REVISTA CHILENA DE HISTORIA NATURAL

Revista Chilena de Historia Natural 86: 465-473, 2013
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RESEARCH ARTICLE

Lichenometric analysis using genus *Rhizocarpon,* section Rhizocarpon (Lecanorales: Rhizocarpaceae) at Mount San Lorenzo, southern Chile

Análisis Liquenométrico usando género *Rhizocarpon*, sección Rhizocarpon (Lecanorales: Rhizocarpaceae), en el Monte San Lorenzo, sur de Chile

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ABSTRACT

In this study we present preliminary results on the use of the lichenometric method for age estimation of moraine formation in the Mount San Lorenzo area (47°30' S, 72°21' W), southern Chile. We estimated lichen growth rates of individuals of genus *Rhizocarpon,* section Rhizocarpon, at two glacier-proximal sites for which independent age estimates were available. These two sites, Lake Shore and Moraine A, presented lichen mean annual growth rates of 0.33 mm and 0.15 mm, respectively. We applied these growth rates to two sites lacking previous dating control: Bedrock and Moraine B, and obtained minimum ages of 70 and 473 years, respectively. Our results allow us to confirm that there is a quantifiable relationship between *Rhizocarpon* size and age of the substrates in this environment. Based on this result we develop age estimates for sites of unknown age in Mount San Lorenzo. We discuss the factors that possibly determine the variability in the growth of *Rhizocarpon* in our study sites and compared them with those described in the literature.

Key words: Chilean Patagonia, glacial moraines, lichenometry, Mount San Lorenzo**.**

RESUMEN

Este trabajo presenta resultados preliminares del uso de la liquenometría indirecta en el fechado de morrenas en el Monte San Lorenzo (47º30' S, 72º21' W), sur de Chile. A partir de la determinación de las tasas de crecimiento de líquenes del género *Rhizocarpon*, sección Rhizocarpon, en dos sitios datados previamente (Costa de Lago, con una tasa de crecimiento de 0.33 mm por año, y Morrena A, con una tasa de 0.15 mm por año) se aplicaron estas tasas en dos sitios sin datar, Roca Basal y Morrena B, obteniendo edades mínimas de 70 y 473 años, respectivamente. Nuestros resultados nos permiten afirmar que existe una relación cuantificable entre el tamaño de los líquenes y la antigüedad de los sustratos, a partir de la que fue posible estimar edades mínimas para los sitios de edad desconocida. Se discuten los posibles factores que estarían determinando la variabilidad en el crecimiento de *Rhizocarpon* en nuestros sitios de estudio y se comparan estos con los descritos en la literatura.

Palabras clave: liquenometría, Monte San Lorenzo, morrenas, Patagonia chilena.

INTRODUCTION

Lichenometry is a technique that is used to establish the age of substrates by measuring the radial growth of lichens growing on the surface of that substrates (Beschel 1961, Innes 1985). In South America, few studies have used this technique. Some of them have used the genus *Placopsis* (Winchester & Harrison 2000, Winchester et al. 2001, Henríquez & Caamaño 2002, Sancho et al. 2011), and *Rhizocarpon* (Ramond ex DC 1805) to date moraines in mountain areas in Bolivia (Rabatel et al. 2006), Peru (Solomina et al. 2007), Argentinean Patagonia (Garibotti & Villalba 2009), and Tierra del Fuego (Sancho et al. 2011).

This age-estimation technique is particularly valuable for dating rock surfaces on glacial landforms in polar and high alpine environments, where other techniques cannot be used or have insufficient temporal resolution. For example, ^{14}C dating requires the presence of suitable organic material, and is imprecise for ages younger than ca. 400 BP (Innes 1985, Lock et al. 1979). Dendrochronology requires woody vegetation growing on the sites and, if present, ages limited by the maximum age of the plant species and by forest fires. In this region, the maximum age of most *Nothofagus* species is less than 500 years (Aravena 2007, Garibotti & Villalba 2007). In addition, the age estimates for glacial landforms based on the colonization of pioneer plants usually underestimate total ages due to ecesis, the unknown time interval between surface stabilization after ice recession and the establishment of the first pioneer vegetation. Other information sources on past environmental conditions such as historical documents or photographs are limited in remote environments and may contain errors associated with authors subjectivity and poor dating information (Lock et al. 1979)

