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Contents lists available at ScienceDirect

## Dendrochronologia

journal homepage: [www.elsevier.de/dendro](http://www.elsevier.de/dendro)

## Detecting spatial connections within a dendrochronological network on Vancouver Island, British Columbia

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## ARTICLE INFO

## Keywords:

Spatial variance  
Dendrochronology  
Ring-width analysis  
Spatial autocorrelation  
Spatial-temporal pattern

## ABSTRACT

In dendrochronology, temporal patterns in radial growth are considered an expression of historical climate processes that cannot be measured. Dendrochronological networks, developed to characterize the geographical and temporal patterns of tree rings, have additional spatial information that can add to our understanding of historical climate conditions. This paper summarizes the use of spatial autocorrelation statistical tools for quantifying spatial trends in dendrochronological networks. Using this approach it is possible to characterize the spatial nature of the process influencing radial growth trends within a tree-ring network. Using a local or mapable measure of spatial autocorrelation it is possible to locate clusters of similar and extreme radial growth trends in any given year and to characterize the persistence of spatial patterns of growth through time. Applied to a dendrochronological network of yellow-cedar (*Chamaecyparis nootkatensis* (D. Don) Spach), our results suggest that spatial patterns in extreme growth are most often associated with growth limiting climate processes.

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### Introduction

A tree-ring chronology describes the radial growth trends of a forest at a particular location over a period of time (Schweingruber, 1996). The inherent annual tree-ring variability can be analysed to reveal the impact of climate on radial growth, a relationship that can then be examined to reconstruct past climate conditions and trends (Fritts, 1976). Given the range of climatic and non-climatic variables that can influence radial growth, however, the findings of these site-specific investigations can infrequently be extended to describe climate teleconnections over large distances (Gedalof and Smith, 2001). In order to overcome this constraint, dendrochronologists have assembled dense networks of tree-ring chronologies to characterize radial growth trends within broad geographical areas (e.g., Schweingruber et al., 1991). Although analyses of these dendrochronological networks have considerably expanded our insights into the regional patterns of pre-instrumental climate variability (Schweingruber et al., 1993; Briffa et al., 1994; Watson and Luckman, 2005), extracting the inherent dendroclimatic signal necessarily requires the application of spatial analysis (McKenzie et al., 2001).

A key assumption of dendroclimatology is that temporal patterns in radial growth are an expression of climate processes at a specific location. Temporal patterns of growth are indicators of historical processes that cannot be measured. Chronology networks also provide information on spatial patterns, or expressions of spatial processes, providing further information on unmeasured conditions. Together, the temporal and spatial patterns of chronology networks can build a more complete understanding of historical climate processes. Statistical examination of spatial patterns of radial growth provides a robust foundation for identifying any spatial variation over time (Fritts and Shao, 1992).

In spatial statistics, spatial patterns are considered the manifestation of a process or processes (Getis and Boots, 1978; Haining, 2003). By quantifying spatial patterns, we illuminate the nature of generating processes. A concept in spatial statistics that has particular utility for exploiting the unmeasured spatial information in dendrochronological networks is spatial autocorrelation. Spatial autocorrelation refers to the premise that all things are related, with near things more so than far (Tobler, 1970). Three types of spatial autocorrelation can be associated with dendrochronological networks. Positive spatial autocorrelation exists when nearby radial growth trends are similar. In annual relationships, positive spatial autocorrelation indicates that the dominant drivers of radial growth are homogenous over some region of the network. Negative spatial autocorrelation exists when near events are dissimilar and

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indicates site-specific processes influencing radial growth for a given location. The third type of spatial autocorrelation is the absence of a spatial trend, which indicates the dominated processes are aspatial or coarser than the network extent.

The purpose of this paper is to demonstrate how measures of spatial autocorrelation can be used to quantify spatial patterns in dendrochronology networks. We also give examples of how the additional information provided by spatial patterns of radial growth, can provide new evidence on historical processes. To facilitate this discussion, we introduce a measure of local spatial autocorrelation, local Moran's  $I$ , and apply it to a dense network of yellow-cedar (*C. nootkatensis* (D. Don) Spach) tree-ring chronologies.

