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Dendrochronologies of San Rafael and Soler areas, Patagonia

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Abstract

Tree ring samples of increment cores were collected during the austral summer of 1985-86, from ten locations around the Patagonia Icefields, of which those of *Podocarpus nubigemus* from the areas around San Rafael and Soler Glaciers were analyzed and respective dendrochronologies were established for the past 250 years. The most outstanding characteristic of these two dendrochronologies was a very unusual increase in growth in the last few decades. The synchronized occurrance of such an increased growth both in the San Rafael and Soler areas separated by the 3,000-m-high Southern Andes indicated that it was not a local phenomenon but likely to be a more extensive one induced by some climatic factor or factors. A comparison between the chronologies and the climatic records of the nearest weather stations didn't show any direct correlation, but a delayed correlation was found between the precipitation and tree growth with the latter lagging behind the former by 10 to 15 years.

1. Introduction

During the austral summer of 1985-86, a total of 600 increment cores were collected by means of boring trees from ten sampling sites in Chilean Patagonia and its northern vicinity. The coverage of these sampling sites ranged from Tierra del Fuego (54°00'S), the southernmost tip of South America, to Lake Chapo (43°30'S) near Puerto Montt, but the major emphasis was placed on the areas around San Rafael (46°40'S, see Map 2) and Soler (46°55'S, Map 3) Glaciers, on which both intensive and extensive observations and surveys were carried out simultaneously by fellow climatologists, glaciologists and hydrologists.

San Rafael Glacier discharges westward, while Soler Glacier discharges eastward from the 4,500-km^2 Northern Patogonia Icefield (Hielo Patagonico Norte) which straddles the Southern Andes. Being temperate glaciers, the lower halves of both glaciers are surrounded by lush forests of primarily the *Nothofagus* species. Three dendrochronological sampling plots were established in this forested area around San Rafael Glacier and four plots around Soler Glacier. Of the remaining three sampling sites, one by Lake Chapo represented the northern extremity and the other two the southern. One of these southernmost plots, located at the base of the Wilcock Peninsula (50° 40'S), was sampled by Mr. Adrian Newton of the Cambridge University Expedition Team and the other in Tierra del Fuego was sampled by Dr. Edmundo Pisano of the University of Magallanes. Sampling in the remaining eight plots was done by the present author.

Reflecting this extensive geographical coverage, the tree species sampled differed considerably from one location to another. The Lake Chapo samples consisted of *Fitzroya cupressoides* (locally called Alerce), the San Rafael samples of *Podocarpus nubigemus* (Mañio) in one location and of *Nothofagus betuloides* (Coigue) in the remaining two, and the Soler samples of *Nothofagus pumilio* (Lengua) and *N. betuloides* in one location, of *Pilgerodendron uviferum* (Cypres) in another and of *Podocarpus nubigemus* in the remaining two. The samples from the Wilcock Peninsula and Tierra del Fuego were both *Pilgerodendron uviferum.*

A preliminary examination of these increment cores revealed that in broad-leaved species, i. e. *N. betuloides* and *N. pumilio,* annual rings were generally wide but often very obscure and difficult to identify. On the other hand in coniferous species, i. e.

Podocarpus nubigemus, Fitzroya cupressoides and *Pilgerodendron uviferum*, annual rings were generally distinctive but were sometimes as narrow as a few hundredths of a millimeter with seemingly frequent appearance of false rings and possible presence of missing rings. These findings suggested that exact and complete crossdating of all the core samples would be a slow and tedious process. In view of the time available for the present analysis, the species having the most distinctive rings, i.e. *Podocarpus nubigemus*, was chosen in combination with the most important localities, i. e. San Rafael and Soler Glaciers. These two sets of samples are henceforth refered to as San Rafael *Podocarpus* and Soler *Podocarpus*.

2. Materials and methods

The San Rafael *Podocarpus* cores were sampled from a mixed stand of *Podocarpus* and *Nothofagus* located on a coastal alluvial plain six kilometers away from the terminus of San Rafael Glacier on the east bank of Lagoon San Rafael. The stand was predominantly of *Nothofagus* but *Podocarpus* trees of height 10 to 21 m and breast-hight diameter (dbh) 11 to 47 cm were growing mixed in canopy and sub-canopy strata. Two increment cores were extracted from each of 25 trees sampled as was usually the case in most localities. However, since twelve cores from six trees were set aside due to poor legibility of rings resulting from incipient to intermediate decay inside the stem, 38 increment cores from 19 trees were used in the present analysis. In most of these samples the rings were legible right back to the pith and the tree ages as counted on these cores ranged from 230 to 308 years.

