Vegetational Responses to Natural and Anthropogenic Change in the St. Clair River Delta

W.R. Skinner

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A Manuscript Report Prepared for the
Canadian Environmental Assessment
Research Council
March 1986

MRS-86

VEGETATIONAL RESPONSES TO NATURAL AND ANTHROPOGENIC CHANGE IN THE ST. CLAIR RIVER DELTA

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The analysis of annual growth-rings of trees in the St. Clair River delta provides an opportunity to study past vegetational responses to natural and anthropogenic environmental change. The knowledge gained from this study will aid in the prediction of future changes as prediction requires a thorough knowledge of past changes coupled with an understanding of the processes which are responsible for such changes.

The factors which influence tree growth can be subdivided into two categories: the physical environment and the physical environment altered by human influences. Climate is the most important process of the physical environment. To conduct this study, standardized tree-ring chronologies were calibrated with regional climatic records. Tree-ring chronologies which did not correlate well with climatic records or which displayed a changing relationship to the same climatic variables over time indicated that non-climatic factors were affecting growth.

In the period after 1945, trees in the St. Clair River delta displayed a reduction in the sensitivity of growth to climate. A number of possible explanations were tested for their significance. Climate has not changed enough to alter the tree growth-climate relationship. The rise in lake levels may have been partially responsible for the decreased sensitivity. The age distribution of the sampled trees did not appear to provide any distinct climatically related information. The final hypothesis advanced by the author is that air pollution, by itself or in combination with other factors, is responsible for the changed relationship of tree growth to climate.

CONTENTS

1. INTRODUCTION

The analysis of annual growth-rings of trees from selected site5 in the St. Clair River delta provides a unique opportunity to study the vegetational responses which have occurred in the past due to natural environmental change and to human influences on both local and regional scales. The natural vegetation of Walpole Island, which is situated in the eastern portion of the delta, consists of a rare and relatively large Carolinian forest. It is presently being managed through an on-going program in conjunction with the University of Windsor, but has been preserved in its natural setting. Future energy supplies from the forest biomass offer a realistic alternative energy source to the people of the Island. Tree-ring samples, representing up to 90 year5 in growth, provide an uninterrupted proxy record of past vegetational response5 to both natural and anthropogenic environmental change. In order to speculate on future changes, there must exist a thorough knowledge of those changes which have occurred in the past, coupled with an understanding of those processes which are responsible for such changes.

The analysis of all factors that influence tree growth can be subdivided into two interrelated categories; the physical environment and the physical environment altered by human influences. Climate represents the most important process behind the physical environment,, The variable growth of natural vegetation can be directly related to variations in regimes of temperature and precipitation (Fritts,1976). In addition, fluctuations in river, lake and groundwater level5 can be directly related to both variation5 in climate and to the human occupancy of the land. The past one hundred years spans a period of both extremely high, and low, lake and thus river and groundwater levels. It also includes the recent construction of the St. Lawrence Seaway which has resulted in the wholesale modification of river channels. Standardized tree-ring chronologies can be calibrated with regional climatic records. Tree-ring chronologies that do not correlate well with climatic records or display a changing relationship to the same climatic variables over time indicate that non-climatic factors are affecting growth (Ashby and Fritts,1972;Puckett, 1982). Such information can have both local and regional significance.

A detailed reconstruction of changing environmental conditions can provide both locally and regionally significant information. Information pertaining to the changing nature of the physical environment on the local natural vegetation can be derived. In addition? an improvement in the understanding of even local environmental change could provide practical input into future environmental impact statements. On the other hand, it can also yield information on a much broader scale. Walpole Island is located in the centre of a large agricultural and industrial complex, situated on the eastern shores of Lake St. Clair opposite the large industrial metropolitan complexes of Detroit, Michigan and Windsor, Ontario. It represents an important location with respect to changing environmental conditions. Such a reconstruction could eventually be incorporated into a regionally based estimate of the frequencies and geographiic extent of both human and climatic modes.

2. THEORETICAL CONSIDERATIONS

The basic hypothetical structure of this investigation is based upon previous studies in dendroclimatology. The initial hypothesis states that inferences ran be drawn about past local and regional environmental conditions through the analysis of the annual growth-rings of trees from Walpale Island in the St. Clair River delta. A secondary hypotheesis states that subsequent inferences can be drawn from the manner in which the growth of the local natural vegetation is related ta climatic variables. A low level in this relationship or a changing relationship over time suggests that non-climatic factors are affecting growth. Since the main objective of dendro-climatology is to statistically describe past climate by analyzing the structure of the annual growth-rings of trees, the general approach, or rationale, of that discipline will is adhered ta in this investigation. This general rationale is to express the nature of a complex system in such a manner that it may be subjected to hypothesis testing and conceptual development. It thus becomes necessary ta simplify the system and ta describe it with the use of a model or a series of models. The internal workings of the system can then be visualized as a process-network model where there is a network of linkages between states in the climate-plant system.

It is best to begin with a general and flexible a priori model and then ta proceed ta apply statistics in a posteriori manner with the intention of shaping the a priori model to the specific annual tree-ring responses (Fritts, 1976). A good a priori model should describe the important relationships between climate and ring-widths. The most important plant processes which affect ring-width growth are light, temperature, water, atmospheric components and physiological factors which affect photosynthesis and respiration. The most important site factors which can alter the energy and water balances of a tree and thus affect ring-width are topography, soils, elevation and orographic factors. Careful sampling and site selection can reduce the influence of the site factors. However, many of the factors which limit the plant processes can be linked to climatic conditions through the energy and water balances. All of these factors which provide linkages between climatic factors and ring-width are part of a complex and interrelated ecological system. Because of the extreme difficulties in modelling the specific biochemical reactions and the physical linkages in the system it has become more practical to generalize the processes by stressing the major pathways in the system (Fritts, 1976). This includes the range but not all the possible physiological components. However, these general i-zations should be consistent with the experimental evidence into both biochemical and physiological processes

Figure (1)shows how the climate of a given year t affects ring-widths for the same year as well as subsequent years t+1 to t+k. Here the response to climate can be seen to lag 1 to k years behind the occurrence of climate. The effects of heat, wind, carbon dioxide and water can be seen on ring-widths in year t and also in years t+l to t+k through the effects on buds, sugar , hormones and the growth of leaves, roots and fruits,, The diagram also shows that because of these year to year linkages the width of the ring in year t-i is statistically related to the ring-width in year t,t+1 up to year t+k. This effect is modelled as autocorrelation in ring width.

FIGURE (1). The climatic influences of heat, wind, carbon dioxide and water in a given year (t) have a large effect on ring-width for the same year and also can have an effect on ring-width in the following years (t+1) up to (t+k) through effects on buds, sugar, hormones and the growth of leaves, roots and fruits. The width of the ring in year (t-1) is statistically related to the ring-width in year (t). This effect is modelled as autocorrelation in ring-width.

Source: Fritts, 1976, p. 26.

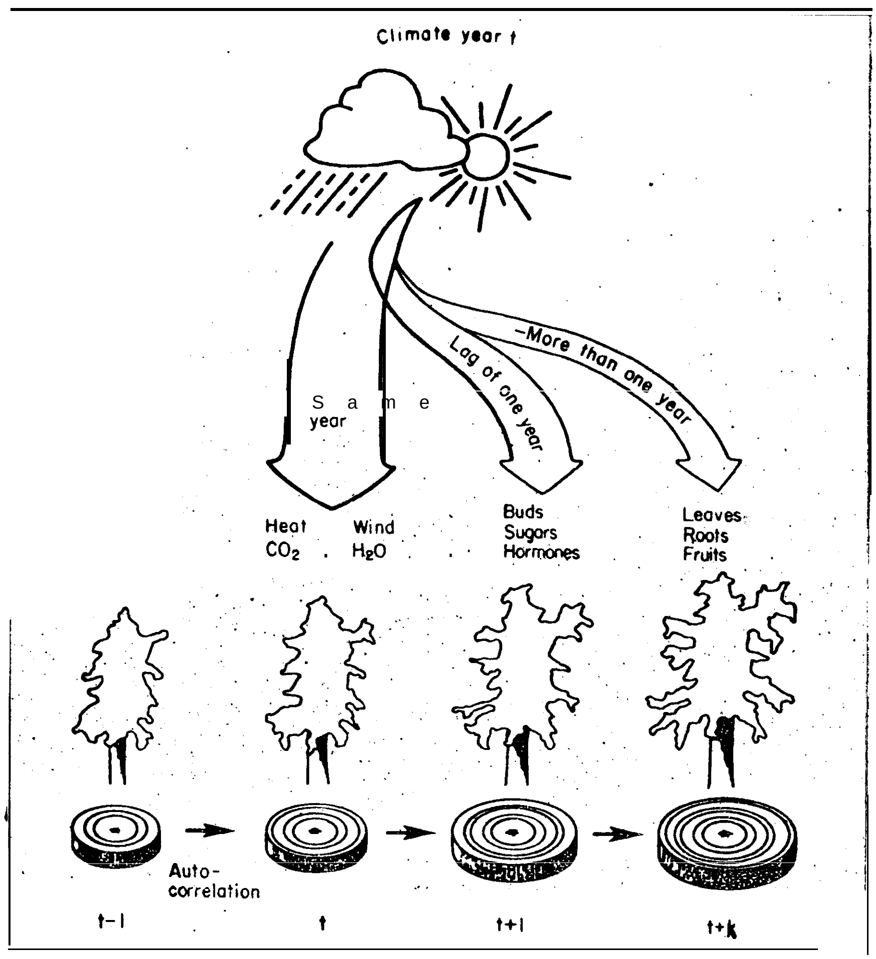
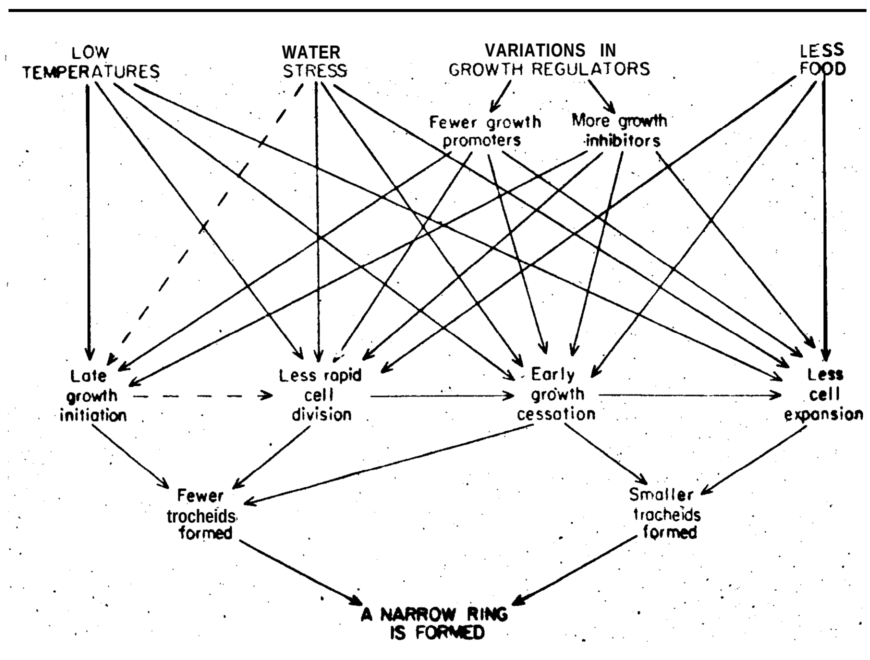


