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2009-2010 PROJECTS

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Keck Geology Consortium: Projects 2009-2010
Short Contributions – SVALBARD

HOLOCENE AND MODERN CLIMATE CHANGE IN THE HIGH ARCTIC, SVALBARD, NORWAY

Project Faculty: *AL WERNER*: Mount Holyoke College
STEVE ROOF: Hampshire College
MIKE RETELLE: Bates College

DIRECTLY-CONTROLLED LICHEN GROWTH CURVES FOR WESTERN SPITSBERGEN, SVALBARD

TRAVIS BROWN: College of Wooster
Research Advisor: Greg Wiles

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CHRISTOPHER FISHER COLEMAN: Wesleyan University
Research Advisor: Suzanne O'Connell

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DAVID A. VAILLENCOURT: University of Massachusetts Amherst
Research Advisors: William J. D'Andrea and Steven T. Petsch

DIRECTLY-CONTROLLED LICHEN GROWTH CURVES FOR WESTERN SPITSBERGEN, SVALBARD

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INTRODUCTION

Lichenometry is a dating technique pioneered by Beschel (1950) on the basis that the largest lichen thallus growing on a substrate is the oldest individual and that by determining the lichen's growth rate, the age of a thallus–and by extension the substrate–may be determined from the thallus diameter (Bradley, 1999). Lichenometry lends itself to the dating of geomorphic features in arctic and alpine environments where other methods are not available, particularly those environments beyond the tree-line (Locke et al., 1979; Bradley, 1999). Features are dated using growth curves relating lichen size to age. Each curve must be calibrated to the species and environment intended to be studied.

Traditionally, such calibration was done by comparing the largest lichen thalli of a species on a set of substrates of known ages, known as the "indirect" method (Beschel, 1958, 1961; Miller, 1969; Miller and Andrews, 1972; Benedict, 1985; Innes, 1985; Werner, 1990; Bradwell, 2001). However, this method and the growth curves produced by it have come in to contention in the scientific community (Loso and Doak, 2006; Bradwell and Armstrong, 2007). Another technique, known as the "direct" method, involves periodic measurement of the growth of individual lichen thalli to develop curves relating growth rate to thallus size. This method has become a useful means to assess the accuracy and validity of indirectly-controlled curves (Bradwell and Armstrong, 2007).

This study was conceived as an extension of doctoral lichenometric investigations by Werner (1988) to establish directly-controlled lichen growth curves for the *Pseudephebe minuscula* lichen in the Svalbard archipelago. Although Werner's (1990) indirect study provided a growth curve for this lichen in Svalbard, a long-term direct study was considered valuable as a means of comparison and as an investigation into lichen growth patterns.

PHYSICAL SETTING

Located between 74º-81º N and 10º-35º E, the Svalbard archipelago is remarkably temperate for its latitude (Harland, 1997). At Isfjord Radio (Fig. 1, Project Overview), on the western coast of Spitsbergen–the largest island in the archipelago–the mean annual precipitation is 435 mm, with a mean annual air temperature of -4.7°C (Steffensen, 1982). The climate of the archipelago is moderated largely by the West-Spitsbergen Current, an extension of the Norwegian and North Atlantic Current (Snyder, 2000). Large-scale atmospheric circulation is also influenced by the low-pressure system over Iceland and the high-pressure system over Greenland and the Arctic Ocean (Isaksson et al., 2003).

The study site was situated on the ice-cored moraine of Linnébreen, a glacier on the western coast of Spitsbergen. The glacier sits at the head of Linnédalen, a long valley, draining to the northwest into Linnévatnet (Lake Linné) and ultimately into the mouth of Isfjorden (Fig. 2, Project Overview). The glacier is underlain by fossil- and coal-bearing Lower Carboniferous quartzites, of which its moraines are mostly comprised.

In August 1985, 14 *Pseudephebe minuscula* thalli on a quartzite boulder on the eastern lateral moraine of Linnébreen were measured and selected for monitoring (Werner, 1988). The boulder lies near where Linnébreen's Little Ice Age (LIA) moraine onlaps an older Neoglacial (1000-2000 yr BP) moraine (Wer-

ner, 1988). The boulder ("Inner Flank"), measuring ca. 50 cm, lies on the inner flank of the moraine crest, within the LIA maximum. Lichen thalli were present on two faces pointing northeast and northwest, each at roughly a 45 degree angle to horizontal.