The present work applies lichenometric methods to the dating of glacier moraines surfaces. We first estimated lichen growth rates from genus *Rhizocarpon*, section Rhizocarpon, on previously dated landforms from Valle San Lorenzo, in southern Chile. Then, we applied this growth rate to estimate ages of surfaces of unknown age, presumably formed during the last 500 years, during the period of glacier readvances known as the "Little Ice Age" (LIA; see Bradley & Jones 1992, Luckman 2000).

METHODS

Study area

Mount San Lorenzo (47°30'S y 72°21'W) is the third highest peak in the Patagonian Andes, reaching 3706 msl (Fig. 1). This mountain has more than 200 ice bodies that according a recent work covered an area of 207 km^2 in 2008 (Falaschi et al. 2013). Three valley glaciers of this mountain, Calluqueo, Río Tranquilo and Arroyo San Lorenzo, have historical and dendrochronological records of its past glacier positions (Aravena 2007).

The closest climate station is at the town of Cochrane located 50 km northwest of Mount San Lorenzo at 167 m of elevation. Mean annual precipitation is ca. 720 mm and the mean annual temperature is 8.1 °C. The climate is classified as continental, with a wide temperature range and a more moderate variation in precipitation (Aravena 2007). The vegetation is characterized as an ecotone between deciduous temperate forest of *Nothofagus pumilio* ((Poepp. & Endl.) Krasser 1896) and the Patagonian steppe. Treeline is at around 1500 m asl and the dominant non-arboreal plant species are those characteristic of the Patagonian steppe (Aravena 2007)

Sampling sites

In a previous work, Vargas & Morano (accepted) determined the diversity of lichen species from the

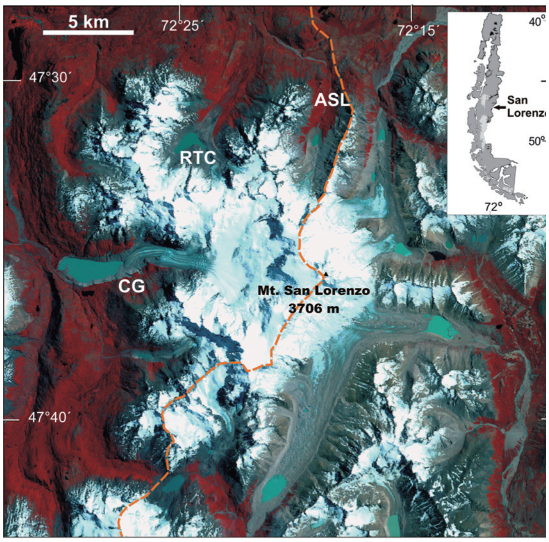

Fig. 1: Satellite image of Mount San Lorenzo, indicating vegetation (forests shown in red), proglacial lakes and glaciers. The dashed line is the Chilean-Argentinan border. CG = Calluqueo valley, RTC = Río Tranquilo valley and ASL= Arroyo San Lorenzo valley (Modified from Aravena 2007).

Imagen satelital del Monte San Lorenzo, indicando vegetación, lagunas proglaciales y glaciares. La línea discontinua señala la frontera Chilena-Argentina; CG =Valle Calluqueo, RTC =Valle Río Tranquilo y ASL =Valle Arroyo San Lorenzo (Modificado de Aravena 2007).

glacier valleys Calluqueo, Río Tranquilo and Arroyo San Lorenzo, and confirmed the presence in these valleys of the two genera commonly used in lichenometry, *Rhizocarpon* and *Placopsis*. These authors established the presence of 30 lichen species in this area including *Rhizocarpon lecanorinum* (Lecanorales: Rhizocarpaceae), (Anders) not previously recorded in Chile.