Figure (2) describes the four major factors causing a reduction in the sire of an annual ring-width. Cause and effect are indicated by the arrows which include various types of interrelations among the processes and variables. Here it is implied that if the temperature and precipitation conditions were opposite then the ring-width would increase. The four major limiting conditions which are depicted are the temperature of the growing tissues, water stress in the tissue, concentrations of growth regulators and the amounts of building materials which includes both foods and mineral salts. If a limiting situation occurs in any one of these factors the rates of cell division and expansion and the start and end of the actively growing period will be altered. Consequently, the number and size of the tracheids that are produced and thus the ring-width will be affected. This model shows the direct relationship of temperature and ring-width. It also implies the indirect relationships between ring-width and precipitation, humidity, temperature, wind and light when dealing with water stress. In addition, the limitation of stored foods, which eventually become building materials, is quite dependent on a number of climatically related processes such as photo-synthesis, respiration, food manufacture and assimilation of carbon dioxide.

Initially, in research such as this, the hypotheses to be tested may involve the model itself . This incorporates the identification of all variables which are part of the model but are not relevant to it and searching for variables that should be included in the model but have been omitted. It also includes the identification of any inaccuracies that might be present in the model, any feasible alternatives to the model structure and the awareness of any constraints that may be incorrectly formulated. The model should then become more and more useful for the testing of inferences

FIGURE (2). A model describing the four major factors causing a reduction in size of an annual ring-width. The arrows indicate cause and effect and include various among the processes and variables. This figure implies that an increase in ring-width will occur due to an effect of the opposite extreme.

Source: Fritts, 1976, p. 227.



and **hypotheses about the system. The** effects of unusual conditions and situations, such as **elevated** levels of atmospheric pollution, can then be better understood and anticipated.

The connection between tree-growth **and** climate is best visualized as a process-network system with different variables entering into the relationship. There are numerous variations in 1 imiting factors. Thus, the most appropriate approach is to priori

ofgrowth, then proceed

of statistical tec order ques in

impor.tan t

3. **LITERATURE REVIEW AND STATUS OF RESEARCH**

The science of dendrochronology, or tree-ring analysis, is based upon the annual ofgtreesw Dendroclimatology is a branch of dendrochronology science of reconstructing past c

of tree-rTreegrsing. chranalagies have a very precise time resolution because they can be dated to the exact year in which an expected change in cl imate ocurred. In general, a new growth-ring is formed ea width of of variaus limiting factors. Ri

to become narrower as the tree becomes older. In addition to this normal

luences.For of **years**

North s u c h

American southwest and at alpine and sub-alpine sites. In subhumid temperate regions, such as the Great Lakes area, ring-widths are related ta a complex interaction of precipitation, temperature and other variables (Fritts,1976).

In dealing with 1000 to 8000 year records from bristlecone pines from the southwestern United States, La Marche(1974) summarized the state of research in which tree-rings have been used to estimate past climates. His concern was based on the exclusive use of one single variable, the width of the annual ring. Interest had been focussed on the departure of the mean value from the norm which was calculated by simple averaging of ring-widths or ring-width indices. There had, until that time, been little use made of other statistics besides the mean value. He called for more research into the study of variations of ring-width statistics through time, the investigation of the physical and chemical properties of wood and the combined multivariate analysis of data for a number of climatic indicators.

Fritts (1976) outlines the current status of the inter-disciplinary field of dendroclimatology. He presents a compilation of the new approaches developed at the University of Arizona. The subject matter is presented in a series of graded chapters beginning with the basic biological facts and principles of tree growth followed by the development of important quantitative methods then by examples of past climatic reconstructions. He presents the most widely used and basic principles and concepts in the field of dendroclimatology;

(1) The uniformitarian principle states that the same biological and physical processes which cause variations in tree growth today must have been in operation in the past. When applied to climate it becomes necessary that the

entire range of past climatic variability be included in the present-day environmental sampling.

(2) The principle of limiting factors states that a biological process cannot proceed at a faster rate than is allowed by the most limating factor. In dendroclimatology, this principle implies that narrower growth-rings provide the most precise information on limiting climatic conditions. A series of wide growth-rings indicates the influence of a wide variety of non-climatic factors.

(3) The concept of ecological amplitude states that, depending on hereditary factors which determine phenotype, each species may reproduce and grow only over a certain range of habitats. Climate of ten becomes limiting to the physiological processes of species growing near the margins of their natural range.

(4) In order to obtain the best possible information, the law of limiting factors and the concept of ecological amplitude must be applied when dealing with site selection. The sampling design is deliberately stratified in order to obtain the maximum amount of information from the population of ring-widths. Also, in order to retain a more or less constant genetic response, the sampling design is restricted to one or two particular species.

(5) A tree which exhibits a high degree of variability in ring-width has a high sensitivity while one which has a lack of ring variability exhibits complacency. A sensitive chronology is thus more desired for it exhibits the law of limiting factors.

(6) The most important principle of dendroclimatology is crossdating. All annual ring-widths must be crossdated among all radii within a given stem, among selected trees within a given stand. The year in which each ring was formed can be correctly determined if there is ample covariation among rings

in **different trees and the sample** is large enough. The mere fact that crossdating is obtainable is evidence that there is some environmental or climatic information common to the sampled trees. Crossdating includes the matching of ring-width patterns among specimens; observing the synchrony among specimens; noticing any lack of coincidences; determining where rings may be absent , false or improperly observed **and** testing this by carefully examining the ring structure in other specimins; and ultimately arriving at a correct regional chronology which is in agreement with the growth sequences observed in trees in nearby stands.

(7) There must also be repetition or replication in sampling. This applies to sampling more than one stem radius per tree as well as from more than one tree. This allows for statistical comparisons of variability within the same tree as well as between trees and between groups of trees. If climate is limiting to growth then the same ring-width variations will be evident in the samples and the rings will be easy to crossdate. If climate is not highly limiting then there may be distinct differences in ring-widths between trees and possibly even differences in growth on two sides of the same tree,, Here a larger sample size would be necessary in order to obtain a reliable ctironology.

(8) The procedure of standardisation is basic to dendroclimatology. Systemmatic **changes** in ring-width that are associated with age are removed from the measurements and the transformed values are called ring-width indices. Indices generally have no linear trend, with a mean value of one,, The large variability in rings-width of young fast-grawing portions of a tree are comparable to the lower variability in the ring-width of the older and slower-growing portion5 of the tree. Standardized indices from individual trees are then averaged to derive a mean chronology for a sampled site.

(9) Models of growth-environment relationships are based upon some idea of how the environment affects growth. Various types of models can serve as hypotheses which can be checked by comparison with information obtained from observation. A mathematical or statistical model describing tree growth serves as a linkage between the inputs and outputs of the system. Models must often be revised when new information contradicts the model relationships. When there is a close resemblence with actual relationships, the model may be accepted as the most suitable inference.

(10) The ultimate principles in dendroclimatology are those of calibration and verification. Ring-width units can be calibrated with units of environmental variables by constructing a statistical model which resembles the actual relationships, then determining the values of the model coefficients then applying the coefficients ta indices from a period prior to the record of past environments. If the relationships are correlated then it becomes necessary to save some of the environmental data for use as an environmental check. The comparison of reconstructions with actual environmental data is necessary in order to verify the accuracy of the estimate,

A small number of researchers have since applied the principles, concepts and methodologies of Fritts (1976). Fritts, Lofgren and Garden (1979) have calibrated spatial anomalies of western North American tree-ring records with spatial anomalies in North American meteorological records. They have developed multivariate transfer functions to scale and convert spatial variations in tree-ring records since the early 17th century into estimates of past variations of seasonal temperature, precipitation and sea-level pressure over the North American and North Pacific sectors,, Stockton and Fritts (1973) have reconstructed long-term water level changes for Lake Athabasca through an analysis of white spruce tree-rings growing on natural levees of the channels of the delta region of the lake. The 33 year record of lake level changes was found to correlate well with water levels in the channels. The record of lake levels was extended to 158 years for late May, early July and late September.

Jacoby, Cook and Ulan(1985) have reconstruted June and July degree-days in central Alaska and northwestern Canada from 1524. Their samples were taken from the long-lived white spruce species, a species which often exhibits temperature sensitive ring-width variations.

Fritts(1962), Schulman and Bryson(1965) and Estes(1970) have shown the growth of oak trees in the midwest to be affected by climatic variables. Ashby and Fritts(1972) employed principal components analysis and stepwise multiple regression analysis to determine the relationship of white oak growth to climate in northern Illinois-Indiana,, Monthly temperature and precipitation variables were found to account for 59% of the growth variance in the 55 year ring-width chronology while prior growth accounted for an additional 2% . Their study indicated that some factor in the LaPorte area became increasingly more limiting to tree growth during the 1940's. They state that the reduction in growth may have been related to high levels of smoke haze reported in Chicago during that decade and not necessarily the precipitation anomaly at LaPorte.

Terasmae(1975)summarized the methods used in tree-ring research and their significance in current attempts to resolve the food supply, water resource and energy problems of mankind. He stressed the close relationships between climate, tree-rings and changes in our natural environment.

Duvick and Blasing (1981) sampled white oak trees from three sites in central Iowa and found the ring-width indices to be good indicators of precipitation over a 300 year period. They found that individual growth-rings were strongly influenced by precipitation over a period of about one year prior to the stoppage in radial growth. This period began in July or August of one year and extended to the next June or July. Stockton and Meko (1983) have, through tree-ring analysis, reconstructed a history of drought from 1700 to present in four regions flanking the Great Plains; Iowa, Oklahoma, Eastern Montana and eastern Wyoming.