TAXONOMY

Pseudephebe minuscula (formerly named *Alectoria minuscula*), a fast-growing, black, fibrous, subfruticose lichen, is differentiated from the similar-appearing *Pseudephebe pubescens* by the length and texture of its thallus fibers (Andrews and Webber, 1964; Calkin and Ellis, 1980). However, this means of identification is difficult in small thalli (<15 mm) and it is possible that some *P. pubescens* thalli were measured in this study. Werner (1990) found the two species to be of comparable size where they could be confidently identified.

METHODS

All 14 *P. minuscula* thalli were initially measured in August 1985 using a 10 cm clear plastic ruler accurate to the nearest millimeter (Werner, 1988). The final observations, in late July 2009, were made using Whitworth digital calipers accurate to within 0.05 mm.

Measurements of *P. minuscula* thalli were made on the basis of the shortest diameter approximately through the center of the lichen (or "short axis") as per Werner's (1988) measurements.

RESULTS

All samples showed measurable growth over the study period (Fig. 1). None of the 14 *Pseudephebe minuscula* thalli was omitted. The Diametral Growth-Rate (DGR) for the short-axis diameter of the *P. minuscula* thalli varies from 0.25 mm/yr to 0.96 mm/yr with a mean of 0.73 mm/yr. The DGR of each thallus was plotted against its short-axis diameter as of August 1985.

The data reveal a quite distinct relationship between DGR and thallus size for *P. minuscula*. The shape of
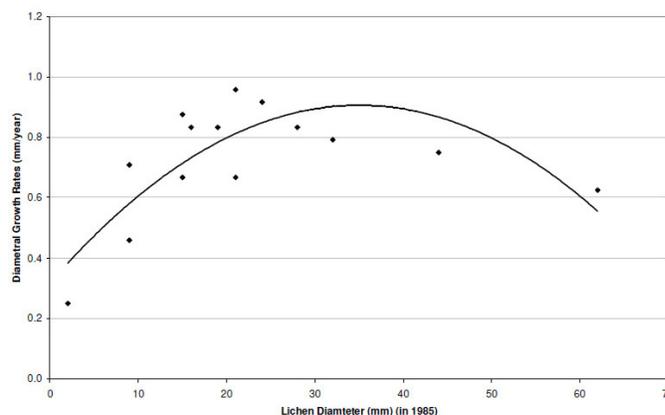

Figure 1. Plot of P. minuscula diametral growth rates (mm/yr) versus short-axis thallus diameter (mm in 1985) from Linné-breen, western Spitsbergen.

the growth curve is well-described by a downwardly-inflected second-order polynomial (r^2 = 0.6364), with growth peaking around 35 mm (Fig. 1).

To determine a growth function, DGR values were inverted to express growth in terms of yr/mm and then plotted against short-axis thallus diameters as of August 1985. The resulting plot shows a relationship best described (r^2 = 0.6338) by an upwardly-inflected second-order polynomial. Once integrated, this polynomial yielded the function:

Equation 1: $f(x) = y = 0.0006x^3 - 0.0663x^2 + 3.2304x$

where $f(x)$ is the age (in yr) of the thallus and x is the short-axis diameter of said thallus (in mm) (Fig. 4a). Error for ages generated from this function is conservatively estimated at ± 11 yr for lichens within the range of this study (<62 mm), based on the variance in ages calculated for lichen thalli at the beginning and end of the study. Growth is not constrained beyond 62 mm for this function and extrapolation of ages for thalli >62 mm should be done with caution.

Based on the growth function for *P. minuscula*, a minimum age estimate of 113 ± 11 yr BP was determined for the exposure, settling and colonization of the Inner Flank boulder. Growth functions were also applied to the documented largest thalli for substrates of known age in Werner's (1990) indirect

Control Point	Age of Substrate (yr)	P. minuscula		
		Thallus Diameter (mm)	Min Age (yr)	Max Age (yr)
B	28	6	6	28
E	80	76*	115	137
F	80	44	54	76
G	80	55	66	88
H	89	52	62	84
I	89	30	42	64
J	366-326	75*	111	133
K	366-326	130*	607	629
L	0-261	123*	500	522

Table 1. Substrates and ages from Werner (1990)
* Indicates thallus diameter outside the constraints of this (2010) study.

study as a means of assessing the accuracy of the functions (Table 1). The data were generally favorable, with only a few unconstrained P. *minuscula* thalli exceeding the substrate age.

