the sample ages and sample lichen thalli diameters and increase non-linearly from there in both directions.) From a geological/geomorphological viewpoint, it is more important to be able to correlate between adjacent deposits on the basis of thallus size than to date these deposits. Correlation is thus the primary function of the lichenometrical method, whereas dating is an important but secondary endeavor. It is for these reasons that we encourage studies on the reproducibility of lichen diameters and wish to encourage standardized methods. The development of lichen growth curves, while many peoples' ultimate ambition, has to be preceded by adequate sampling of lichen thalli. It is worth noting that all the published lichen growth curves that extend beyond 600 years use the maximum single lichen as their input.

The results of size/frequency measurement are highly amenable to statistical treatment. Judging from published data, the distribution of lichen sizes on a substrate should follow a log/normal distribution. It is suggested that the format of Andersen and Sollid (1971), in computation and publication, be followed. A linear regression can be fitted to the log-transformed data. Anomalous thalli can easily be detected (Figure 9) by their effect on the correlation coefficient of the regression. Thallus should be excluded from the final regression calculation, although they should be reported. The vital statistics of the final regression equation, including the slope, intercept, correlation coefficient, degrees of freedom, F-statistic, standard error of the estimate, and variations in the parameters at the 95 and/or 99\% confidence levels, should be reported.

For graphical representation, the format of Andersen and Sollid (1971, Figure 3), as modified in Figure 9 should be used. The 0.1\% frequency (log; frequency = -1) can be used as the horizontal axis, thus the 1-in-1000 thallus diameter can be read directly from the graph. As in all statistical procedures confidence limits should be indicated on the published figure. We suggest that the 95\% confidence limits be shown, rather than the standard error of the estimate.

If percentage cover on individual boulders is recorded, it should be reported as mean percentage, with standard deviation...
Figure 9. Format for publication of size/frequency results. Graphical representation includes data points (filled circles), computed regression line (heavy) and 95 and 99% confidence limits (shaded and light lines, respectively), and running correlation coefficient (open circles). Data points omitted from the final regression should be reported, but clearly differentiated (open squares). The regression parameters should be reported in tabular form. (From Andersen and Solild, 1971.)
and sample size. If the observed frequency of percentage cover on individual boulders does not follow a normal distribution, then a histogram of the observed values should be included, and possible explanations for the observed distribution should be suggested. For the alternate methods of fixed-area and fixed-time search, all of the largest thalli measured at each site should be reported, as well as the mean. There is as yet no valid method of excluding anomalous thalli from such measurements. It is up to the individual author to determine whether or not all of the observed thalli are representative. As a general rule, however, the largest observed thalli should not vary by more than 10% from the second largest, and several thalli should be found of nearly the maximum size.

6. APPLICATIONS

The need for lichenometry is indicated by the number of applications which have been found for it. Beschel (1961a) suggested the following as possible applications: sea-level changes, former lake levels, outwash fans, glacier forelands, trimlines, rockfalls and talus, solifluction, and human action. To this date, all of the above have been studied in published investigations using lichenometry except outwash fans. J.T. Andrews, University of Colorado (unpubl.), has attempted the use of lichenometry on outwash, but suggests that the normal grain size of such deposits controls the lichen population to such an extent that normal lichenometric techniques are not applicable. Among the other uses, Donner et al. (1977) found that great variations in the rate of growth of R. geographicum occur near sea-level in N. Norway, making lichenometric dates on raised marine features untrustworthy in that area. Former glacial basins which were exposed subaerially after rapid lowering of lake levels have been used to demonstrate that over 10¹ to 10² km there is negligible change in the growth of lichens (Andrews and Webber, 1964; Miller, 1972b). Glacier forelands have been commonly dated using lichenometry, with most of the references cited above being drawn from the glacial literature. Vegetation trimlines were clearly observed by Beschel (1961a, p 196): 'the very old lichen cover...stubs abruptly at planes cutting through larger boulders. The bases of the boulders may be bare or covered with lichen corpses side by side with young thalli, while their tops still have an ancient epipetric cover. A former extensive nivation has brought this about.' Lichenometry of trimlines and associated lichen-free areas has yielded information concerning the inception of continental glaciation (Ives, 1962; Locke and Locke, 1977). In addition, size/frequency techniques may be used to decipher detailed climatic records from the multiple trimzones around small snowpatches (Pitman, 1973; Locke and Locke, unpubl.). Rockfalls, talus, and solifluction deposits have been dated by lichenometry (Benedict, 1970), along with protalus ramparts and debris flows, and rock glaciers (Birkeland, 1973). Human action provides multiple opportunities for lichenometry in the establishment of growth curves (above), in the dating of structures of
human origin, both in the alpine (Benedict, 1967) and in the Arctic, and in the evaluation of the effect of man on lichen populations through pollution. In short, it appears that lichenometry can, in one form or another, be applied to virtually any substrate to determine recent geomorphic action and climatic or environmental change.