In a more humid environment, Cook and Jacoby (1977) have shown the relationship between tree-ring indices and a drought index in the Hudson Valley, New York while Cook and Jacoby (1983) have reconstructed Potomac River streamflow by using tree-ring chronologies from sites in or near the river basin. Each of these investigations used the same general principles, concepts and methodologies as outlined by Fritts (1976).

La Marche et al. (1984) have considered the possibility of accelerated natural vegetation growth due to increased atmospheric carbon dioxide concentrations. They feel they may have detected this in the annual growth-rings of subalpine conifers growing in the western United States. They have observed greatly increased tree growth since the mid-19th century to be consistent in magnitude with increases in global carbon dioxide, especially in recent decades. Also, laboratory experiments have shown that carbon dioxide can be an important limiting factor in the growth of plants.

Puckett (1982) utilized tree-ring indices from white pine, eastern hemlock, pitch pine and chestnut oak in order to determine the relationship of tree growth to climate in southeastern New York state. Changes in the derived relationship through three specified time intervals corresponded with suspected increases in acid rain and air pollution in the area in the early 1950's. He suggested that the change might be the result of physiological stress due to increased pollutants which in turn cause climatic conditions to be more limiting to tree growth.

Phipps (1982) and Cook, Conkey and Phipps (1982) present disussions dealing with the problems in developing climatically sensitive tree-ring chronologies from eastern North America. Problems with site and species selection are discussed as well as the problems involved in the removal of growth and competition trends through standardisation of individual chronologies and merging of several chronologies, respectively. Because tree-ring collections from eastern forests are not as sensitive as those from western collections they conclude that the greatest potentiel for dendroclimatological studies in eastern deciduous forests lies in the better resolution of local climatic conditions, in estimating hydrologic variables such as streamflow and in examining climatically related variables such as air pollution and arid rain.

The analysis of tree rings from the St. Clair River delta offers a unique opportunity to fill some gaps in the present knowledge of both local and regional environmental change. While the actual span of chronologies is not much longer than the regional climatic record, information derived from such an analysis could prove to be valuable in many respects. There is no documented history of the responses of natural vegetation to either natural or human change in this entire area. Finally, derived changes in microclimatic and mesoclimatic regimes can be incorporated into both local and regional models of climatic change.

4. STUDY AREA

The St. Clair River delta is situated in the centre of a large agricultural and industrial complex and represents an important location with respect to changing local and regional environmental conditions. The rare and naturally preserved Carolinian forest of Walpole Island, located in the eastern portion of the delta, has been designated as a portion of an environmentally sensitive area. It has also been targeted as a realistic alternative energy source to the people of the Island. The forest should thus serve as an indicator of past local and regional environmental conditions. A more thorough knowledge of human-forest-climate interactions would improve conservation and management techniques aimed at maximizing the economic, social, aesthetic and ecological value of the resource.

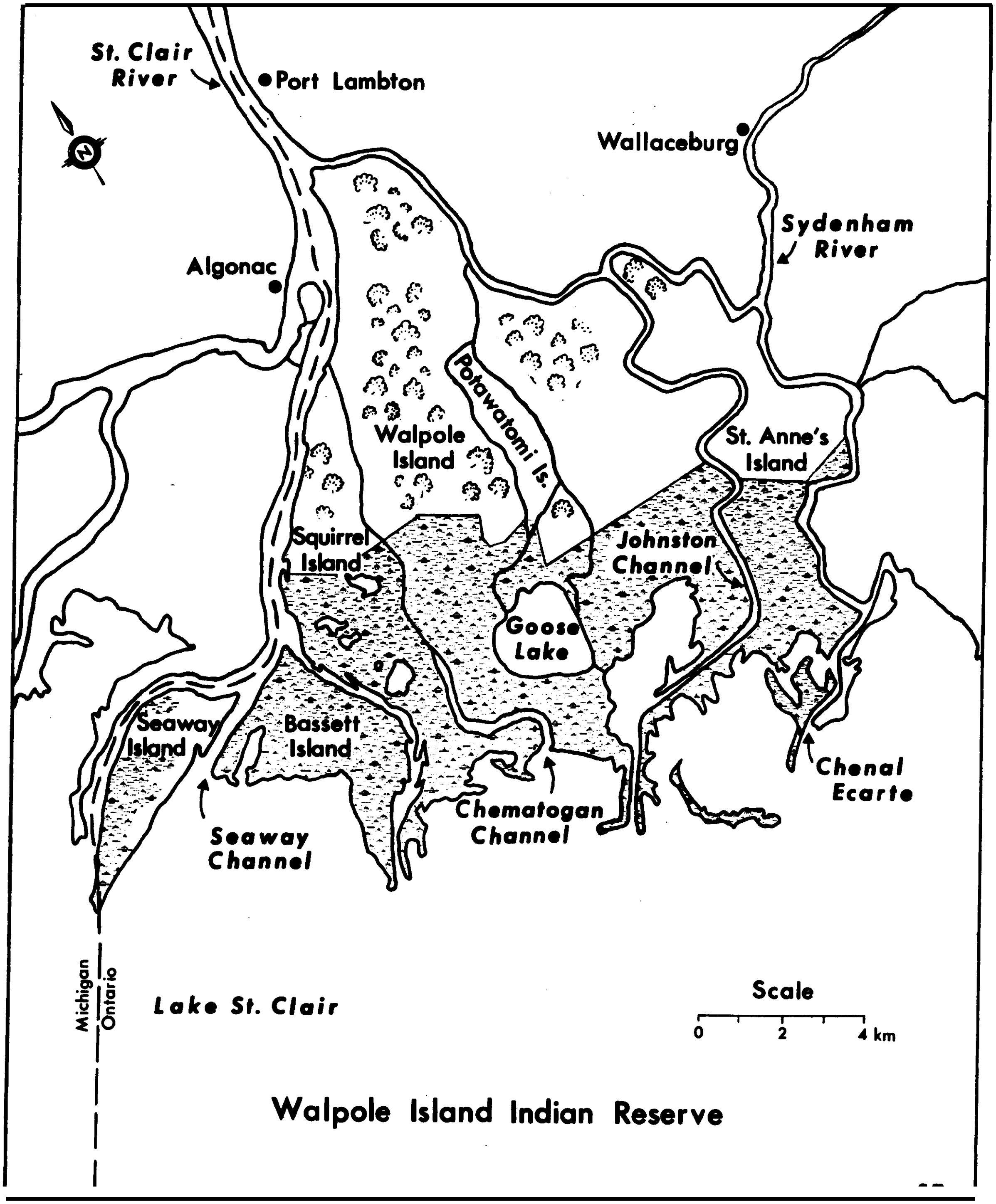
The Walpole Island Indian Reserve and individuals from the Reserve own and provide administration for approximately 16,000 hectares of land on the Canadian side of the St. Clair River delta. The Reserve consists of 4 large delta islands, Walpole, Squirrel, Bassett and St. Anne's at the mouth of the St. Clair River as can be seen in Figure (3).

The fallowing descriptions of the St. Clair River delta are as outlined in Wightman(1962). The delta is a large sand depositional feature built out onto Lake St. Clair from the mouth of the St. Clair River and lies in a large clay basin which is bordered in Michigan and Ontario by much older moraines. Water flowing from the Huron to Erie basins during the Lake Algonquin stage about 8000 years ago built a delta at the mouth of the St. Clair River. This delta was subsequently destroyed by waterfalls in the basin during the Lake Stanley low period. During the Lake Nipissing stage, about 4000 years ago, a second delta was formed. The present delta incorporates this and remnants of the first delta in its head. Today, it receives little or no material from the St. Clair River although the fall in lake level due ta the dawncutting af the Detroit and St. Clair River-s gives it an appearance of continued growth. The islands of Walpole and St. Anne's have not shown any signs of activity far some period of time. Both of these islands are slightly higher and drier than Bassett and Squirrel Islands.

Walpole Island can be divided into subaerial and subaqueous delta. The subaerial delta can be further subdivided into dry and wet portions. The dry delta is any portion of the delta which slopes gradually from the high head towards the lake level. The wet delta begins where the sloping surface is so close ta the water table or lake surface that it is saturated but not submerged. The average gradient far the del ta is 0.27 meters per kilometer.

These minor differences in elevation are of major importance in

FIGURE (3) THE ST. CLAIR RIVER DELTA



the effect on the distributions of both soils and vegetation. There are three classes of soils on the delta formed from the same basic materials, sand and silt. The dry delta has a fine sandy loam while the wet and subaqueous portions of the delta have progressively sandier soils. On high delta land, where the water table is a few meters below the surface, a hardwood Carolinian forest of primarily oak, ash, maple and elm has developed. The limits of this forest, where cutting has not taken place, are distinct. As soil moisture content increases the forest yields to areas of grass and sedges. At the waters edge this changes rapidly to cat-tails and reeds.

The channels on the delta are in constant competition for dominance. This has resulted in numerous abandoned distributaries, which are now classified as wet delta, within the dry delta area. The rate of growth, size and activity of the delta channels generally increases from the Ontario eastern portion to the Michigan western portion. However, the artificial deepening of the South Channel, which delimits the western boundary of Walpole Island, and the St. Clair River for the St. Lawrence Seaway has somewhat dampened this west-east gradient in channel activity. The connection between soils, vegetation and moisture availability on Walpole Island is quite distinct. Any alterations in moisture avai labi 1 ty through time should be evident an the growth patterns of the local natural vegetation.

Extensive rural and residential development has occurred on the Reserve. Much of the land area is under cultivation for corn and there has been extensive drainage diking and channel improvements. The forested area of the Reserve is divided into both private and public ownership. The public bush area is located in the north-central area of Walpole Island as can be seen in Figure (4). Figure (5) shows the fire breaks which were recently cut as a safety measure and drainage ditches which were dug to alleviate flooding problems.

Carolinian Canada, a conservation program initiated in 1984 under the Ontario Heritage Foundation? has included the sensitive complexes of Walpole Island as one of the 36 outstanding natural areas in the Carolinian life zone of Canada, a small area in the extreme southwestern portion of Ontario. Its prime objectives are for the protection and management of these significant and natural areas of Ontario. Non-purchase methods, or cooperation with the people of the Reserve, are felt to be necessary in order to meet their goals;.