DISCUSSION & CONCLUSIONS

Indirectly- and directly-controlled *P. minuscula* growth curves display considerable differences. The indirectly-controlled growth curve from Spitsbergen (Fig. 2b) displays a quasi-logarithmic shape, as does its counterpart from Baffin Island. The directly-controlled growth curve (Fig. 2a), by contrast, displays a more complex period of initial slow growth accelerating to a period of fast growth from 15-50 mm (35-70 years), ultimately decelerating (possibly asymptotically) toward slower growth. The final phase of growth also appears markedly slower than those seen in the indirectly-controlled curves from Spitsbergen and Baffin Island.

Based on the conclusions of Miller and Andrews (1972) in the Canadian Arctic, Werner (1990) theorizes that *P. minuscula* thalli growing on Spitsbergen will reach senescence at ca. 130 mm–or ca. 200 yrs according to his growth curve–as indicated by the solid line marked "L" (Fig. 2b). This determination was supported by the limited and deteriorated appearance of *P. minuscula* thalli on features older than ca. 200 yrs. While this study, using the same diameter of Miller and Andrews (1972), would conclude a much older age of senescence for *P. minuscula* (~618 yrs), the absence of large, healthy *P. minuscula* thalli on features >200 yrs in age and the lack of controls for this region of the growth curve preclude a confident determination on Werner's (1990) age of senescence.
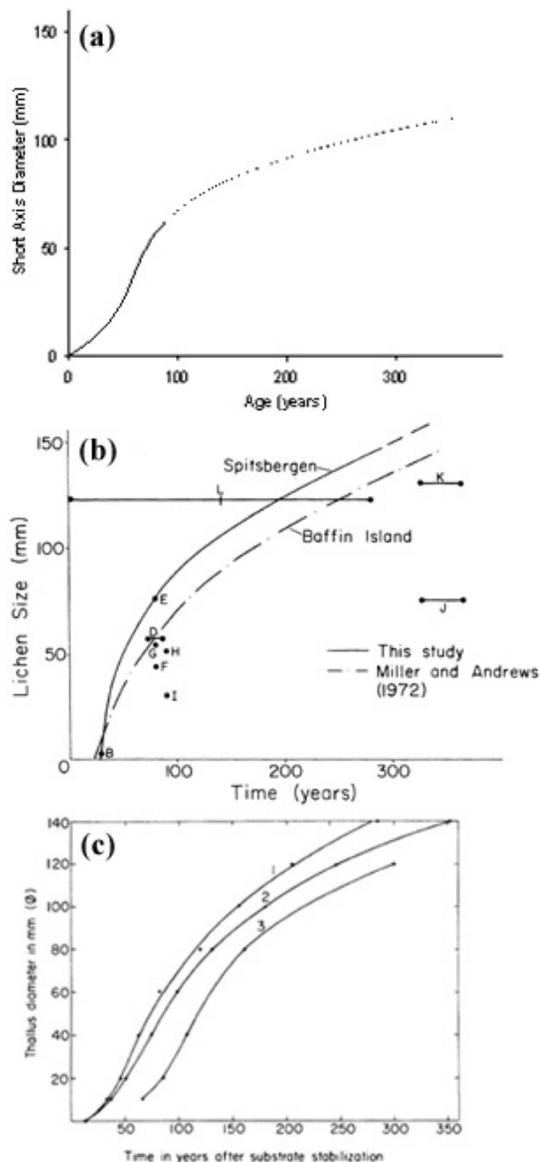

Figure 2. (a) Directly-controlled P. minuscula growth curve (short axis) from Linnébreen (this study). The solid line indicates constrained growth and the dotted line indicates projected growth. Colonization period is not included in this growth curve. (b) Indirectly-controlled P. minuscula growth curves (short axis) from northwestern Spitsbergen and the eastern Canadian Arctic (Werner, 1990, Fig. 10). (c) P. minuscula growth curves from Baffin Island: Curve 1 from Miller and Andrews, 1972; Curve 2 from Miller, 1973; Curve 3 from Andrews and Webber, 1969 (Miller, 1973, Fig. 2B).

While this study utilizes a greater number of samples, Werner's dataset (1990) encompasses a significantly broader geographic distribution within Spitsbergen than does this study. Constrained growth ranges are nearly equivalent for both studies, despite Werner's (1990) greater sample of large thalli.