We selected Arroyo San Lorenzo valley as the best area for lichenometric analyses based on the following considerations. Calluqueo valley has a clear sequence of lateral and frontal moraines, but most of the forests were affected by fires between 1940 and 1983 and the moraines could not be dated using tree-ring methods. Río Tranquilo valley has seven formerly confluent glacier tongues that became separated in the twentieth century as glacier fronts retreated (Aravena 2007). This valley also has well formed lateral and frontal moraines, but they were also affected by past forest fires. Arroyo San Lorenzo valley (Fig. 2) is a smaller valley located at higher elevation (between 1000 and 1700 masl). It faces north and has a well formed sequence of frontal and lateral moraines. Those lateral moraines located closest to the glacier are not covered by forest yet, presumably because they are still too young to be colonized by closed forests, while the older moraines have old-growth forests not affected by fires. Therefore, the Arroyo San Lorenzo valley presents the best conditions for lichenometric studies in the Mount San Lorenzo area. This valley shows less perturbation by processes affecting the colonization and survival of the lichen populations, and probably lichens represent the first colonization after the glacier retreat. Within Arroyo San Lorenzo valley, we established four sampling sites: Moraine A, Lake Shore, Moraine B, and Bedrock (Fig. 2).

The age of the first two sites had previously been estimated from dendrochronology (Aravena 2007) and historical information (D'Agostini 1945). The ages of the other two sites, Moraine B and Bedrock, is unknown.

The Moraine A site is located on the distal slope of the lateral moraine closest to the glacier (Fig. 2). It has no forest cover, and it is almost entirely formed by bare rocks with small patches of *Empetrum rubrum* (Vahl ex Willd, 1806) and isolated dwarf *Nothofagus pumilio* individuals. At this site we found large, partially buried rocks, located in slope not receiving rolling material; all these characteristics allow us to consider it as stable rocks where to measure lichen sizes on surfaces that were at this place since the moraine formation. Aravena (2007) estimated that Moraine A was formed around the year AD 1802, based on tree-ring counts on 10 dwarf *N. pumilio* individuals, considering an ecesis of 36 years.

The Lake Shore site is on the southern shore of the proglacial lake of the Arroyo San Lorenzo valley (Fig. 2). The Lake Shore area sampled is from a section ca 20 m wide and 150 m long that is stable and has not received retransported material from other areas of the valley. The glacier front position was occupying the southern

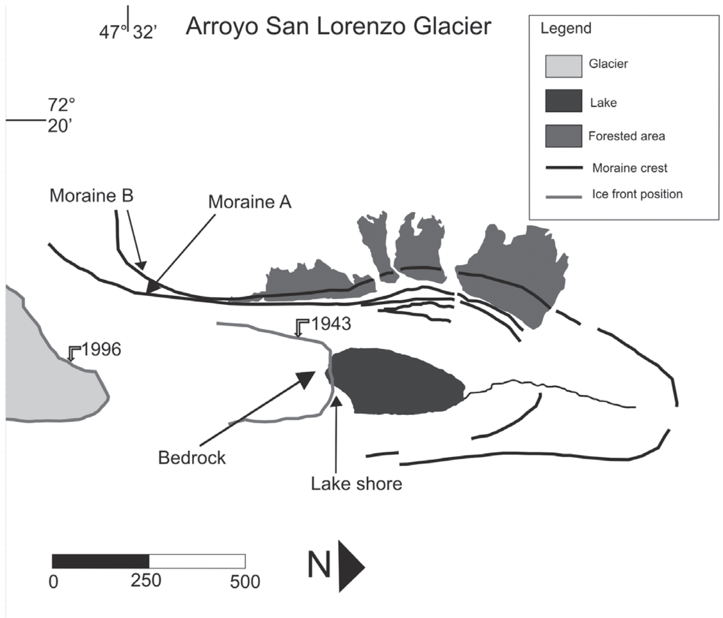

Fig. 2: Arroyo San Lorenzo glacier valley. The light gray represents the glacier, dark gray represents forest and black represents the proglacial lake. The gray lines show the glacier front positions and the black lines the edge of the moraine. Air photographs: SAF96 CONAMA río Baker 7275-7276.