The band Office is now conducting a variety of programs and studies to develop energy, agro-forestry and recreational opportunities. The newly establ ished NIN-DA-WAAB-JIB or "those who seek to find" cooperative research program engages personnel from the Walpole Island Band Community, the University of Windsor and the Ontario Ministry of Natural Resources. A forest management and job creation program has been initiated through both private and public funding.

Andresen (1984) provides details of a 1983 study concerned with a Walpole Island energy profile. The major energy demand on the Island is for space heat ing. The forest bimass provides an accessible energy source and appears to be the best energy resource to satisfy expected increases in demand. The current forest management program and improved silvicultural practices should improve forest productivity and regeneration.

FIGURE (4) PUBLIC BUSH LOCATION ON WALPOLE ISLAND

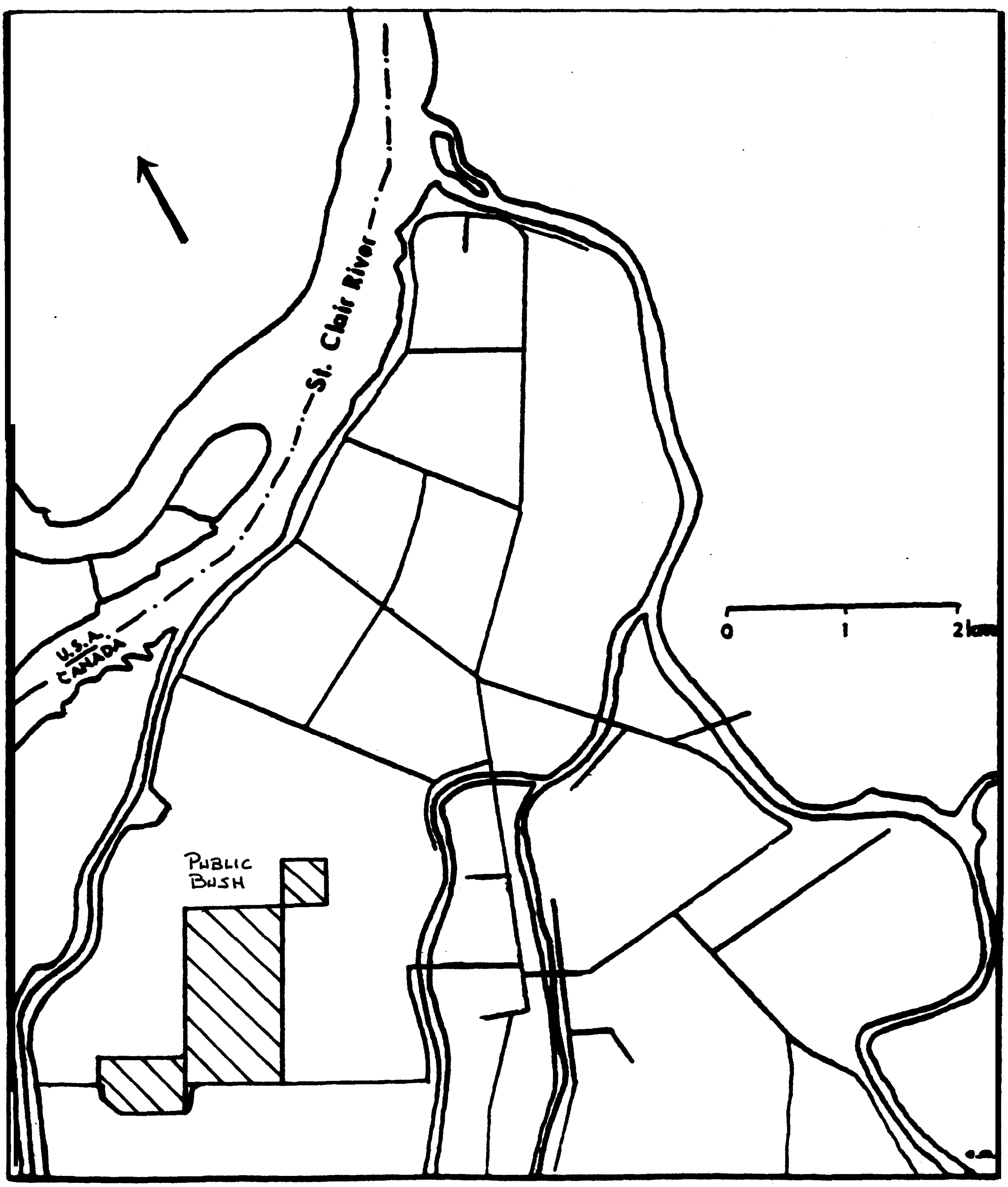
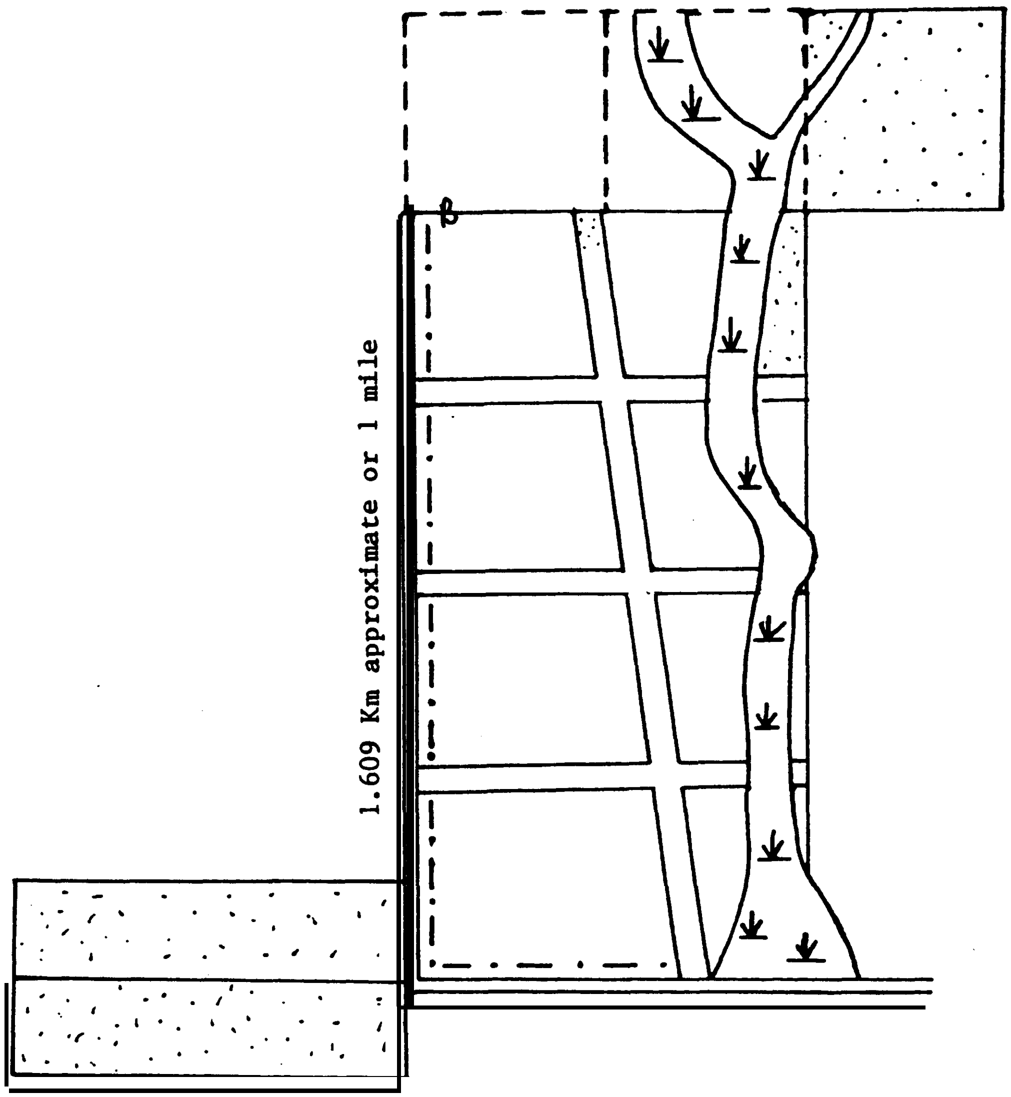


FIGURE (5) PUBLIC BUSH AREA OF WALPOLE ISLAND



Private:

Bush Access Road:

Fire Breaks:

Ditch:

Marsh Land:

Non Completed Area

Scale: 1 mile = 4 inches

5. METHODOLOGY

Basic data were required in order to evaluate the process-network model and its numerous inherent variations. The data considered in this investigation were ring-width measurements and climatic and climatically related variables. Each data set were then averaged and transformed for the purposes of the analysis. It was extremely important to strictly adhere to a number of important procedures to ensure the correct collection and processing of the tree ring and climatic data. This began with a clear definition of the pertinent study variables? an effective sampling design and field plan and a justifiable mode of analysis to assess the hypotheses,-

5.1 Dependent Variable

The dependent variable in this investigation was annual tree-ring width. The public bush area of Walpole Island was felt to be the most climatically sensitive available area of the delta from which to sample trees. Phipps (1982) stresses that the most important factor in sample site selection is the degree to which growth is limited by environmental factors, not whether the site is normally wet or dry. There has been success in deriving climatically sensitive collections in temperate subhumid areas by using sites of soil water discharge such as swamps and wetlands. A direct correlation between precipitation and growth of selected trees in swamps has been demonstrated (Phipps et. al., 1979). The public bush area of Walpole Island can be classed as a seasonally wet site. Even with the construction of drainage ditches in 1982-83, the drainage of surface water during the spring and summer months is slow. Phipps(1982) claims that wet site trees are relatively more sensitive to dry conditions than are dry site trees. During drought the root systems may be left high and dry. Also, during very wet conditions there is reduced growth through lower respiratory gas exchange.

In order to retain a more or less constant genetic response only one particular species, red oak (Quercus rubra), was sampled. Kramer and Kozlowski(1960) state that this species has an intermediate tolerance or capacity to endure shade. The sampling design was thus deliberately stratified in order to maximize the climatic information from the population. Overstory, rat her t han understory , trees were sampled since the public bush is a closed canopy site with a moderate degree of crown crowding. This method of sampling gave preference to older trees where competition with nearby trees was minimal. A Swedish increment borer was used to remove two core samples at breast height from opposing radii of each tree. This replication in sampling, from a north and a south exposure, was done to allow for statistical comparisons of variability in the same tree. If climate is a limiting factor then the same ring-width variations should be evident in each core.