Direct method studies of *P. minuscula* growth rates on Baffin Island (69° N, 72° W) show similar growth curves to those of this study (Fig. 2a&c). The Baffin Island curves, despite smaller sample sizes, are constrained over greater intervals than this study can claim (Andrews and Weber, 1969; Miller and Andrews, 1972; Miller, 1973). Still, the Baffin Island growth curves generally agree with the growth curve from this study.

For this study, dates for the Inner Flank boulder apply to the interior LIA moraine. Glaciers in northern Scandinavia are thought to have reached their LIA maximum between the 17th and early 18th centuries while glaciers near Lyngen, Troms (69° N) appear to have reached their LIA maximum positions during AD 1890-1929 (Nesje, 2009). A similar glaciation history to Lyngen would be compatible with the dates applied to the LIA moraine at Linnébreen.

Constrained calculated ages based on *P. minuscula* thalli were quite close to that of the substrate. However, unconstrained calculated ages often exceeded the age of the substrate, emphasizing the need for monitoring of larger thalli to constrain this region of the curve. Still, for the constrained portion, the *P. minuscula* dating function seems to provide reliable and high-resolution minimum age estimates. This study originally assumed that a longer time interval between measurements would be beneficial, as it might help to minimize error from imprecision. However, long study likely also results in growth curve distortion. In many studies, growth curves are presumed to represent instantaneous growth rates, when the curves are actually only approximations based on average growth rates, an instantaneous rate being equivalent to an average rate over an infinitesimal time interval. Longer time intervals thus lead to less accurate approximations. Ideally, direct method lichenometric studies should incorporate the shortest time interval in which growth can be observed. The extreme length of this study compared to other direct method investigations (Andrews and Webber, 1969; Miller and Andrews, 1972; Miller, 1973; Matthews, 1994; Bradwell and Armstrong, 2007) may have resulted in a distortion

of the growth curve.

Another factor that may induce error in directly-controlled lichen growth curves is the effect of climatic nonstationarity on lichen growth. It has been shown that lichen growth rates vary with climate as climate varies geographically and that more temperate regions (longer snow-free growing season, higher frequency of rain days, and warmer average daytime temperatures) are conducive to faster growth (Beschel, 1961; Rydzak, 1961; Armstrong, 1973; Benedict, 1990; Bradwell and Armstrong, 2007). However, climate also varies through time, as seen in the LIA and other paleoclimatic events. Furthermore, lichens, being photosynthetic organisms, are distinctly impacted by atmospheric CO_2 concentration as well as the concentration of other airborne pollutants (Green et al., 2008; Nash, 2008)–variables which have changed greatly over time, particularly in the post-Industrial Revolution era (IPCC, 2007). It is reasonable to conclude, then, that lichen growth trends vary in both space and time, and thus, growth trends are nonstationary.

This concept of nonstationarity becomes particularly important in the context of very old lichens, which have likely been subject to a variety of climates within the same geographical area, and thus have adopted a variety of growth trends to suit each climate. This is problematic when trying to use lichen growth curves calibrated to a specific climate to date features that have undergone climatic shifts, which includes the vast majority of geomorphic features. While growth curves generated via the indirect method may account for this nonstationarity within the time frame for which they are constrained, curves generated via the direct method do not, since they represent a growth trend within only the climatic paradigm of the study period. Thus nonstationarity may induce a significant amount of error in directly-controlled lichenometric growth curves.

REFERENCES

Andrews, J. T., and Webber, P. J., 1964, A lichenometrical study of the northwestern margin of the Barnes Ice Cap: a geomorphological tech-

nique: Geographical Bulletin, v. 22, p. 80-104.

––––––, 1969, Lichenometry to evaluate changes in glacial mass budgets: as illustrated from north-central Baffin Island, N.W.T.: Arctic and Alpine Research, v. 1, p. 181-194.

Armstrong, R. A., 1973, Seasonal growth and growth rate-colony size relationships in six species of saxicolous lichens: New Phytologist, v. 72, p. 1023-1030.

Benedict, J. B., 1985, Arapaho Pass: glacial geology and archaeology at the crest of the Colorado Front Range: Center for Mountain Archaeology, Ward, Colorado, Research Reports, v. 3, p. 1-197.

––––––, 1990, Experiments on lichen growth, I. Seasonal patterns and environmental controls: Arctic and Alpine Research, v. 22, p. 244-254.

Beschel, R. E., 1950, Flechten als altermassatab rezenter möranen: Zeitschrift fur Gletscherkunde und Glazialgeologie, v.1, p. 152-161.