Valle del Glaciar Arroyo San Lorenzo. El gris claro representa el glaciar, el gris oscuro el bosque y en negro el lago proglacial. Las líneas grises muestran posiciones del frente del glaciar y las líneas negras el límite de las morrenas. Fotografías aéreas: SAF96 CONAMA río Baker 7275-7276.

Fig. 3: Moraine B. Arrows show the rocks sampled. The position of the treeline is clearly visible beyond the sampling site. To the right is the proglacial lake, with the Lake shore sampling site.

Morrena B. En el fondo se pueden ver las rocas medidas en este estudio. Las flechas señalan las rocas medidas y la línea el límite arbóreo, a la derecha se ve el Lago proglacial y el sitio de muestreo Costa del Lago.

edge of the proglacial lake between 1943 and 1945 according to historical records (D'Agostini 1945).

The Moraine B site is on the highest portion of the outermost LIA moraine upslope of Moraine A (Fig. 2). Downvalley most of Moraine B is covered by a dense forest of *Nothofagus pumilio,* but its highest portion is above the treeline. In this sector of the Moraine B we found several massive and stable rocks deposited there since the formation of Moraine B, with their basal portions totally inserted in the moraine soil (Fig.3)

The Bedrock site is on a bedrock cliff, 70 meters upvalley of the lakeshore and 1,000 meters from the glacier snout. Several small waterfalls flow down the cliff and the lichen sampled was located within a protected zone (lateral rock sides, cracks) to avoid influence of the waterfall.

Lichen measurements

From a previous work we know that *Rhizocarpon geographicum* ((L) DC.), *R. superficiale* (Schaerer) Vainio, 1922) and *R. lecanorinum*, are present in our study sites (Vargas & Morano, accepted). We measured in each site lichens with uniform radial growth, living on stable rocks showing the classic morphological characteristic of the *Rhizocarpon* genus, namely a yellow green color with black or very dark apothecia (Lock et al. 1979, Innes 1985, Redon 1985). These characteristics were determined through visual observation using 10 x magnifying glasses. We discard all the individuals belonging to *Rhizocarpon lecanorinum*, which is easily identifiable by its reproductive structure shape, called lecanora. Thus, we measured only *R. geographicum and R. superficiale* individuals. In addition, we took pictures of every individual measured, collecting samples of it. We also selected lichens not competing for space with other lichens, to avoid interferences on the diameter growth (Lock et al. 1979, Innes 1985, McCarthy 1999).

We measured in situ the maximum axis for each thallus using an electronic Mitutoyo caliper, model 500-144, with resolution of 0.01 mm and with an error of 0.02 mm. We called this maximum axis length "diameter" since most of the thalli were regular in shape, nearly circular (Sancho & Pintado 2004). At each sampling site, we recorded the altitude with a GPS with barometer GARMIN Extrex Vista. The altimeter was calibrated daily in a sector with a known elevation.

Lichen size estimates were based on the mean diameter of the five largest lichens measured. To detect individuals that by micro-environmental conditions grow to an anomalous rate we discarded the largest lichen if it was > 10 % larger than the second one largest measured individual in each site (Innes 1985, Garibotti & Villalba 2009). After a complete searching for all the Rhizocarpon in each sampling site, the largest individuals were measured, totalizing 58 samples 27 at Moraine A, 18 at Shore Lake, 10 at Bedrock site, and 3 at Moraine B. At Bedrock site, we considered only one lichen that was completely accessible for the analysis, while the remaining nine were partially inside rock fissures and for this reason their sizes were underestimated, and in some cases wrongly identified. At Moraine B sampling site, we measured the only three individuals clearly separated from the surrounding lichens and consequently not in competition for space. From these three lichens measured, one of them was discarded because was 10 % bigger than second one largest measured.

Estimated growth rates were applied in sites without previous age estimation: Moraine B and Bedrock. We seek to determine if exists any relationship between lichen growth and the age of the substrate where lichen lives. To avoid microenvironmental variations resulting from geomorphologic and historical differences, we selected to apply the growth rates estimated from the closer sampling sites for each case: Moraine A to estimate the Moraine B age, and Lake Shore to estimate Bedrock age.