### Background local Moran's $I$

Measures of spatial autocorrelation may be either global or local and are used to quantitatively evaluate the amount of spatial autocorrelation in a data set. Global measures of spatial autocorrelation generate one value for the entire study area, summarize average trends, and assume that the processes under study exhibit spatial stationarity (Anselin, 1995). When the aim is to investigate broad scale trends, global measures may be useful. Local measures quantify spatial autocorrelation at each data site within the study area and are more appropriate when data are non-stationary.

If the observed values  $x_i, i \in \{1, \dots, n\}$  of a random variable  $X$  are recorded at a set of  $n$  data sites, measures of spatial autocorrelation take the general form of a cross-product statistic

$$\Gamma_i = \sum_j w_{ij} y_{ij}, \quad (1)$$

where  $w_{ij}$  is a measure of the spatial relationships of data sites  $i$  and  $j$  at a given time and  $y_{ij}$  is a measure of their relationship in attribute space (Getis and Ord, 1992; Boots, 2002). Spatial relationships are typically defined by distance or spatial contiguity (Nelson and Boots, 2008).

Moran's  $I$  is a measure of spatial autocorrelation well suited to characterizing spatial pattern in dendrochronology networks and has both a global and local component. Global and local Moran's  $I$  characterize spatial autocorrelation in values that are extreme relative to the mean, thus emphasizes patterns associated with large and small radial growth (Getis and Ord, 1992; Anselin, 1995). Global Moran's  $I$  defines  $y_{ij}$  as  $(x_i - \bar{x})(x_j - \bar{x})$  and is given by

$$I = \left( \frac{n}{W} \right) \left( \frac{\sum_{i=1}^n \sum_{j=1}^n w_{ij} z_i z_j}{\sum_{i=1}^n z_i^2} \right), \quad (2)$$

where  $z_i = (x_i - \bar{x})$  and  $W = \sum_{i=1}^n \sum_{j=1}^n w_{ij}$ . Observed values of global Moran's  $I$  can be compared with expected values under the null hypotheses of no spatial autocorrelation. When  $n$  is less than 50 it is necessary to assess signification using randomization, as the assumption of normality is problematic (Boots, 2002).

Local Moran's  $I_i$  takes the form

$$I_i = \left( \frac{z_i}{(\sum_i z_i^2/n)} \right) \sum_j w_{ij} z_j, \quad (3)$$

where  $z_i = (x_i - \bar{x})$ . Positive values of Moran's  $I_i$  indicate positive spatial autocorrelation in values that are extreme relative to the mean. Negative Moran's  $I_i$  indicate negative spatial autocorrelation in values that are extreme relative to the mean. When Moran's  $I_i$  approaches zero it could be that there is no spatial autocorrelation, or that spatial autocorrelation is present but in values near the mean.

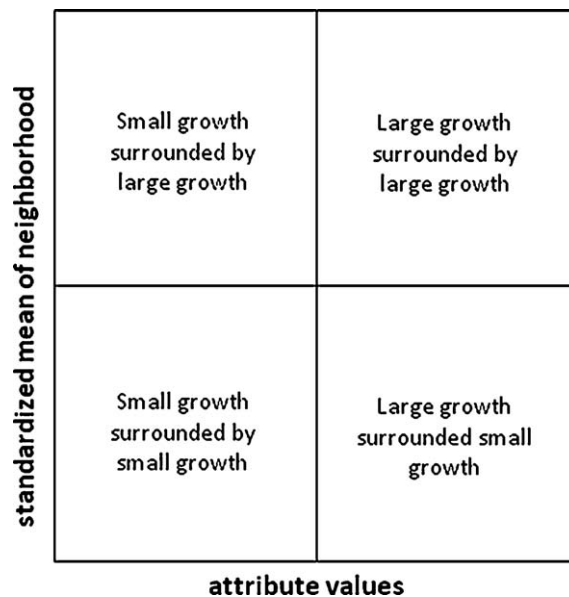


Fig. 1. Moran's scatterplot.