A total of fourteen core samples were removed from seven red oak trees growing in the public bush of Walpole Island in October, 1985. A number of fire breaks were cut in the public bush during the winter of 1983-84 as part of the forest management program. A large number of tree slabs cut from the tops of tree stumps of a variety of tree species were saved for various interests. Ten of the best red oak. slabs were selected in order to compare and to possibly supplement the red oak cores taken for this study"

Each core or slab was dried, mounted and sanded and the rings were crass-dated from the outermost ring at 1985 far the cores and 1983 for the slabs ta the innermost ring which was farmed a variety of years earlier, The distinct nature of the growth rings and the consistent occurrence of wide or narrow rings provided the initial check for the crossdating technique. For example, rings far 1980, 1966 and 1942 were consistently wide while rings far 1954,1950, and 1934 were consistently narrow. After each ring was dated the widths were measured ta the nearest 0.04 mm with a binocular microscape. Total ring-widths, or the sum of earlywood and latewood for a given growth year, were measured and all data were entered an microcomputer disk.

Table (1) shows age and correlation coefficients between corresponding ring-widths fram opposing radii far each of the 17 trees measured. Tree 16 and tree 13 were deleted from further study due to the low correlation coefficients. The 2 sets of ring-widths far each of the remaining 15 trees were then averaged to yield a mean set of ring-widths for each tree. The keypunching and dating were checked by overlaying graphs from different trees and observing the consistent occurrence of wide and narrow rings.

The ring-widths from each tree were then converted to ring-width indices by the process of standardizatian (Fritts, 1976). This was done in order ta remove systemmatic changes in ring-width, or the growth trend, due to the increasing age of the tree. The resultant standardized ring-width chronologies can then be examined with the trend remaved and a mean and variance that is more homogeneous with respect to time. This was accomplished by first fitting an exponential or quadratic curve ta the data by computer program. Once the appropriate curve equation was developed it was salved for

TABLE (1) CORRELATIONS BETWEEN ACTUAL RING-WIDTHS OF OPPOSING RADII FOR EACH TREE MEASURED

TREE NUMBER	AGE (YEARS)	CORRELATION COEFFICIENT
1	56	0.633
2	79	0.901
3	88	0.532
4	55	0.491
5	51	0.765
6	90	0.492
7	63	0.861
8	63	0.607
9	49	0.810
10	60	0.750
11	60	0.602
12	68	0.913
13	72	0.469
14	61	0.857
15	49	0.928
16	36	0.425
17	54	0.639

the expected yearly growth (Yt). Measured ring-widths were then converted to ring-width indices (It) by dividing each width for each year t (Wt) by the expected yearly growth from the growth curve. The indices from each of these chronologies display increasingly similar statistical properties. Means all approximate a value of one, the differences in the standard deviations are less than those for the ring-widths and much of the autocorrelation due to trend is eliminated.

Three trees illustrate the variations that occurred between ring-width chronologies. Figures (6-8) show actual growth and expected growth from the best-fit curve for these three trees. Figures (9-11) show the autocorrelation coefficients calculated for 20% øof the number of observation years for each of these trees;. It is evident that the standardization process has removed varying degrees of autocorrelation from each ring-width series. Tree 2 shows a gradual decline in indice autocorrelation while tree 10 shows a much more rapid decline. The decline in tree 7 is much slower but is insignificant by the fourth order.

Table (2) shows the correlation coefficients between the standardized ring-width indices derived for each tree. Trees 1-7 represent core samples while trees 8-17 represent slab samples. Some measure of intercorrelation was expected in order to retain a given sample. As a result trees 9 and 15 were deleted from further study due to the persistence of negative correlations.

Table (3) shows the statistics of the remaining 13 ring-width series and their indices. The mean sensitivity statistic measures the

FIGURE (6) RED OAK # 2 "Quadratic Model"

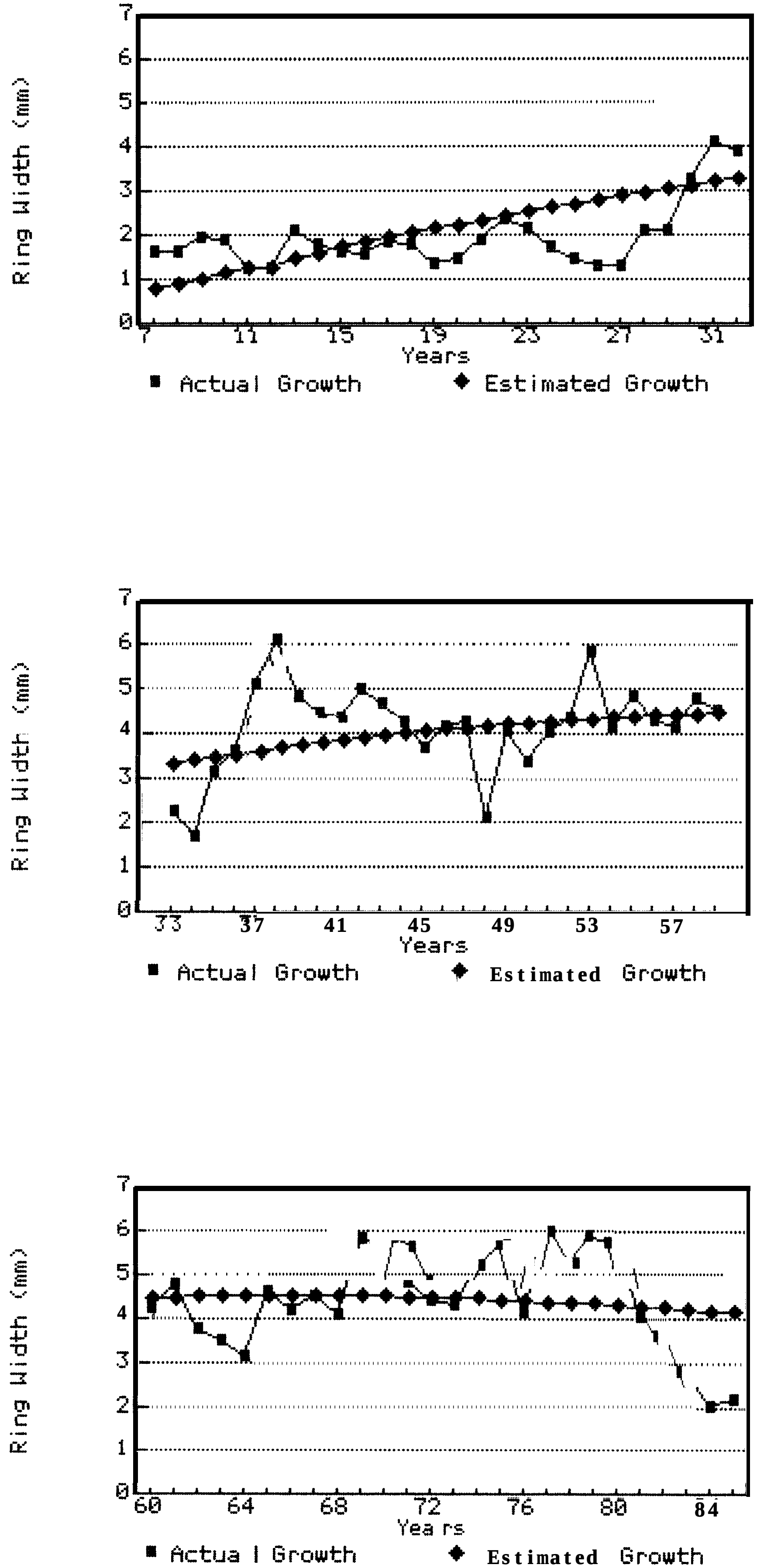
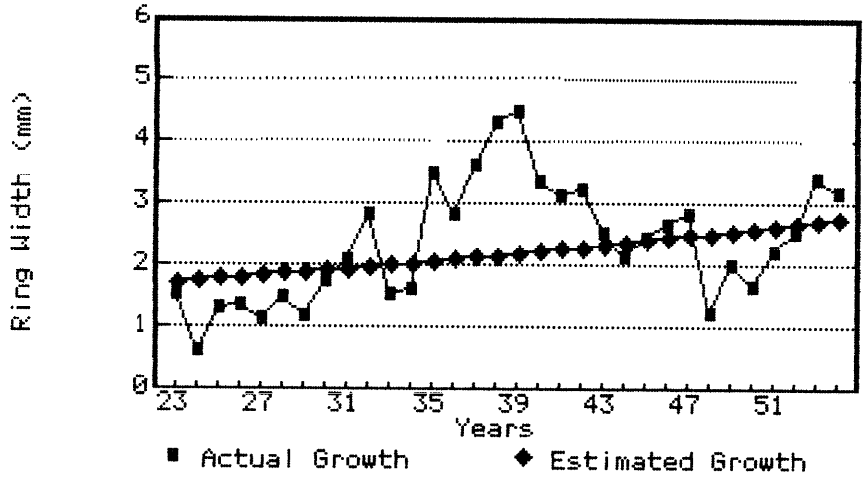


FIGURE (7) RED OAK #7 "Exponential Model



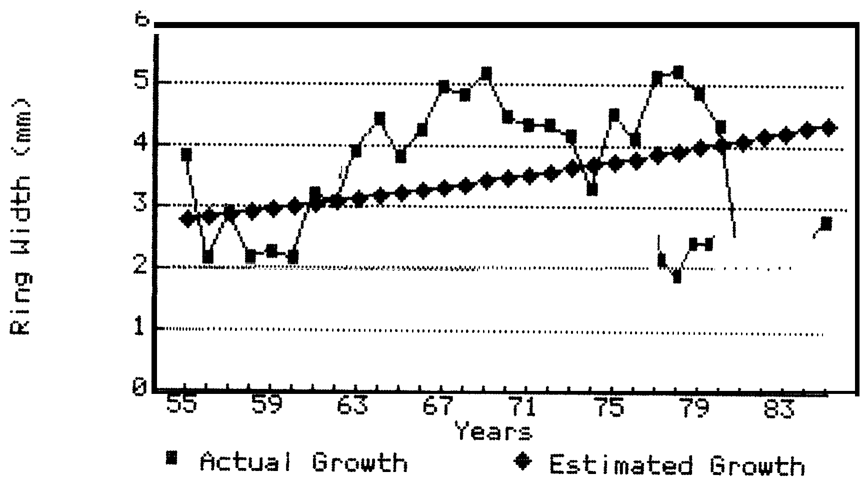
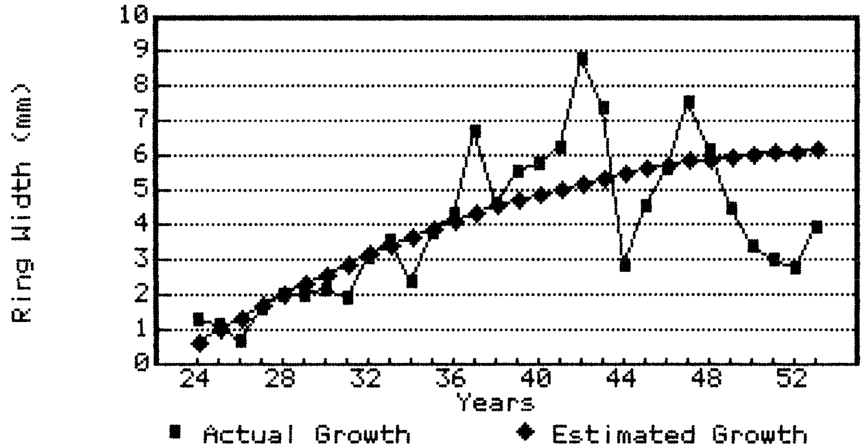