The Soler *Podocarpus* cores were sampled also from a mixed stand of *Podocarpus* and *Nothofagus* growing on a gently south-facing fan formed by the River Piña on the left bank of the Soler River 16 km downstream from the terminus of Soler Glacier. Here again the stand was predominantly of *Nothofagus* with a sporadic mixture of *Podocarpus* of height 11 to 20 m and dbh 17 to 61 cm. Different from the San Rafeal samples, most of the 34 trees sampled were subjected to final decay toward the center of the stem. This hindered age determination in most of the samples, but judging from the stem diameter and the ring count of 250 or more even on the truncated cores, the Soler *Podocarpus* population is nearly the same age as or slightly older than its San Rafael counterpart. In the event, 64 cores representing 34 trees were used in the analysis.

Back in the laboratory each increment core was crossdated against the pairing core from the same tree, and subsequently yearly ring-width was measured core by core to a precision of one hundredth of a millimeter under a microscope with a semi-automatic ring-width-measuring device. An average ring-width chronology for a given tree was obtained by simply taking the arithmetic mean of the two series of measurements from the same tree. Whenever the length of the paired chronologies do not match due to differential inner decay the shorter of the two was adopted as the tree chronology. On these averaged tree chronologies, such statistics as mean ring-width, mean sensitivity, and autocorrelation coefficients at successively-increasing lags of up to five years were calculated.

To obtain a series of standard ring-width indices (RWI) which is supposed to represent the dendrochronology for a given sampling site, the individual tree chronologies were further subjected to the following standardization and averaging processes. First, the individual-tree chronology was standardized by fitting a growth curve and then by dividing the observed ring-width by the corresponding mean increment expected from the fitted growth curve. This process converts the original or raw chronology into another chronology of indices with mean 1.0 (dimensionless). These standardized ring-width chronologies were then averaged for each sampling site and the standard RWI for that site was obtained.

The two standard RWIs thus obtained were compared with climatic records from nearby weather stations, i. e. San Rafael *Podocarpus* with the record of Puerto Aisen (45°24'S, 72°42'W) and Soler *Podocarpus* with that of Chile Chico (46°36'S, 71°44'W). Though Puerto Aisen is 170 km north of San Rafael, both are on the Pacific coast facing directly into the prevailing westerly wind in front of the Andes, which brings heavy precipitaion in both localities with mild oceanic variation in temperature throughout the year. On the other hand both Soler and Chile Chico, 110 km apart, are on the leeward side of the prevailing westerly behind the Andes and are characterized by a drastically drier continental climate. For more details of the climatological contrast across the Patagonia Northern Icefield, see Inoue et al. (1987).

3. Dendrochronological characteristics

Both San Rafael *Podocarpus* and Soler *Podocarpus* showed very unusual growth patterns with a sudden and extraordinary rise in the last few decades as will be seen in Fig. 1, in which the annual increment and yearly stem radius of San Rafael *Podocarpus* stem No. 5 were plotted as an example. Generally growth of the tree is characterized by a sigmoid skewed toward younger ages when considered in terms of radial growth, or by a sharp and short rise followed by a gradual negative exponential decline when considered in terms of radial increment. However, in most of the present samples, the growth pattern was exactly the other way around, i. e. a slow plodding increase for the first two centuries or so till around 1960, followed by an extraordinary rise and fall in the last few decades at the senescent age of 200 years or more. The synchronized occurrence of such an extraordinary growth pattern can't be explained without some corresponding change in environment as will be discussed in the next section.

This unusual growth pattern casted a problem in standardizing the raw ring-width chronologies into indices since none of the existing and commonly-used growth curves such as the Mitscherlich, logistic, Gompertz or Richards functions (Sweda and Koide, 1981) were applicable. Thus in the present analysis a simple straight line was used to represent the mean trend of growth.