A Moran's scatterplot can be used to distinguish positive and negative spatial autocorrelation based on the attribute value of a location in relation to the attribute value of its neighbours and enables detection of clusters and outliers. On a Moran's scatterplot, the x-axis is the attribute value in deviation form and the y-axis is a standardized average of the neighbour values also in deviation form (Anselin, 1995). The upper right quadrant indicates chronology sites of large growth surrounded by other sites of large growth (large growth clusters), the upper left quadrant indicates chronology sites of small growth surrounded by sites of large growth (small growth outliers), the lower right quadrant indicates sites of large growth surrounded by sites of small growth (large growth outliers), and the lower left quadrant indicates sites of small growth surrounded by other sights of small growth (cluster of small growth) (Fig. 1). The Moran's scatterplot can be combined with statistical testing. Although the expected values of  $I_i$  can be derived under the hypothesis of no local spatial autocorrelation (Sokal et al., 1998), the distribution does not follow a known distribution (Boots and Tiefelsdorf, 2000), and so a randomization approach must be adopted for statistical testing (Table 1).

### Study sites

The dendrochronological data used for these analyses was derived from a tree-ring network established at high-elevation sites on Vancouver Island, British Columbia, Canada (47–52° North Latitude; 123–128° West Longitude; Fig. 2). Vancouver Island is 450 km long and 75 km wide and has relief that varies from sea

Table 1

Results of the number of significant sites for time periods where growth is above or below mean annual growth. Bold values indicate the null hypothesis of similarity in means was rejected using a one-tailed  $t$ -test and  $\alpha = 0.05$ .

Moran's I class	Mean number of significant chronology sites	
	Annual growth above mean	Annual growth below mean
Clusters of large growth	<b>1.650</b>	<b>2.084</b>
Clusters of small growth	<b>1.720</b>	<b>2.179</b>
Outliers of small growth	0.837	0.853
Outliers of large growth	0.880	0.811



**Fig. 2.** Vancouver Island, located along the southwestern coast of British Columbia, Canada between 47° and 52° North Latitude, 123° and 128° West Longitude.

level to 2200 m asl in the Vancouver Island Insular Mountain Range. On the west coast of Vancouver Island, prevailing westerly winds bring moisture-laden air masses onshore, creating climates that are cool and very wet. Moisture condenses out of these air masses as they reach further inland to the mountainous central portion of the island, where cooler air temperatures and deep seasonal snow packs are common (Hnytko, 1990). The northern reaches of Vancouver Island are characterized by cool and wet conditions, but a more gradual elevation gain diminishes the total amount of moisture received. On the eastern side of the island a rainshadow effect created by the central Vancouver Island Insular Mountain Range makes for drier localized conditions. The southeastern portion of Vancouver Island is the driest of all regions, largely due to the Insular Mountain rainshadow and a leeward rainshadow from the Olympic Mountains in nearby Washington State.

The tree-ring data set was constructed by sampling yellow-cedar trees located within the Vancouver Island Mountain Hemlock Zone (MHZ) (Klinka et al., 1991). These trees are growing at their ecological-tolerance limits, typically co-habiting upper-elevation areas with mountain hemlock (*Tsuga mertensiana* [Bong] Carr.) at treeline sites (Smith and Laroque, 1996, 1998a,b). The MHZ is commonly associated with severe climatic conditions and a short growing season (Klinka et al., 1991). The annual air temperature averages only 3 °C, with only 1.7 months of the year exhibiting a mean air temperature above 10 °C. Total annual precipitation in the MHZ averages 2620 mm, with 31% falling in the form of snow during the colder winter months (Klinka et al., 1991). The soil remains unfrozen throughout the year in nearly all areas of the MHZ due to the deep insulating snowpacks (Klinka et al., 1991).