FIGURE (8) RED OAK # 10 "Quadratic Model



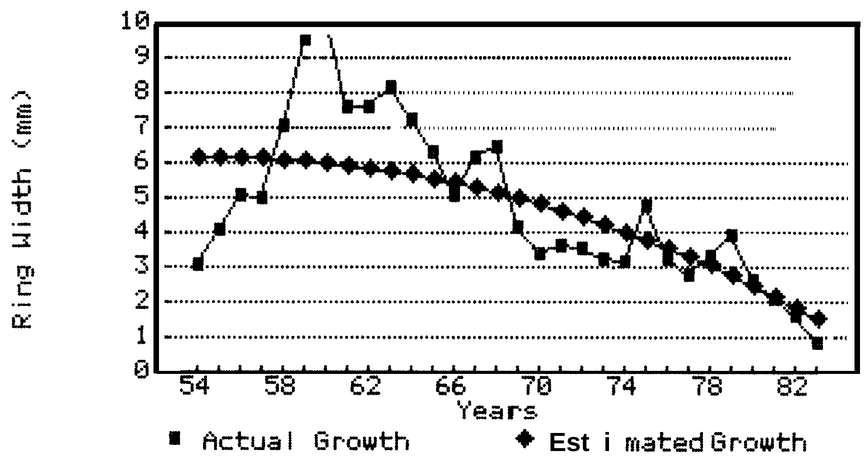


FIGURE (9) Tree # 2 Autocorrelations

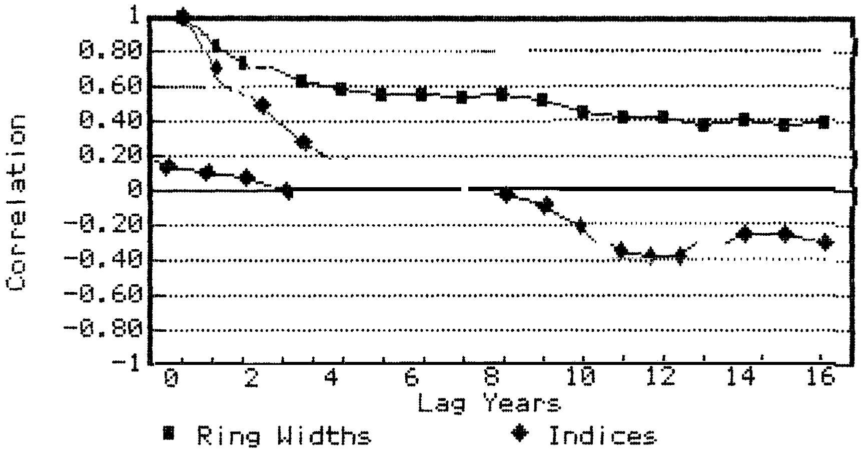


FIGURE (10) Tree # 7 Autocorrelations

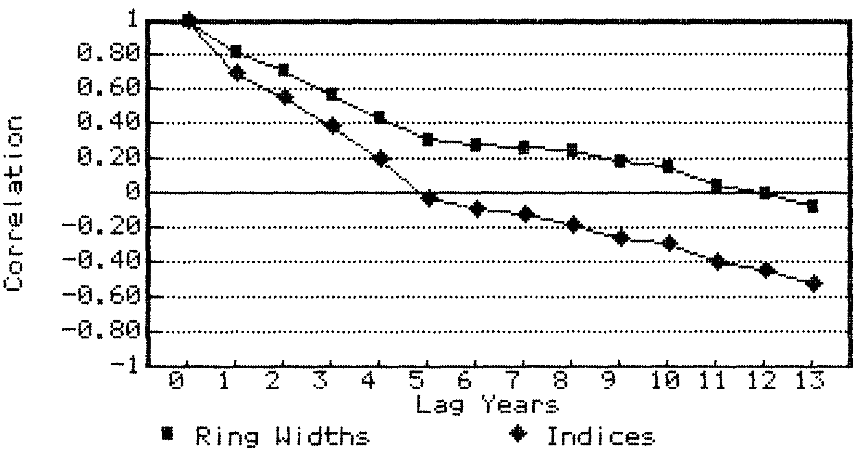


FIGURE (11) Tree # 10 Autocorrelations

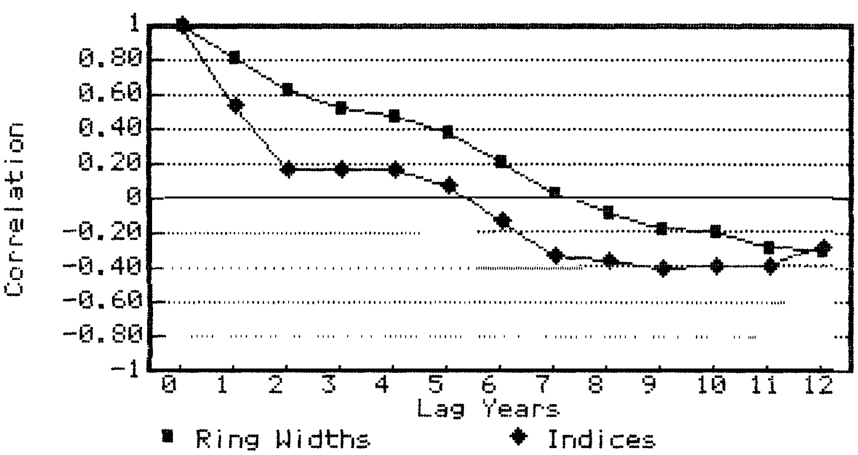


TABLE (2) CORRELATION COEFF I C IENTS BETWEEN
RING-WIDTH INDICES FOR EACH TREE

TREE:	1	2	3	4	5	6	7	8	9	10	11	12	14	15	17
1.	1.0	.40	.65	.22	.65	.23	.61	.20	.27	.50	.47	.45	.32	-.39	.30
2.	-	1.0	.31	.65	.36	.36	.59	.46	.00	.17	.31	.68	“ 4 5	-.23	.21
3.	-	-	1.0	.22	.55	.24	.59	.38	.13	.62	.22	.47	ml.6	-.12	.03
4.	-	-	-	1.0	.40	.23	.58	.61	-.20	.10	.30	.56	.30	-.11	.39
5.	-	-	-	-	1.0	.33	.53	.26	.11	.56	.48	.43	.40	-.45	.24
6.	-	-	-	-	-	1.0	.37	.05	.31	.33	.35	.40	.39	-.12	.13
7.	-	-	-	-	-	-	1.0	.45	-.10	.25	.40	.79	.35	-.27	.33
8.	-	-	-	-	-		-	1.0	-.20	.19	.22	.46	.24	.01	.33
9.	-	-	-	-	-			-	1.0	.25	.18	-.22	.20	.27	-.33
10.	-	-	-	-	-					1.0	.41	.16	.42	-.24	.06
11.	-	-	-	-	-						1.0	.40	.82	-.19	.10
12.	-	-	-	-	-							1.0	.43	-.31	.17
14.	-	-	-	-	-								1.0	-.12	.02
15.	-	-	-	-	-									1.0	-.32
17.	-	-	-	-	-										1.0

TABLE (3a) RING-WIDTH AND INDICE STATISTICS

TREE	1	2	I3	4	5	6	7
MEAN WIDTH (mm)	2.94	3.55	2.83	2.61	3.16	2.77	3.02
MEAN INDEX (mm1	1.08	1.01	1.05	1.00	1.04	1.01	1.07
STD.DEV. WIDTHS (mm)	1.14	1.44	1.16	0.63	0.81	0.88	1.21
STD.DEV. INDICES (mm)	0.37	0.30	0.32	0.23	0.27	0.27	0.36
LAG 1 CORR. WIDTHS	0.86	0.84	0.09	0.49	0.54	0.68	0.82
LAG 1 CORR. INDICES	0.80	0.72	0.81	0.40	0.55	0.61	0.70
MEAN SENSI-TIVITY WIDTHS	0.165	0.181	0.149	0.208	0.184	0.189	0.217
MEAN SENSI-TIVITY INDICES	0.161	0.186	0.149	0.206	0.185	0.186	0.206

TABLE (3b) RING-WIDTH AND INDICE STATISTICS

TREE	8	10	11	12	14	17	MEAN
MEAN WIDTH (mm)	2.50	4.44	3.37	2.71	3.44	1.50	2.99
MEAN INDEX (mm)	1.05	0.99	1.00	1.08	1.01	1.01	1.03
STD.DEV. WIDTHS (mm)	0.91	2.24	1.22	1.92	1.29	0.62	1.19
STD.DEV. INDICES (mm)	0.31	0.30	0.18	0.43	0.21	0.33	0.30
LAG 1 CORR. WIDTHS	0.82	0.82	0.85	0.89	0.85	0.58	0.76
LAG 1 CORR. INDICES	0.64	0.54	0.46	0.66	0.60	0.33	0.60
MEAN SENSI-TIVITY WIDTHS	0.168	0.240	0.160	0.236	0.160	0.271	0.194
MEAN SENSI-TIVITY INDICES	0.167	0.229	0.158	0.237	0.162	0.262	0.192

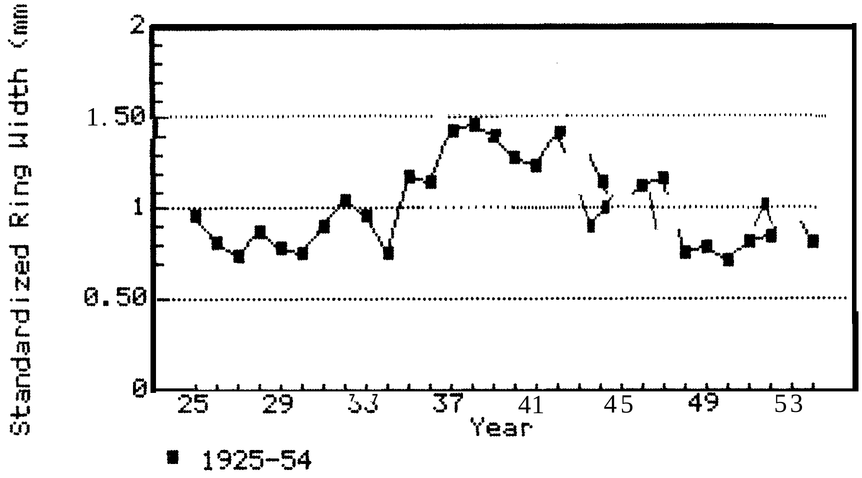
relative difference in width from one ring to the next. Values range from zero where there is no difference to a value of 2 where there is maximum difference. Mean sensitivity values for Walpole Island red oak trees are slightly lower than those for western North America conifers (Fritts, 1976) but are slightly higher than those for eastern North America Quercus stellata (Phipps, 1982). It is important to note that mean sensitivity was not affected by the standardisation process.