The statistics on dendrochronological characteristics of each tree are given in Table 1 for San Rafael *Podocarpus* and in Table 2 for Soler *Podocarpus*. The chronology lengths given in these Tables do not represent tree age in general, though in some cases they do. Owing to the decay loss, the Soler chronologies were shorter than those of the San Rafael *Podocarpus* with the former mean at 146 years and the latter at 212 years.

The mean ring width for all of the San Rafael samples was 0.74 mm, while it was 0.86 mm for the Soler samples. This does not necessarily mean that the growth was generally better in the latter locality than in the former but decay in the narrow-ringed

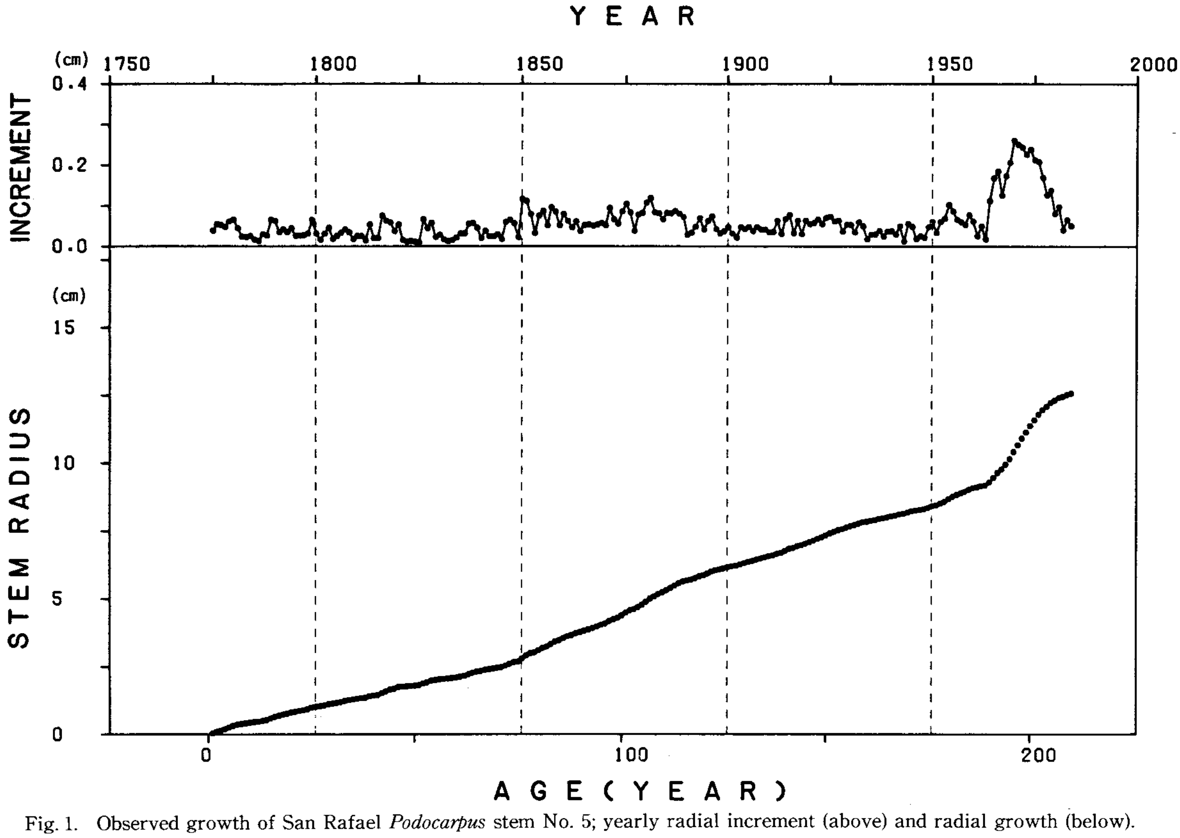

Fig. 1. Observed growth of San Rafael *Podocarpus* stem No. 5; yearly radial increment (above) and radial growth (below).

Table 1. Dendrochronological characteristics of San Rafael *Podocarpus* samples.