The tree-ring network consists of 32 tree-ring chronologies collected at sites positioned along three east–west latitudinal transects that bisect a northwest–southeast longitudinal transect (Fig. 2). Sites along the east–west transects were selected to iden-

tify any orographic/rainshadow effects on radial growth that might be present along the length of Vancouver Island. Whenever possible, sampling occurred within open canopy stands of yellow-cedar trees located at the local upper-elevation limit of growth, usually at elevations between 1100 and 1400 m asl. (Laroque and Smith, 2003).

Climate–growth relationships for yellow-cedar indicate that about 60% of the annual variance in radial growth can be explained by reproducible climate parameters (Laroque and Smith, 1999, 2003). Three distinct temperature variables and three precipitation variables have consistently been shown to significantly influence radial growth of yellow-cedar (Laroque and Smith, 1999; Laroque, 2002). The radial growth of yellow-cedar trees responds positively to warm July air temperatures but negatively to excessive August heat in both the current and preceding year. Excessive precipitation in June of the growth year and in October of the preceding year results in small tree rings; whereas above normal precipitation totals in February of the growth year results in the production of larger than normal tree ring (Laroque, 1995; Laroque and Smith, 1999).

## Methods

At each sampling site two cores per tree were collected at dbh using an increment corer from a minimum of 20 yellow-cedar trees (minimum 40 cores per sample set). The cores were inserted into plastic straws and transported to the University of Victoria Tree-Ring Laboratory where they were allowed to air dry before being glued in slotted mounting boards. After being sanded to a fine polish, the annual-ring widths were measured using either WinDENDRO (Version 6.1b 1996; Guay et al., 1992) software or a Velmex-type stage with a 40× microscope.

Cores from each site were first visually cross-dated and then the ring-width data were checked for signal homogeneity using the International Tree Ring Data Bank program routine COFECHA (Holmes, 1983). The program ARSTAN (Cook, 1999) was used to detrend and standardize the tree-ring data. Standardization was used to eliminate variation in ring widths resulting from changes associated with age-related growth trends, exogenous disturbances (e.g. fire damage to a stand) or endogenous processes (e.g. gap-phase responses by an individual tree). A second detrending was undertaken to highlight the climate signal using a smoothing spline (Cook and Briffa, 1990). As yellow-cedar are found at the high-elevation at each site where little exogenous and endogenous disturbance occurs (e.g., fire, drought, human impacts) (Fowells, 1965), a conservative scaling spline was used (70% series cut-off length). Once all of the individual cores from a site were detrended, they were averaged into standardized tree-ring chronologies using program ARSTAN (Cook, 1999).

#### Quantifying spatial autocorrelation

Global Moran's  $I$  and local Moran's  $I_i$  were computed on annual-ring growth for each year from 1808 to 1994 for the entire yellow-cedar network. For both global and local measures, the null hypothesis that the spatial autocorrelation in the observed data is the result of a random process was tested using 999 permutations of the observed data ( $\alpha = 0.05$ ). Neighbourhoods are defined based on spatial contiguity. The Moran's scatterplot was used to categorize types of local spatial autocorrelation. Results of global spatial analysis were investigated for trends relating to annual average growth. Years with no significant Moran's  $I$  were partitioned from those with significant Moran's  $I$  and average growth for each category compared using a one-tailed  $t$ -test ( $\alpha = 0.05$ ).

Local Moran's  $I_i$  results were assessed for spatial and temporal trends. We mapped locations with the greatest number of years exhibiting non-random spatial patterns (clusters and outliers). One map was generated for each of the Moran's scatterplot categories. There were natural breaks in the frequency distribution of years with outliers; four locations had greater numbers of outlier years. No natural breaks were apparent in the frequency distribution of years with clustering. The five most frequently clustered locations were the same for clusters of large and small growth. We mapped the six sites with the greatest number of years exhibiting clustering, as for both clusters of large and small growth two sites ranked fifth in the number of years with significant patterns.