The remaining 13 trees were comprised of 7 core samples (trees 1-7) and 6 slab samples (trees 8,10,11,12, 14,17). The youngest tree was 51 years old while the oldest tree was 90 years old. The mean tree age was 65.6 years old. The derived indices were then averaged to yield a single mean red oak chronology for the public bush of Walpole Island. This merging technique eliminates much of the competition trends present in individual trees (Phipps, 1982). Figure (12) shows this mean chronology from 1925 to 1984 while Figure (13) shows the autocorrelation coefficients for this mean chronology. It is interesting to note the prescence of substantial negative correlations at lags of 11 and 12 years. This indicates cyclic behavior in the mean chronology.

5.2 Independent Variables

The independent variables considered were the important climatic and climatically related variables in the climate-plant system, temperature, precipitation, sunshine, lake levels and prior growth. Data describing temperature, precipitation and sunshine for a number of stations surrounding the St. Clair River delta were obtained from Atmospheric Environment Service

FIGURE (12) MEAN 13 TREE CHRONOLOGY



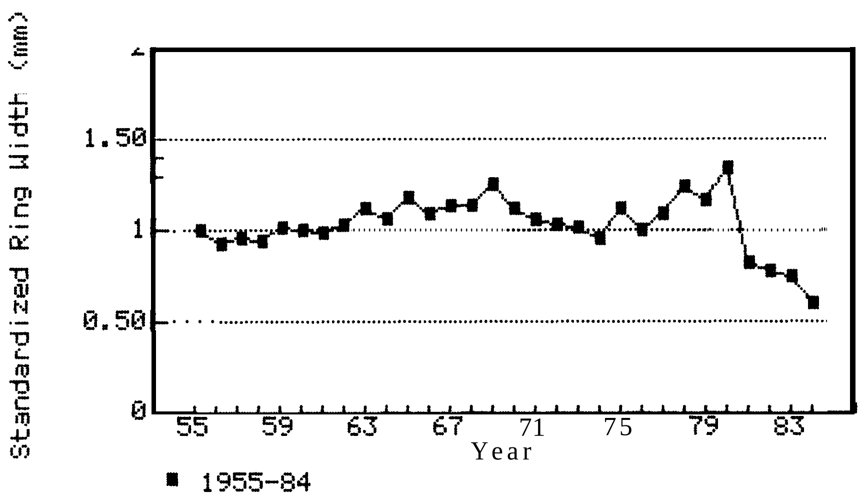


FIGURE (13) 13 TREE AUTOCORRELATIONS

in Toronto. A limited number of temperature and precipitation measurements from a farm location on St. Anne's Island, situated in the eastern portion of the delta (see Figure 3), were used in order to compare and adjust the regional record to that of the delta. Total monthly growing degree-days greater than 5C and total monthly precipitation were used for each growing season. Three years of prior growth were used to account for autocorrelation in the tree ring series.

Stations used for a regional degree-day and precipitation analysis were St. Anne's, Sarnia, Wallaceburg, Chatham, Courtright, Petrolia, Ridgetown, Windsor and Waodslee. The shortest of these records was St. Anne's with 33 complete months of daily temperature values and 22 complete total monthly precipitation values for various months from 1982 to 1984. The longest records were from Wallaceburg and Ridgetown, beginning in the 1920's. Longer records were available from Chatham and Wallaceburg but many missing values and changes in observation sites made these records unreliable. The Ridgetown observation site, the Western Ontario School of Agriculture situated about 1.5 km east of the town, had few missing values and was felt to be the most reliable of the longer term records. On the other hend, the Wallaceburg observation site, at a factory in an industrial area near the town centre, had a number of missing values especially during the 1960's. The instruments at this location have a relatively poor exposure taday.

All missing monthly values for all stations from 1924 to 1984 were estimated by multiple linear regression. In the case of a few missing values in the earlier portion of the Wallaceburg record bivariate linear regression with the Ridgetown record was used. Complete coverage became available for all stations, excluding St. Anne's, from 1975 for degree-days and from 1970 for precipitation.

Thirteen total monthly degree-day values for St.Anne's were correlated with corespanding values for all other stations. Correlation coefficients with Wallaceburg and Ridgetown were the best at r = 0.997. Multiple linear regrression was used ta estimate monthly St. Anne's records from these 2 stations for the period 1925-84. The resulting equation explained 99.34% of the variance and was significant at the 0.005 level.

The St Anne's Island precipitation guage is a Belfort type recording rain guage. Guages at all other stations are Standard Canadian rain guages. The Belfort type guage is taller than the Canadian guage and it is believed that because of wind turbulence they undercatch precipitation (Griffiths,1966). In addition, there are some drawbacks in the location of the guage that might make it unrepresentative of precipitation over the entire Reserve. St. Anne's Island is located on the easternmost portion of the delta and is comprised mainly of land cleared far agriculture, a considerably different surface cover than elsewhere on the islands of the Reserve. The prescence of Lake St. Clair provides a further complicating factor. The influence of the lake on the precipitation pattern of the Reserve might not be accurately represented by a single guage. However, the data frrom St. Anne's were considered useful, particularily over the monthly time period required for this study, due to the relatively small size of the area and the lack of topographical variation.

Twenty-two total monthly precipitation values from St. Anne's were correlated with coresponding values far all other stations. This was done for all months except December, January and February as there were no St. Anne's values for these months. Correlation coefficients ranged from r = 0.430 for Sarnia and r = 0.934 for Dresden. Correlation with the Wallaceburg record was only r = 0.551. Good correlations were found with most of the other stations, the best being Dresden, Ridgetown (r = 0.891), Courtright (r = 0.746), and Chatham (r = 0.717). Multiple linear regression was used to estimate St. Anne's precipitation for the months March to November from these 4 stations for the period 1970 to 1984. The reulting equation explained 88.87% of the variance and was significant at the 0.005 level. The 15 year monthly estimates were next regressed with the corresponding monthly values for Ridgetown and Wallaceburg to provide monthly equations to estimate St. Anne's precipitation to 1925. All monthly equations were significant at the 0.1 confidence level or better.

A long record of total bright sunshine hours (1919-85) has been kept at the Harrow Agricultural Research Station near Lake Erie. The only at tier station in the entire region to measure this variable has been Sarnia, but for a much shorter period (1969-85). Overlapping monthly values were compared for each station and no spatial trend was apparent during any month in the data. A simple averaging technique was felt to be the best estimate of Walpole Island sunshine for the 1969-85 period. Individual monthly estimates were then regressed with the known Harrow values to extend the estimated Walpole Island record to 1919.

Mean monthly Lake St. Clair levels were obtained from circulars published by the Canada Centre for Inland Waters in Burlington for the period

1977-84. These measurements were recorded at Belle River on the opposite side of Lake St. Clair. Lake level data for the period 1901-76 were obtained from model estimates produced by the Great Lakes Institute at the University of Windsor.

It was important to include prior growth as an independent predictor variable because photosynthates retained from previous growing seasons are an expression of prior climate that can affect growth during the current growing season (Fritts,1976). Figure (13) shows that significant autocorrelation still exists at lags of 1 ta 3 years in the mean red oak chronology. Since the standardizatian and merging procedures eliminate much of the trend associated with growth and competition it was assumed that the remaining autocorrelation had climatic value.

5.3 Response Function Analysis

Response function analysis, as outlined in Fritts et. al. (1971) and Fritts (1976) and used by Ashby and Fritts (1972) and Puckett(1982) was used to determine the relationship of tree growth to climate. This method of analysis decomposes climatic data time series' into orthogonal components which represent uncorrelated modes of behavior. Orthogonal variables have proven to be more stable than monthly climatic data in multiple regression because intercorrelation has been removed. The climatic data were transformed into orthogonal amplitudes using principal components analysis. The ampl i tudes were used, albng with indices of prior growth, in stepwise multiple regression analysis to predict ring-width indices.

Initially a correlation matrix is calculated from climatic data,

$$_mC_m = 1/n * {_mF_n}F'_m ,$$

where m is the number of monthly climatic variables and n is the number of years used in the analysis, $_mF_n$ is the matrix of standardized climatic data and (') denotes its transpose.

A principal component matrix, E, was next calculated,

$$_mC_mE_m = {_mE_m}L_m ,$$

where $_mL_m$ is the eigenvalue matrix and $_mC_m$ is the correlation matrix. Factor scores, or amplitudes, were then calculated as

$$_mA_n = {_mE'}\,{_mF_n} ,$$

where A is the matrix of factor stores and E' is the transpose of E. The factor score, or amplitude, matrix is assumed to be representative of the data matrix F (Fritts, 1976).

The amplitudes of the principal components were then used in a stepwise mutiple regression analysis to predict the tree-ring chronology,

$$_1P_n = {_1R_p}A_n ,$$

where $_1P_n$ are the estimated ring-width indices for n years and $_1R_p$ are the significant partial regression coefficients associated with each of the amplitudes of the selected set of p principal component amplitudes. Each regression coefficient value expresses the relative importance of each amplitude in predicting growth. A value of zero was assigned to the amplitude if it was not important.