STEM No.	LGT (YRS)	MEAN (MM)	S.D. (MM)	SENS	AUTOCORRELATION OF LAG 1	2	3	4	5
1	261.	0.54	0.31	0.29	0.84	0.78	0.74	0.70	0.67
2	189.	1.16	0.76	0.38	0.80	0.83	0.73	0.67	0.58
3	191.	0.78	0.78	0.33	0.93	0.91	0.86	0.83	0.79
4	186.	0.97	0.55	0.38	0.70	0.70	0.70	0.61	0.67
5	212.	0.60	0.46	0.36	0.85	0.79	0.73	0.68	0.62
6	262.	0.57	0.26	0.39	0.53	0.58	0.35	0.40	0.24
7	227.	0.68	0.37	0.36	0.66	0.65	0.58	0.54	0.48
8	220.	0.65	0.57	0.36	0.88	0.84	0.78	0.71	0.70
9	235.	0.35	0.18	0.46	0.39	0.43	0.27	0.24	0.21
10	235.	1.04	0.71	0.39	0.78	0.76	0.64	0.62	0.59
11	230.	0.70	0.36	0.19	0.85	0.83	0.79	0.73	0.71
12	235.	0.68	0.42	0.35	0.82	0.76	0.64	0.58	0.51
13	218.	0.58	0.36	0.43	0.70	0.75	0.66	0.64	0.58
14	190.	0.48	0.29	0.42	0.66	0.62	0.49	0.49	0.39
15	193.	0.84	0.46	0.37	0.72	0.75	0.69	0.64	0.61
16	89.	0.86	0.48	0.27	0.75	0.77	0.54	0.54	0.37
17	104.	0.54	0.36	0.46	0.68	0.59	0.45	0.34	0.29
18	116.	0.71	0.54	0.39	0.83	0.79	0.68	0.58	0.51
19	216.	0.52	0.41	0.45	0.58	0.57	0.46	0.51	0.42

Table 2. Dendrochronological characteristics of Soler *Podocarpus* samples.

STEM NO.	LGT (YRS)	MEAN (MM)	S.D. (MM)	SENS	AUTOCORRELATION OF LAG 1	2	3	4	5
1	82.	1.72	1.32	0.27	0.89	0.82	0.78	0.77	0.76
2	122.	0.41	0.32	0.27	0.92	0.88	0.85	0.78	0.75
3	249.	0.71	0.47	0.36	0.75	0.69	0.61	0.66	0.65
4	110.	1.27	0.73	0.25	0.84	0.82	0.80	0.77	0.70
5	91.	1.69	1.22	0.25	0.91	0.84	0.78	0.69	0.68
6	226.	0.57	0.51	0.25	0.89	0.82	0.76	0.69	0.66
7	178.	1.01	0.87	0.28	0.93	0.88	0.83	0.79	0.75
8	130.	1.28	0.87	0.30	0.82	0.82	0.84	0.78	0.76
9	158.	0.98	0.53	0.23	0.83	0.74	0.64	0.54	0.51
10	165.	0.50	0.19	0.20	0.78	0.76	0.67	0.66	0.59
11	181.	0.66	0.25	0.19	0.74	0.65	0.61	0.51	0.48
12	117.	0.93	0.26	0.19	0.63	0.63	0.55	0.45	0.48
13	179.	0.82	0.44	0.19	0.91	0.87	0.84	0.80	0.78
14	186.	0.52	0.36	0.37	0.80	0.75	0.68	0.60	0.54
15	147.	0.69	0.53	0.32	0.86	0.88	0.79	0.76	0.72
16	106.	1.44	0.94	0.26	0.83	0.75	0.60	0.52	0.50
17	179.	0.77	0.64	0.28	0.87	0.82	0.75	0.66	0.62
18	152.	0.50	0.44	0.27	0.84	0.43	0.40	0.36	0.35
19	139.	0.55	0.48	0.26	0.83	0.41	0.37	0.35	0.33
20	149.	0.60	0.53	0.28	0.90	0.85	0.76	0.69	0.65
21	169.	0.41	0.25	0.27	0.87	0.82	0.80	0.77	0.73
22	90.	0.67	0.78	0.30	0.93	0.89	0.82	0.75	0.69
23	112.	0.99	0.51	0.23	0.85	0.72	0.56	0.47	0.40
24	191.	0.72	0.66	0.38	0.79	0.59	0.39	0.23	0.13
25	127.	0.99	0.94	0.20	0.92	0.88	0.84	0.81	0.80
26	133.	0.77	0.47	0.26	0.85	0.80	0.76	0.72	0.69
27	101.	0.51	0.27	0.34	0.72	0.72	0.61	0.59	0.55
28	136.	0.50	0.27	0.35	0.67	0.62	0.54	0.48	0.45
29	135.	0.78	0.36	0.31	0.71	0.49	0.35	0.24	0.18
30	130.	0.91	0.76	0.26	0.91	0.86	0.81	0.79	0.81
31	141.	0.79	0.45	0.25	0.79	0.70	0.67	0.54	0.54
32	108.	0.82	0.56	0.30	0.83	0.72	0.58	0.49	0.45
33	101.	0.89	0.69	0.26	0.85	0.72	0.60	0.51	0.47
34	84.	0.78	0.54	0.33	0.84	0.70	0.60	0.50	0.40