Temporally, we assessed the relationship between the number of chronology sites with significant local spatial pattern and annual growth. Data were partitioned based on years where annual growth was above or below the mean growth for all years. For years of growth above and below the mean, we compared the number of chronology sites having significant patterns. Comparisons were conducted for each of the four Moran's scatterplot patterns. A map of the year with the strongest spatial trends, defined as the largest number of chronology sites with non-random patterns, was generated.

## Results

#### Dendrochronological network

The yellow-cedar chronologies collected at the 32 sites on Vancouver Island span the interval from 1145 to 1997 A.D. (Laroque, 2002). The chronologies have a mean series correlation of 0.443, a mean sensitivity of 0.253, a mean series autocorrelation value of 0.764, and yielded strong EPS statistics when 29 or more series

made up each chronology. The 32 chronologies share a common interval from 1808 to 1994 A.D., and this 186-year period was selected as representative of the spatial and temporal patterns of short- and long-term yellow-cedar radial growth variability at high-elevation on Vancouver Island.

#### Spatial analysis

Global Moran's  $I$  was significant in 62 years; 58 years had significant positive spatial autocorrelation in extreme values and four years had significant negative spatial autocorrelation in extreme values. One hundred and twenty-five years had no significant spatial autocorrelation in extreme values. The average annual growth associated with the 62 years exhibiting significant spatial autocorrelation was lower (0.923) than the average annual growth associated with non-significant years (0.968). A one-tailed  $t$ -test rejected null hypothesis of similar means in annual growth ( $t = 1.821$ ,  $\alpha = 0.05$ ).

Every chronology site had significant spatial autocorrelation in extreme growth in at least one time period and all were outliers and part of clusters in at least one year. In general, clustering was the more common spatial pattern of growth. The San Juan Ridge site, the most southern chronology, had the fewest number of years of significant spatial autocorrelation (5 out of 187), where as Mount Menzies, on the far east mid island, had the greatest number of years with significant spatial pattern (70 out of 187). In Fig. 3, we show locations where significant clustering, positive spatial autocorrelation in extreme large and small growth, and outliers, negative spatial autocorrelation in extreme large and small growth, occur most frequently. The four sites that most commonly associated with large growth outliers include Mrs. Wade Mountain, Mt. Menzies, Silver Spoon Saddle, and T-A-D Ridge. The four sites that most commonly associate with small growth outliers include Mt. Menzies, Hanging Valley, Mt. Apps and Heather Mountain. The five locations most frequently associated with clustering are the same for both large and small growth. These include Colonial Creek, Bulldog Ridge, and Castle Mountain, in the north, and Lupine Mountain and Mt. Washington, on the mid Island.

