Modeling Uncertainties in Lichenometry Studies

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Abstract
To date glacial and periglacial landforms, lichenometry is a valuable method but, to improve efficiency, the estimated surface dates derived from traditional methods need to be more accurate. In other words, the statistical uncertainty associated with inferred dates has to be reduced. How to perform such a reduction is the main question that we will address in this paper. An interdisciplinary approach (lichenometry and statistics) allows reduction in the main sources of uncertainty: lichen diameters and their associated ages. Around 2600 lichen measurements collected on moraines from the Charquini glacier in Bolivia (Cordillera Real) are used to illustrate the advantages of our approach over past studies.

As for any statistical estimation procedure, the error analysis in lichenometry is directly linked to the type of observations and the statistical model used to represent accurately these data. The attribute of lichenometry studies is that the measurements are not averages but maxima; only the largest lichen diameters provide information about the surface ages. To take this characteristic into account, we propose a novel statistical way to model maximum lichen diameters. Our model, based on the extreme value theory, allows us to compute small confidence intervals for the inferred surface ages. In addition, it offers three other advantages: (1) a global statistical model, as all our data (dated surfaces and all lichen maximum diameters) are represented with a unique function; (2) a mathematical framework within which the maximum lichen distribution is derived from a statistical theory; and (3) flexibility, as different types of growing curves can be investigated.

Introduction
Lichenometry has principally been used to date periglacial and glacial landforms. Since the pioneering work of Beschel (1961), this technique has been applied to a large variety of environments. It is especially well suited for arctic and alpine regions because other dating methods are either difficult to implement or even fail at these high altitudes. For example, the sparsity of vegetation near glaciers makes the use of dendrochronology problematic. Although lichenometry may be used to date old surfaces (e.g. the late Holocene in South America; Rodbell, 1992), it is best suited to analyze recent centuries for which classical 14C dating techniques are tainted with a low precision.

The basic premise of lichenometry is that the diameter of the largest thallus growing on a surface is proportional to the length of time that the surface has been exposed to colonization and growth in a specific environmental context. Hence, if one can establish a temporal link between lichen sizes and their ages, i.e. construct a growth curve, it is then possible to date moraines. However, this relationship between the lichen size and its age varies with the characteristics of the surroundings. Lichen growth depends on the climate (Benedict, 1967, 1990, 1991), the lithology (Rodbell, 1992), as well as the orientation of the colonized surface (Pentecost, 1979). The most popular approach that involves measurements of the largest lichens is assuming that the largest individual lichens are among the first to colonize a surface. Although there is a common agreement among geomorphologists about the basic concepts of this method, there is still controversy concerning its implementation, e.g. the number of lichens sampled, the design of the experiment, and the choice of a robust statistic.

Recently, McCarroll (1994) proposed a new strategy where only the largest lichen on a block is selected. This procedure is then repeated many times on different blocks. However, McCarroll incorrectly assumed that the largest lichen sizes are near normally distributed (see figures 2 and 7 in McCarroll, 1994). This assumption was only based on a visual inspection of histograms, and neither statistical tests were provided to confirm this choice nor mathematical concepts employed to justify this approach. The latter point is important because probability theory dedicated to extreme values (largest lichen diameters belonging to this category) dictates that the distribution of maxima cannot be normal (Fig. 1) but instead must follow a specific distribution (the Generalized Extreme Value distribution), whenever the sample size is large enough. This mathematical result has been used in many fields since the pioneering work of Gnedenko (1943) but has rarely been applied to lichenometry (e.g. Bull and Brandon, 1998; Karlen and Black, 2002). (A detailed description of this theory, as well as a list of references, will be given in the section MODELING MAXIMUM DIAMETERS.) An immediate consequence of this mathematical constraint is that past computations of confidence intervals based on the assumption of normality are at best questionable and at worst flawed. To illustrate the importance of the appropriate choice for the distribution of maxima, we plot in Figure 1 the histogram of the maximum lichen diameters from the Charquini glacier in Bolivia (the same result has been obtained for different moraines and regions). From the histogram shapes, it is very clear that the distributions of maxima are rarely symmetric, and the fit by a Gaussian density distribution (dotted line) is too restrictive to represent accurately maximum lichen sizes (e.g. Fig. 1a). In comparison, the fit by a Generalized Extreme Value