heartwood in the latter samples pronounced the representation of wider rings of recent years. This conjecture is supported by the fact that shorter chronologies are almost always associated with large mean ring width and standard deviation, whereas the long chronologies are the other way around.

The mean sensitivity defined by and calculated according to

$$ms_x = \frac{1}{n-1}\sum^{n-1}\frac{2\ (x_{t+1}-x_t)}{x_{t+1}+x_t}$$

where x_t and x_{t+1} are two adjacent ring widths in a chronology of length n years, serves as a measure of magnitude in the year-to-year ring-width variation. As far as the calculated results are concerned, San Rafael *Podocarpus* showed higher sensitivity than Soler *Podocarpus* against the general dendroclimatological expectation that in response to a more fluctuating and limiting continental climate, trees growing under such conditions would show a higher sensitivity than those of the same species growing under wet oceanic conditions.

There are two possible causes of this apparent discrepancy. The first is possible failure to account for missing rings in the Soler samples. According to di Castri and Hajek (1976), the region including our Soler sampling site is classified as BSK (cooler dry Steppe) with the aridity index of de Martonne ranging from 8.89 (Chile Chico) to 33.08 (Balmaceda) which is the threshold for tree growth even at its moistest end. Our own experience and observations (Fukami *et al.*, 1987) suport this presumption. Thus it is very likely that in dry years when photosynthesis was inhibited by lack of moisture the little photosynthetic assimilates barely produced up in the foliage couldn't reach down to the lower portion of the stem where dendrochronological samples are usually taken, especially in such tall and old trees as our samples. Of course this results in lack of annual rings, the neglect of which will certainly lower the sensitivity as might well be the case in our present samples. The second possibility is incidental variability in ring-width sensitivity which may account for the present difference as a realization of random fluctuation.

4. Correlation with climatic variation and other external factors

Figure 2 shows the standard RWI reduced from the individual chronologies for San Rafael *Podocarpus* and Soler *Podocarpus*. The unusual increase in growth in the last few decades which has already been pointed out can be seen as a conspicuous hump even