RESULTS

Age control for the sample sites

Lake shore site. The first historical record of the proglacial lake of Arroyo San Lorenzo valley was published by the Italian priest Alberto D'Agostini (D'Agostini 1945) who visited the area in 1943. He described a small proglacial lake with muddy water that gives rise to Arroyo San Lorenzo and a glacier that occupied the shoreline of that lake. The first aerial photographs from the Arroyo San Lorenzo area were made by the US Air Force in 1945 (Trimetrogon, USAF). These photos were used in 1956 as the main information source by the Chilean Geographic Military Institute (IGM), to develop the 1: 50000 map. In this map, the glacier was in 1945 occupying the area of the present shore lake (Fig. 4). As seen in Fig. 5 the glacier was in the lake shore in 1945. Thus, the year 1945 defines the maximum period covered by the glacier for the surface of our Lake shore sampling site.

Moraine A

Aravena (2007) estimated the year AD 1802 as the minimum age formation for Moraine A (Table 1). This estimation is based on tree-ring counting of basal discs of 12 small stunted *Nothofagus pumilio* trees (< 30 cm height, and 3-10 cm of basal diameter) growing on the distal slope of Moraine A. Given that the basal disc of the oldest stunted tree had 162 rings in the year 2000 when was cut, its recruitment year was thus estimated for the year 1838. Considering a 36 year ecesis interval the year 1802 results discounting the ecesis interval from the oldest tree recruitment date (Aravena 2007). (Ecesis is defined as the estimate of the elapsed time between moraine surface formation and the germination of the oldest tree on the surface. McCarthy & Luckman 1993).

Growth Rates and age estimations

Growth rates and age estimations were made in pairs of contiguous sampling sites, one with known age and another without this information; in this way the differences due

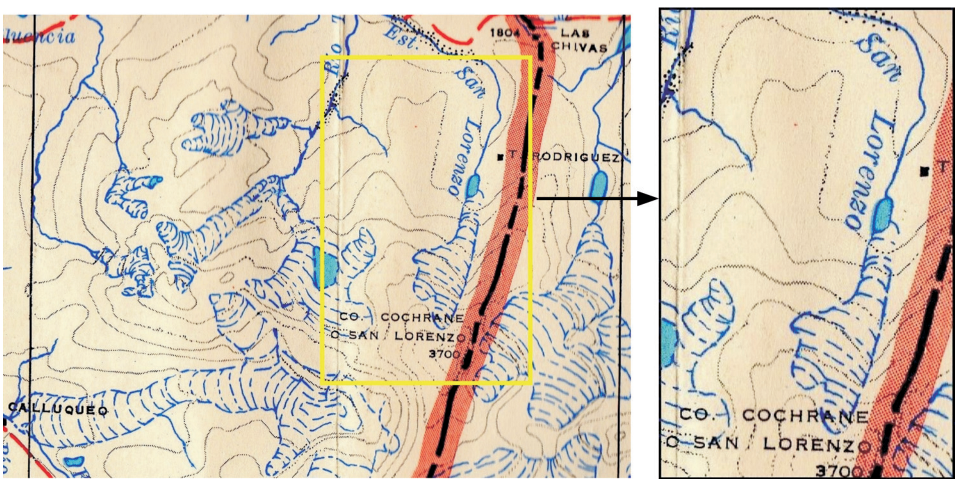

Fig. 4: Glacier position in relation to the Shore Lake sampling site in 1945 according to a IGM map of 1956 based on aerial photograph of 1945. The right hand enlargement magnifies the Shore Lake site.

Posición del glaciar respecto al sitio costa del Lago en el año 1945 según un mapa IGM de 1956 basado en fotografías aéreas de 1945. A mano derecha una vista amplificada del valle.