Future applications of lichenometry will be largely determined by evolution in the techniques used. If most researchers are content to use non-rigorous sampling procedures, lichenometry will remain at best a relative age dating technique. If, on the other hand, random sampling and valid statistical procedures are implemented, more information can be gathered as to the form of the distribution of lichen sizes over time. Present information suggests that, on substrates with low percentage cover, thus little competition, a log/normal distribution holds. It does not, however, appear reasonable to suggest that such a distribution should also hold on densely populated surfaces. It is possible that as the space available for colonization decreases the size/frequency distribution of lichens on a surface will follow a Poisson distribution, and approach a normal curve (Farrar, 1974). Further studies must be undertaken to investigate this.

A major effort has been made using lichenometry to determine both relative and absolute glacial chronologies in isolated areas. As more information becomes available concerning growth rates in various climates, and if more researchers use comparable sampling procedures, the investigation of global correlation of such events can be undertaken. Such efforts are already underway, but are hampered by the lack of uniformity among sampling techniques to the present.

7. PROBLEMS

Lichenometry is not without its share of problems. Jochimsen (1973) suggests a number of factors which could invalidate lichenometric dates, among which are the presence of previously colonized rocks, contamination of a deposit, as by rockslide, measuring of non-circular thalli or groups of thalli, time required to initiate colonization, interaction between species, species identification, variations in substrate, and variations in environment, including radiation, temperature, and precipitation. Many of these variables, however, can be held constant, or their effects could be identified and quantified by a rigorous sampling technique. Previously colonized rocks and other anomalous thalli can be identified and excluded using size/frequency methods. Species interaction has not yet proved to be a problem, as most studies have focused on deposits with low lichen cover. Species identification, although nearly impossible in the field, has not been proven to be a major difficulty, as most closely related species appear to have approximately similar rates of growth. Variation in substrate may be of great importance in interregional
correlation, but tends to be nearly constant within a limited area, thus usually need not be considered. The effect of the environment is not yet fully known, however, application of a consistent sampling technique and further derivation of growth curves should help to clarify the problem. Until such information is known, interregional correlations can be only approximate. It appears, therefore, that the statements of Jochimsen (1973, p 424) - 'there is no linear growth curve for epiphytic lichens from which one can simply read off the age, and the thallus size is certainly not simply a reflection of elapsed time,' and 'a lichenometry based on this purely measuring method can scarcely lead to success' - are an overstatement of the case. It is true that there is not one simple curve, and that size of a lichen thallus is not simply a function of time, but it is also true that a curve which appears to closely reflect lichen growth can be established, and that, if all other variables are held constant, the approximate age of a substrate can be determined simply by measurements of lichen thalli.

It must be emphasized that there are other variables than the rate of lichen growth which can render interregional correlations difficult. Miller (1973a) reported that water-saturated Alectorion minuscule averaged 31% larger than the same thalli when dry, therefore field studies undertaken in inclement weather or shortly thereafter may lead to slightly anomalous results. Correlation of glacial deposits is complicated by the differences in response time of glaciers to the same environmental change and by the fact that the change may not be synchronous across a large area. In addition, some moraines may not be evidence of climatic fluctuations, but may be 'merely segments of formerly expanded glacier termini preserved by a debris cover' (Denton and Karlén, 1977), and may thus have no basis for temporal correlation.