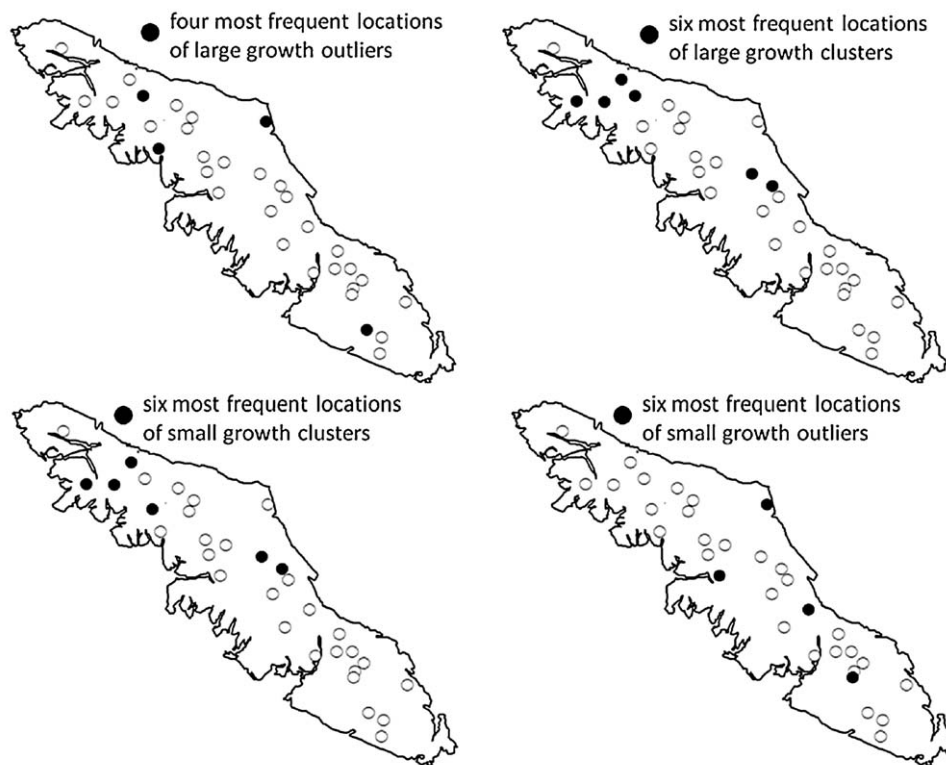
Mrs. Wade Mountain and Apple Tree Hill are tied with the sites having the fifth greatest number of years with clustering in large and small growth clusters respectively.

Comparing the spatial pattern of growth for years with above and below average growth indicates that there are stronger spatial relationships in years with low growth. The mean number of sites exhibiting clusters of large and small growth are greater when average growth is small and differences are statistically different (large clusters  $t = 1.694$ ,  $\alpha = 0.05$ ; small clusters  $t = 1.685$ ,  $\alpha = 0.05$ ). Difference in mean number of sites found to be outliers is not statistically different for years with above and below average growth.

The year with the strongest spatial trends, or the largest number of sites with significant spatial autocorrelation, is 1916 (Fig. 4). The next two strongest spatial trend years include 1929 and 1930.

## Discussion

Dendrochronology relies on the assumption that temporal patterns of growth are indicative of past climate conditions and processes. It follows, that dendrochronological networks which exhibit spatial patterns provide additional information on historical climate processes. We demonstrate use of spatial pattern measures, global and local Moran's  $I$ , for quantifying spatial dependence and explore trends associated with different levels of spatial pattern.



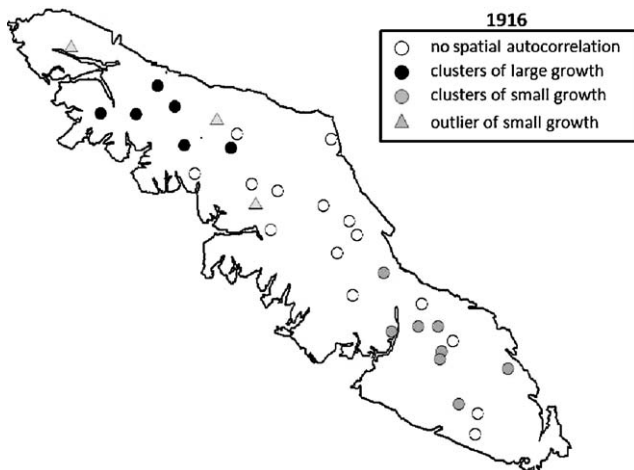
**Fig. 3.** From 1808 to 1994 the locations with the greatest number of large growth outliers, large growth clusters, small growth outliers, and small growth clusters (clockwise).

Our results indicate that processes associated with small annual growth may be more spatial than processes associated with large annual growth. Smaller growth is associated with years where global positive or negative spatial autocorrelation is observed. As well, spatially local analysis indicates that when annual growth is below the average growth of all years, a greater number of sites tend to exhibit spatial clustering. The spatial trends associated with small growth are further highlighted by individual years where many sites had significant spatial patterns. 1916, 1929, and 1930 had the strongest spatial trends. Climate records for Vancouver Island (1896–1994) indicate that in these years, annual temperature and precipitation were lower than average. 1929 was the year

with the lowest annual precipitation and 1930 had the sixth lowest annual precipitation. The second lowest temperature occurred in 1916. For yellow-cedar, strong spatial patterns in extreme growth are associated with limited growth due to either precipitation or temperature. Yellow-cedar is a generalist (D'Amore and Hennon, 2006), and for species that have more specific requirements spatial patterns may be more strongly linked to explicit climate limiting processes.