TABLE 1

Lichonometric data from Arroyo San Lorenzo study site, showing for each of the the sampling sites chronologically ordered, the number of measured lichens, biggest lichen registered, number of anomalous lichens discarded (those lichens that have diameters 10 % larger than the second biggest measured). Also we indicate the estimated age since each surface became available for lichen colonization, the dating technique, and the source of the date estimation. * indicates the presence of only one lichen for that site. ** indicates the presence of the two lichen after the anomalous discarded, in that site.

Información liquenométrica del sitio de estudio Arroyo San Lorenzo, mostrando para cada uno de los sitios de muestreo ordenados cronológicamente, el número de líquenes medidos, el líquen mas grande registrado, número de líquenes anómalos descartados (aquellos que presentaron diámetros al menos 10 % más grandes que el segundo mas grande medido). También indicamos la edad estimada desde cuando cada una de las superficies estuvieron disponibles para ser colonizadas por líquenes, la técnica de fechado, y la fuente de donde proviene el fechado. * Indica la presencia de solo un líquen para este sitio. ** Indica la presencia de dos liquenes, después de el descarte de anómalos, para este sitio.

Site	Number of lichen measured	Biggest measured Lichen (mm)	Number of anomalous	Mean value of 5 largest lichens (SD)	Date	Dating technique	Reference
Lake Shore	18	23.80	1	21.088 (2.16)	1945	Historical reference and cartographic map	D´Agostini,1945; IGM 1956
Bedrock	10	22.94	0	22.94*	1939	Lichenometry	This work
Moraine A	27	36.89	0	31.398 (3.818)	1802	Dendrochronology	Aravena, 2007
Moraine B	3	73.26	1	71.195** (1.305)	1536	Lichenometry	This work

to microenvironmental conditions can be diminished. Sampling sites on Moraine A are at elevations between 1194 and 1262 m asl, while the sampling site from Moraine B is at 1278 m asl. The mean value of Moraine A is 1200 m asl, and mean value of Moraine B is 1278 m asl. These sites are similar with respect to topography, distance to water reservoirs, and vegetation cover. Thus the Moraine A did not present significant differences with the Moraine B in terms of microenvironment. In the same way, a mean elevation of 1035 m asl is share by Bedrock and Lake Shore sampling sites, and both sites have similar microenvironmental conditions. On the other side, between MoraineA/Moraine B and Lake Shore/Bedrock the altitude difference is up to 250 m. For this reason we avoid to mix measuring comparisons among sites with such large differences.

The lichenometric data are summarized in Table 1. In this table the sampling sites are ordered from the younger to the older ones, indicating for each sampling site how many lichens were measured, the largest lichen measured, and the number of anomalous lichens discarded. Table 1 also shows the mean size of the five largest lichen measured after discarding the anomalous for the sampling sites with known ages, Moraine A and Lake shore, the year when we estimated that the studied surfaces were ice-free or stabilized, the technique utilized to estimate the age of the respective surface and the references in each case.

At the younger site, Lake shore sampling site, 18 lichens were measured, the largest lichen was 23.8 mm wide, one anomalous lichen was discarded, and the mean size of the five largest measured lichen was 21.1 mm with a standard deviation of 2.16 mm (range 23.8-17.93 mm). Given that Lake shore site was covered by ice at least until 1945 (Table 1) we have a maximum period of 64 years until 2009 (the year when we measured the lichens), for the lichen colonization of that surface, without considering any ecesis period. Dividing the mean size of 21.1 mm obtained from the five largest lichens by the 64 years of ice-free surface, we estimated a growth rate of 0.33 mm year^{-1} for Lakeshore site. We used this growth rate to estimate the recruitment age for Bedrock sampling site. At that site, we measured 10 lichens but only one of them was identified as *Rhizocarpon,* section Rhizocarpon (Lecanorales: Rhizocarpaceae). The size of that lichen was 22.94 mm, and dividing that size by the growth rate 0.33 we obtained an age of 70 years. According to these results, the recruitment year at bedrock site was 1939, year in which that surface would have been free of ice.