8. SUMMARY

The practice of lichenometry can provide useful information about the ages of substrates, and possibly the environment, over the last several thousand years. 'Any rapid field method introduces errors' (Bescel, 1961, p 1047), thus, where possible, sampling of substrates by multiple methods should be undertaken. Sample sites should be representative of the lichen cover on the substrate, and should avoid either optimal or minimal growth localities. If more information is desired concerning anomalous environments, or if different size/frequency distributions are observed at the two sites sampled, additional measurements should be taken. For comparison with previously published results, or to meet special criteria, other searches using fixed-area (100 m²) should be undertaken; the latter is necessary if isophyses (Figure 7) are to be drawn. Maximum lichen diameter or the mean of the 5 largest thalli can both be used for purposes of interregional correlation; the latter is less variable, thus is preferred. As an independent age estimator, percent of lichen
cover, determined as the average cover on a minimum of 50
boulders, can be measured. Where more than one lichen species
is ubiquitous, all such species should be measured if time per-
mits.

Growth curves for all common lichen species should be deter-
mined wherever possible, using the same method as for substrates
of unknown age. With a view towards establishing directly the
growth rates of common lichen species, and determining the vari-
ability of short-term growth rates, photographs in 35 mm format
should be taken of easily accessible and identifiable thalli,
using an internal control for distortion. The Institute of Arctic
and Alpine Research, University of Colorado, Boulder, Colorado
80309, will gladly serve as a repository and clearinghouse for
such baseline information.

In his initial publication, Beschel (1950) stated that
‘however unpretentious they may be in themselves, lichens thus
offer, through the regularity of their growth under otherwise
uniform conditions, a useful method of establishing the age of
recent...deposits’ (p 309). Despite the criticism of lichenometry
for the lack of uniformity in both its techniques and its results,
time has proved Beschel correct. Although it is certain that
arguments will continue to be raised as to the validity of the
basic assumptions of lichenometry, ‘lichenometry will justify
itself not through theoretical argumentation, but by results
achieved’ (Vareschi, 1970, p 81).

ACKNOWLEDGEMENTS

We have benefited greatly from the advice and criticism of
the many students and colleagues who have discussed the method
with us over the years. In particular, we would like to thank
Drs. J.B. Benedict, P.W. Birkeland, T.N. Caine, K.R. Everett,
K. Faegri, J.D. Ives, W. Karién, J.A. Matthews, C.H. Miller,
V. Vareschi, and W.A. Webber for their interest.
A good general source on the literature on lichenometry can be found in Arctic and Alpine Research, 5(4), 1973. This issue was compiled by P.J. Webber and J.T. Andrews and dedicated to the memory of R.E. Beschel.

INTRODUCTION

Beschel, R.E. 1950. Flechten als Altersmassstab rezenter Moränen. Zeitschrift für Gletscherkunde und Glazialgeologie, 1, 152-161 (Translation as Arctic and Alpine Research, 5, 303-309, 1973). This paper includes the initial discussion of the assumptions and basis for lichenometry as well as the first effort at indirect determination of a lichen growth curve.


SPECIES AND IDENTIFICATION

The problem of species differentiation is generally ignored by lichenometrists: most of the work on this subject can be found in the biological literature. A general reference follows.


ENVIRONMENT

No comprehensive study has yet been made as to the effect of the environment upon lichen growth; the following are representative of specific studies.


**SAMPLING AND RECORDING**


**STATISTICAL TREATMENT**

ANALYSIS OF RESULTS - RELATIVE AGE


ANALYSIS OF RESULTS - ABSOLUTE AGE


PROBLEMS

Jochimsen, M. 1966. Ist die Grösse des Flechtenthallus wirklich ein brauchbarer Maßstab zur Datierung von glazialgeomorphologischen Relikten? Geografiska Annaler, 48(A), 157-164. (Translation as Does the size of lichen thalli really constitute a valid measure for dating glacial deposits? Arctic and Alpine Research, 5, 417-424, 1975.) Includes a complete list of biological and environmental variables which must be considered in the application and interpretation of lichenometry and its results.
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Miller, G.H. 1973b. Late Quaternary glacial and climatic history of northern Cumberland Peninsula, Baffin Island, N.W.T., Canada. Quaternary Research, 3, 561-583.


APPENDIX I

Charts to be used for the determination of percentage cover

(Data Sheet 6 of Geotimes, American Geological Institute,
Reprinted here by permission of the authors and the Society
of Economic Paleontologists and Mineralogists.
Technical Bulletins of the British Geomorphological Research Group

7. The measurement of soil frost-heave in the field. Peter A. James, 1971.
22. HYDRODAT - a system of FORTRAN computer programs for the preparation and analysis of hydrological data from charts. K.J. Beven & J.L. Callen, 1979.

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