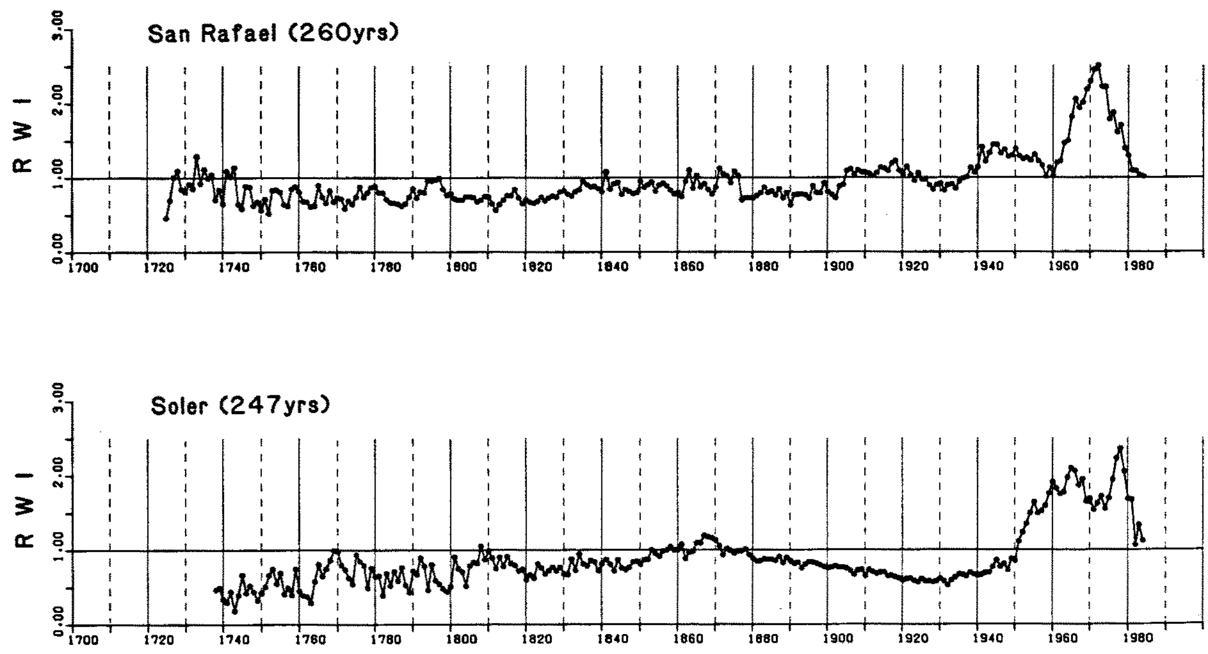

Fig. 2. Standard ring-width indices for San Rafael *Podocarpus* (above) and Soler *Podocarpus* (below).

after the moderating processes of standardization and averaging. The common appearance of such characteristic humps both in the San Rafael and Soler areas which are separated by the 65-km-wide Northern Patagonia Icefield across the 3,000-m-high Southern Andes indicates that it is not a local but rather trans-Andean phenomenon induced by a factor or combination of factors operating over an extensive geographical area, most possibly weather.

In Figs. 3 and 4, available annual precipitation and mean annual temperature for Puerto Aisen and Chile Chico are compared respectively with the standard RWIs for San Rafael *Podocarpus* and Soler *Podocarpus* truncated to the length of the available climatic records. Although the scantiness in climatic data, except Puerto Aisen precipitation, makes any detailed comparison difficult, neither the San Rafael nor Soler RWI showed any direct correlation with the corresponding temperature or precipitation, contrary to what was expected.

However, the direct correlation is not everything that can be expected between the tree growth and the climatic factors. Owing to trees' physiology, the effect of climatic variation on radial increment of trees may lag behind the operating weather by a year or two (Fritts, 1976). Figs. 3 and 4 indicate however that this too is not likely the case with temperature. On the other hand it seems that precipitation is more strongly correlated with RWI when time-lag is taken into consideration. Especially, a comparison between the San Rafael RWI and the longest-documented Puerto Aisen precipitation showed a certain correlation between them with the former lagging behind the latter by a decade or two. The conspicuous increasing trend in Puerto Aisen precipitation beginning in the mid-1940s, culminating in the late '50s