At the older site, Moraine A, we measured 27 lichens, the largest had a diameter of 36.89 mm, and no anomalous lichens were found. Mean size of the five largest lichens was 31.4 mm with a standard deviation of 3.818 (range 36.89-25.82 mm). Moraine A stabilization year was estimated as 1802, according the dendrochronological dating technique (Table 1). Thus, we have 207 years as maximum period for the establishment of lichens on that surface. Consequently, we estimated a growth rate of 0.15 mm year^{-1}. This growth rate was used to estimate the recruitment age on Moraine B, where three individuals were measured and one of them was discarded as anomalous (Table 1). The resulting estimation for the period since Moraine B surface became stable is 474 years. Thus, we estimate that the distal surface of moraine B became stabilized since the year 1535.

DISCUSSION

The lichen growth rate estimated from the younger Lake Shore sampling site is approximately twice than that estimated for Moraine A. Several possible factors may account for these differences. Many lichen studies have shown that lichen growth curves are divided into two phases, an early "great growth" period and a later "attenuated" phase (Innes 1985, Solomina et al. 2003). It may therefore be that these two estimates correspond to two different parts of the same growth curve for this locality. Differences could also respond to different microenvironmental conditions, as they are separated by 180 m in altitude that could determine differences in temperature and the Lake shore site may be considerably wetter than moraine A due to differences in distance to water reservoir.

Garibotti & Villalba (2009) determined differences in growth rates for wet and dry sites in Argentinean Patagonia. At the sites with similar climate conditions, they found growth rates that varied with the age of the substrate. In the early growth stages the growth is faster, tending to decrease with time. At their sites younger than 50 years old, mean sizes of the five largest lichens were between 1.5 and 3 cm approximately. The average of the five largest lichens at our Lake shore sampling site is 2.1cm which is quite similar. For sites greater than 200 years old, the sizes reported in the literature vary between 4 and 6 cm approximately (Garibotti & Villalba 2009). Moraine A study site has an average size of 3.1 cm, from the five largest lichens. This average size value is smaller than the found in the Argentinean study, most probably due to microclimate condition differences. These comparisons suggest that the preliminary estimates from the San Lorenzo sites are similar to other sites in Patagonia, but further work is needed to develop a growth curve for the Mount San Lorenzo area.

Aravena (2007), using tree-ring analysis with a 36-year ecesis interval, estimated a minimum age of 334 years for Moraine B. Our lichenometric estimation provided a minimum age of 474 years that is considerably older than the dendrochronological reference. A date of 1536 for moraine B is within a period described as very active in terms of moraine formation in the Andes of southern Patagonia (Masiokas et al. 2009).

The age of deglaciation for the Bedrock sampling site was estimated with the growth rate obtained from Lake Shore sampling site. The estimated age was 70 years that resulted to be 6 years older than the maximum period of ice free condition for the reference surface, Lake shore site. This may be explained by an irregular glacier retreat that determined that Bedrock site was ice free before than Lake shore site. Another possibility is that glacier front retreat was very fast, leaving ice free both sampling sites more or less at the same time, and their lichens are part of the same population given that their sizes are not significantly different (Table 1).

We concluded that, although very preliminary, results of our study already indicate that it is possible to establish a reasonable relationship between substrate age and *Rhizocarpon* lichen size in Mount San Lorenzo area. Estimated mean growth rates of 0.33 and 0.15 mm year^{-1} were derived from lichens growing on surfaces ca 70 and 207 years old, respectively, major differences may be attributed to micro-environmental conditions or different phases of the lichen growth curve. These preliminary estimates are similar to rates found in dry sites in Argentinean Patagonia. Further research it is necessary to build a Rhizocarpon growth curve that improves minimum age lichenometric estimations for our study areas.

ACKNOWLEDGEMENTS: This research was funded by project Fondecyt 1080320 and CEQUA-CONICYT Regional R07K1002. We thank C. Mansilla and R. Villa-Martínez for helping support at fieldwork, and BH Luckman for his critical and helpful review of an initial version of our manuscript.

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Editorial responsibility: Fernando T. Maestre
Received June 18, 2012; accepted August 18, 2013