––––––, 1958, Lichenometrical studies in west Greenland: Arctic, v. 11, p. 254.

––––––, 1961, Dating rock surfaces by lichen growth and its application to glaciology and physiography (lichenometry), in Proceedings, Geology of the Arctic (First International Symposium on Arctic Geology), Volume 2, Toronto: University of Toronto Press, p. 1044-1062.

Bradley, R. S., 1999, Paleoclimatology: San Diego, CA, Elsevier Academic Press, 2nd ed., 614 p.

Bradwell, T., 2001, A new lichenometric dating curve for southeast Iceland: Geografiska Annaler, v. 93A, p. 91-101.

Bradwell, T., and Armstrong, R.A., 2007, Growth rates of Rhizocarpon geographicum lichens: a review with new data from Iceland: Journal of Quaternary Science, v. 22, p. 311-320.

Calkin, P. E., and Ellis, J. M., 1980: A lichenometric dating curve: its application to Holocene glacier studies in the central Brooks Range, Alaska: Arctic and Alpine Research, v. 12, p. 245-264.

Green, T. G. A., Nash, T. H., III, and Lange, O. L., 2008, Physiological ecology of carbon dioxide exchange, in Nash, T. H., III, ed., Lichen biology (second edition): New York, Cambridge University Press, p. 152-181.

Harland, W.B., 1997, The geology of Svalbard, London, The Geological Society, 521 p.

Innes, J.L., 1985, Lichenometry: Progress in Physical Geography, v. 9, p. 187-254.

IPCC, 2007, Climate Change 2007-Fourth Assessment Report, Cambridge, Cambridge University Press.

Isaksson, E., Hermanson, M., Hicks, S., Igarashi, M., Kamiyama, K., Moore, J., Motoyama, H., Muir, D., Pohjola, V., Vaikmäe, R., van de Wal, R. S. W., Watanabe, O., 2003, Ice cores from Svalbard–useful archives of past climate and pollution history: Physics and Chemistry of the Earth, v. 28, p. 1217-1228.

Locke, W. W., Andrews, J. T., and Webber, P. J., 1979, A manual for lichenometry: British Geomorphological Research Group, Technical Bulletin, v. 26, p. 1-47.

Loso, M. G., and Doak, D. F., 2006, The biology behind lichenometric dating curves: Oecologia, v. 147, p. 223-229.

Matthews, J. A., 1994, Lichenometric dating: a review with particular reference to 'Little Ice Age' moraines in southern Norway, in Beck, C., ed., Dating in surface contexts: Albuquerque, New Mexico University Press, p. 185-212.

Miller, C. D., 1969, Chronology of neoglacial moraines in the Dome Peak area, North Sawatch Range, Colorado: Arctic and Alpine Research, v. 5, p. 385-400.

Miller, G. H., 1973, Variations in lichen growth from direct measurement: preliminary curves for Alectoria minuscula from eastern Baffin Island, N. W. T., Canada: Arctic and Alpine Research, v. 5, p. 333-339.

Miller, G. H., and Andrews, J. T., 1972, Quaternary histor of northern Cumberland Peninsula, East Baffin Island, N. W. T., part VI: preliminary lichen growth curve for Rhizocarpon geographicum: Geological Society of America Bulletin, v. 83, p. 1133-1138.

Nash, T. H., III, 2008, Lichen sensitivity to air pollution, in Nash, T. H., III, ed., Lichen biology (second edition): New York, Cambridge University Press, p. 299-314.

Nesje, A., 2009, Latest Pleistocene and Holocene alpine glacier fluctuations in Scandinavia: Quaternary Science Reviews, v. 28, p. 2119-2136.

Rydzak, J., 1961, Investigations on the growth rate of lichens: Annales Universitatis Mariae Curie-Sklodowska, v. 16, p. 1-15.

Snyder, J. A., Werner, A., and Miller, G. H., 2000, Holocene cirque glacier activity in western Spitsbergen, Svalbard: sediment records from proglacial Linnévatnet: The Holocene, v. 10, p. 555-563.

Steffensen, E., 1982, The Climate at Norwegian Arctic Stations: Klima-Norwegian Meteorological Institute, 44 p.

Werner, A., 1988, Holocene glaciation and climatic change, Spitsbergen, Svalbard [Ph.D. thesis]: Boulder, University of Colorado.

Werner, A., 1990, Lichen growth rates for the northwest coast of Spitsbergen, Svalbard: Arctic and Alpine Research, v. 22, p. 129-140.