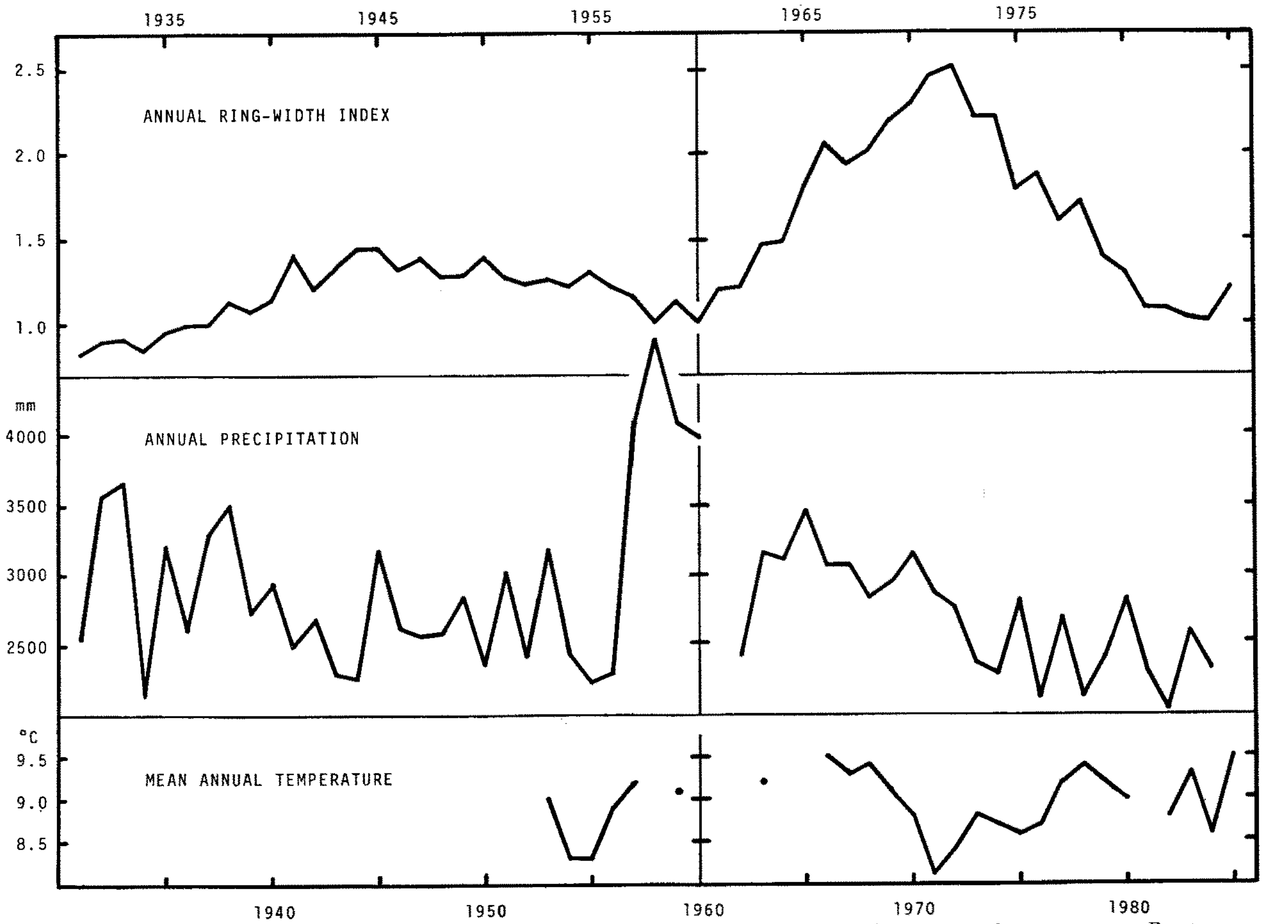

Fig. 3. Recent San Rafael ring-width indices as compared with annual precipitation and mean annual temperature at Puerto Aisén.

and declining toward the '60s, corresponded well with the similarly conspicuous rise and fall in the San Rafael RWI during the 1960s and '70s. Though less obvious, a similar correspondence was found between the gently declining precipitation through the '30s to the mid-'40s and the similarly decling RWI 15 years later. A visual comparison using remarkable peaks and troughs showed a lag of 15 years, whereas the correlation coefficient calculated at successive lags of 0 to 20 years culminated to 0.49 and 0.48 at respective lags of 8 and 12 years.

Such a long-lagging effect of precipitation can't be explained by the trees' physiology alone. The most probable alternative is the huge mass of the Icefield and the outlet glaciers which might have acted as an enomous reservior to cause the lagging effect of precipitation upon tree growth. With our present knowledge, however, it is neither possible to determine whether this lagged correlation between tree growth and precipitation is causal or just incidental.

A close examination of the conspicuous peaks at the end of the chronologies in Fig. 2 revealed minor