Assessing temporal trends in local spatial patterns reveals that clustering of extreme large or small growth tends to occur in two regions, near the north and mid-east sections of Vancouver Island (Fig. 4). In these two regions extreme processes tend to be more consistent than in other locations. The north region has the lowest precipitation and coolest temperatures on Vancouver Island. Detection of spatial patterns in the north provides confidence that these methods are identifying spatial patterns associated with extreme growth within the study area. The mid-east island sites often associated with clustering (Lupine Mountain and Mt. Washington) are surrounded by sites of similar elevation (1300–1400 m). These sites may be operating in similar ways due to topographic effects. In contrast, Mt. Menzies, which is often an outlier, is situated at lower elevations (970 m) than nearby sites. There may be benefit to further normalizing for topography, prior to quantifying spatial patterns in growth.

In dendrochronology recent temporal records are often used to calibrate relationships between growth and climate. A similar approach is difficult for dendrochronological networks, as even in present day, spatially dense weather stations are rare. In cases where there is a spatially dense network of weather stations, there are substantive opportunities to relate spatial patterns of annual growth for dendrochronology sites to spatial data. Quantifying the presence or absence of significant spatial pattern in combination with information on spatial scale of patterns is a first step towards



**Fig. 4.** Local Moran's  $I_i$  results for 1916, the year with the greatest number of sites having significant spatial autocorrelation.

using the spatial information inherent in networks to better understand historical climate processes.

## Conclusion

It has long been appreciated that the radial growth of high-elevation trees varies temporally in response to local and regional limiting growth conditions. The additional information available following the spatial analysis of a dendrochronological network provides for an expanded appreciation for any spatial patterns within these parameters within a given year. As dendrochronological networks increase in areal extent, the role that the limiting climate process plays would be expected to vary spatially. Using measures of spatial autocorrelation, we can characterize general trends in the spatial expression of climate and identify location where growth is homogeneous (clusters) or heterogeneous (outliers).

Like the temporal growth patterns used in dendroclimatology to reconstruct proxy records of climate, recognition of the spatial tendencies inherent within tree-ring networks provides an opportunity to quantify the temporal–spatial nature of the climate processes that limit tree-ring growth. By quantifying the spatial pattern of annual-ring growth in a tree-ring network several new questions can be answered. For instance, was the dominant limiting growth process(es) spatial? If so, regionally, was the spatial scale of influence fine or coarse? Within a region, where are the spatial processes homogenous and how does the spatial scale of dominant processes vary over the landscape? Finally, by tracking trends in spatially autocorrelated patterns through time, dendrochronological sites that are sensitive to variability in the spatial component of radial growth processes can also be determined.

This paper was intended to provide an introduction to the value of undertaking a quantitative spatial pattern analysis of tree ring data retained within dendrochronological networks. By demonstrating how measures of spatial autocorrelation can be implemented and interpreted, we set the stage for further research in this arena. We will continue exploring the use of spatial statistics and dendrochronological networks for addressing the spatial component of other phenomena (e.g., Pacific Decadal Oscillation). As well, we are interested in exploring the application of spatial statistics to networks of non-standard dendrochronological measures such as the coefficient of variation in annual tree-ring growth.

## Acknowledgements

Our research was supported by individual grants from the Natural Sciences and Engineering Research Council of Canada (NSERC) to Nelson, Laroque, and Smith. Funding for creation of the tree-ring network was granted by Forest Renewal BC to Smith. We wish to thank Carson Farmer and Jed Long for assistance with the accompanying figures.

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