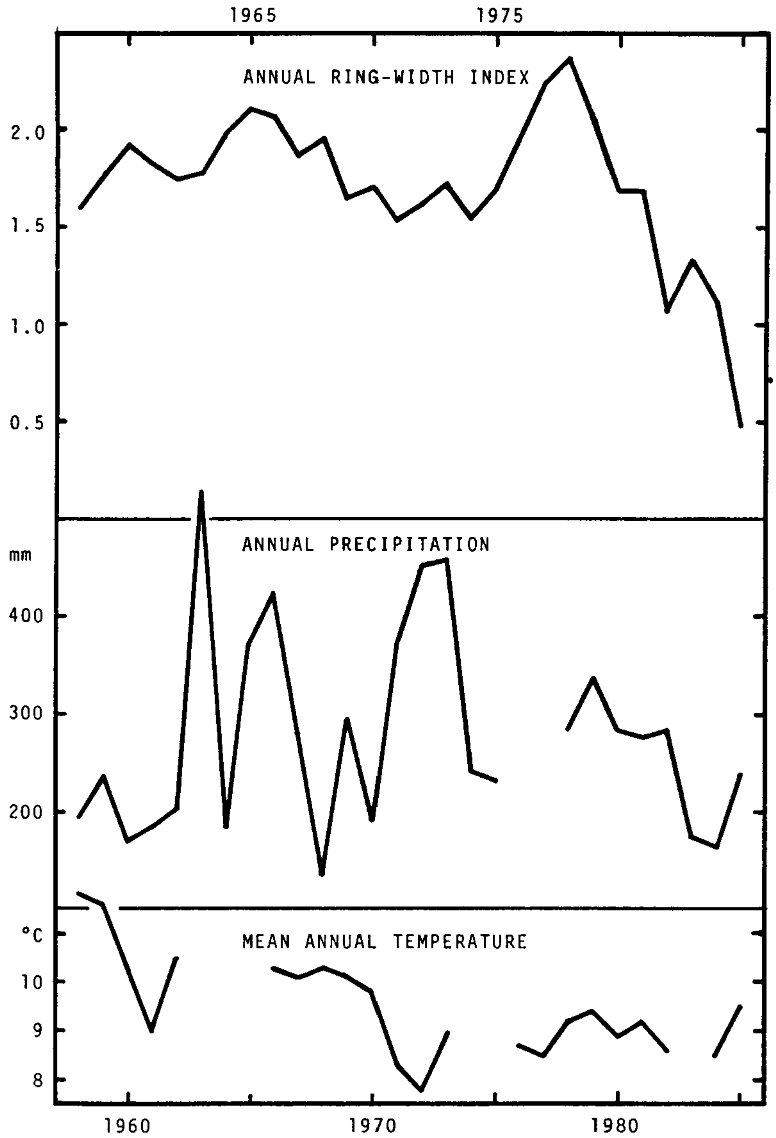

Fig. 4. Recent Soler ring-width indices as compared with annual precipitation and mean annual temperature at Chile Chico.

but definite differences between San Rafael *Podocarpus* and Soler *Podocarpus*. One of them was the bimodal peaks in the Soler *Podocarpus* which did not show in the San Rafael counterpart. This difference may be explained by differential fallout of volcanic ash from Mt. Hudson (45°54'S, 72°58'W) which erupted in the early 1970s (Guzman, 1981). The nourishing effect of volcanic ash is well established ; as a matter of fact, the yield of agricultural crop in the area around Coihaique, 90 km northeast of Mt. Hudson, increased significantly for some years following the eruption (Aguilera, personal communication). The Soler area, 100 km due south of Mt. Hudson and further leeward than the San Rafael area, was more likely to have benefitted from the falling ash.

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Resumen

Dendrocronología en la zona de los Glaciares San Rafael y Soler, Patagonia

Durante el verano austral de 1985-86 se recolectó muestras dendrocronológicas de testigos de incremento en diez localidades alrededor de los campos de hielo Patagónicos. En este trabajo se analizó las muestras de Podocarpus nubigemus de las zonas alrededor de los Glaciares San Rafael y Soler y se estableció sus respectivas dendrocronologías en los últimos 250 años. La característica más sobresaliente fue un singular aumento de crecimiento en las últimas décadas. La ocurrencia sincrónica de tal crecimiento en las zonas de los Glaciares San Rafael y Soler, separadas por alturas de 3.000 m de los Andes Patagónicos, indica que no se trata de un fenómeno local sino que más bien de un fenómeno global inducido por uno o varios factores climáticos. No se encontró ninguna correlación directa al comparar esta cronología con el registro climático de estaciones meteorológicas vecinas. Sin embargo, se encontró una correlación retardada del crecimiento arbóreo con respecto a la precipitación, siendo el desfase de 10 a 15 años.