The response function was calculated,

$$_1T_m = {_1R_p}E'_m ,$$

where $_1T_m$ is the response function with a weight corresponding to each of the original climatic variables. An estimate of ring-width indices , $_1\hat{P}_n$, based solely upon climatic variables was determined by multiplying the original climatic data, $_mF_n$, by the response function $_1T_m$,

$$_1\hat{P}_n = {_1T_m}F_n .$$

Up to 3 years of prior growth indices were then added as predictor variables to account for autucorrelation in the ring-width series. Residuals between actual and predicted tree growth were then checked for autocorrelation. Either a negative or sufficiently low correlation ensures that autocorrelation is not a problem (Fritts,1976).

6. DATA ANALYSIS

This investigation began with a general model based upon a simplified relationship between the growth of red oak trees on Walpole Island and the climatic degree-day and precipitation variables. These two variables were first consisered in order to compare the reslts with previous findings from similar studies (Ashby and Fritts,1972;Puckett,1982). The initial response functions were developed on the basis of 22 climatic variables. In addition, the climatically related ring-width indices for up to 3 years of prior growth were used, Since mean ring-width chronologies can be related to the climate of the year in which a ring was formed and also to the climate of the preceding year (Fritts, 1976), total monthly degree-days greater than 5C and total monthly precipitation values for the period April to September of the prior growing season and April to August of the current growing season were used.

It was assumed that if non-cl imat ic factors were for some reason more limiting to tree growth than climatic factors then tree growth may not correlate well with climate. In addition, it was assumed that if the relationship of tree growth to climate had been altered over time then some other factor not considered might be responsible for such changes;. The sunshine and lake level data were then added as independent variables to make the model more representative of reality and also to validate the relationships found in the original degree-day and precipitation response functions.

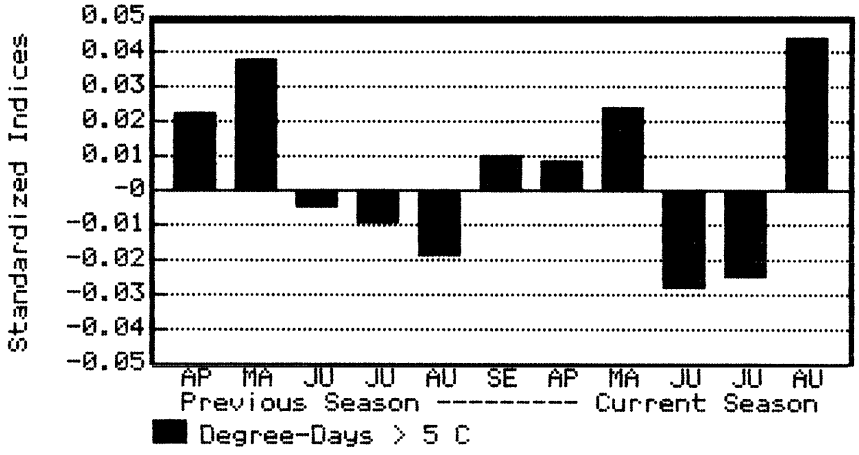
6.1 Sixty and Forty Year Response Functions

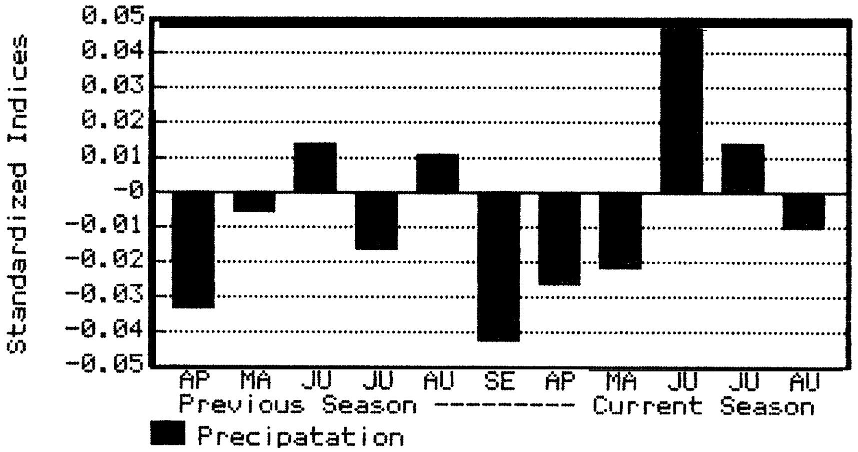
Initially, a 60 year response function was developed for the period 1925 to 1984. The first 18 amplitudes of the principal components explained 97.4% of the total variance of the climatic data set. The resulting response function, based on the best 11 amplitudes, explained only 29% of the variation in the 60 years of ring-widths. This was significant only at the 0.50 level. Indices for 3 years of prior growth were added as predictor variables and the variation in ring-width explained was increased to 75% , and was significant at the 0.001 level. This large increase was due in part to the low climate and tree-growth relationship for the 60 year period and also in part to the significant first to third order autocorrelation in the mean chronology, as seen in Figure (13).

Figure (14) shows the calculated 60 year response function for the climatic variables. Each element of the response function shows the relative effect of increased total monthly degree-days and total monthly precipitation on the standardized growth indices for the 60 year period. Negative values indicate an inverse effect on growth while positive values indicate a direct effect on growth.

The weak relationship between tree growth and climate led to the necessity of examining a shorter time period. A second response function was developed for a 40 year period from 1945 to 1984. The first 18 amplitudes of the principal components, in this case, explained 93.98% of the total variance of the climatic data set. The response function, also based on the best 11 amplitudes, explained 53% of the variation in the 40 years of ring-

FIGURE (17) RESPONSE FUNCTION 1925-84



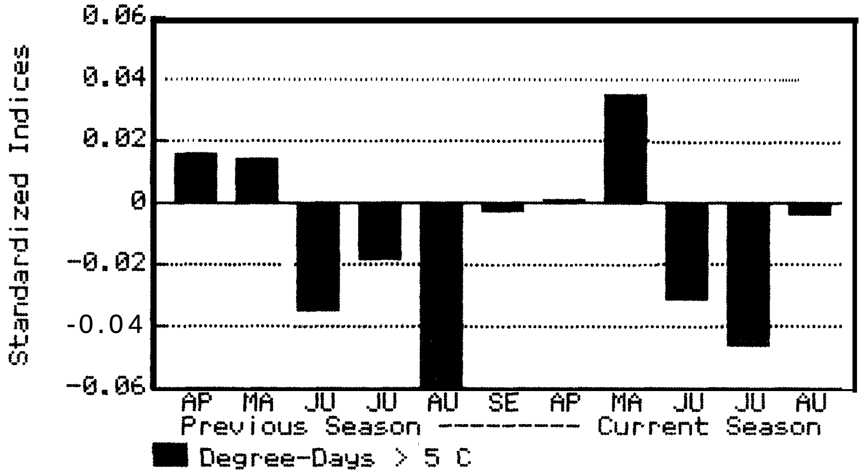


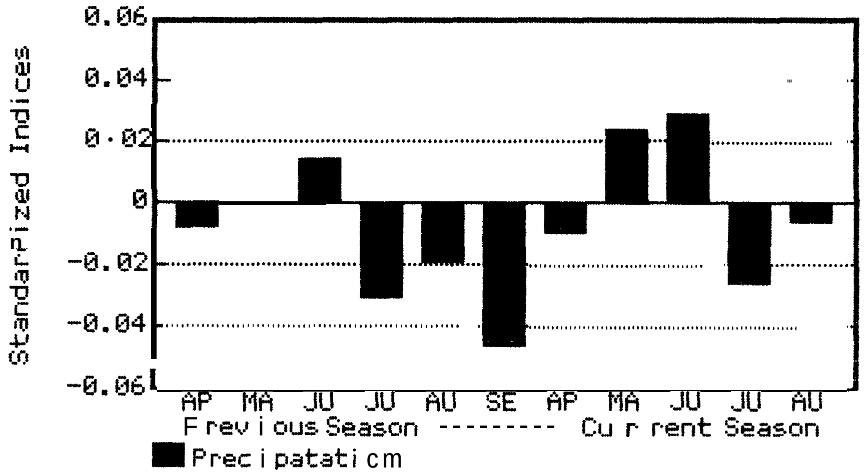
widths and was significant at the 0.05 level. This is similar to the 59% value found by Ashby and Fritts (1972) for a 55 year response function of white oak to the same climatic variables in northern Illinois-Indiana. However, when 3 years of prior growth indices were added to the response function the variatian in ring-width explained increased to 78% and a 0.001 significance level, considerably more than the 2% found in the northern Illinois-Indiana study. In that study, only the first year of prior growth proved to be significant while in this study the first year reduced 22% of the ring-width variance, the second year reduced no variance and the third year reduced 3% . Figure (15) shows the calculated 40 year response function for the climatic: variables. Table (4) summarises the statistics dealinq with the 60 and 40 year response functions.

The next step in the analysis was to apply the 40 year response function based on the 22 climatic variables alone to the corespandinq climatic data for the period 1925-44 in order to predict a **known set** of ring-width indices. Predicted ring-width indices were correlated with actual ring-width indices for the earlier period and the relationship was found to be insignificant. Only 0.07% of the variation in ring-width was explained with a correlation coefficient of $r = 0.03$. When 3 years of prior growth were added the relationship became significant at the 0.1. level, explaining 54.6% of the variation in ring-width, However, this was clearly independent of the 22 climatic variables initially considered in the 1945-84 response function.

The poor relationship between climate and tree growth for the 60 year period and the lack of similarity between the 40 year period and the earlier 20 year period indicated two aspects of the climate-tree growth

FIGURE (15) RESPONSE FUNCTION 1945-84





TABLE(4) MULTIPLE REGRESSION RESULTS FOR THE
60 AND 40 YEAR RESPONSE FUNCTIONS

	F-ratio	Sig. Level	R^2	R^2	r of res.
1925-84					
Climate:	1.78	0.500	0.29	0.13	0.66
+ 1 yr prior	9.67	0.001	0.71	0.64	0.16
+ 2 yr prior	8.81	0.001	0.71	0.63	0.10
+ 3 yr prior	9.67	0.001	0.75	0.67	0.10
1945-84					
Climate:	2.82	0.050	0.53	0.34	0.46
+ 1 yr prior	6.58	0.001	0.75	0.63	0.21
+ 2 yr prior	5.85	0.005	0.75	0.62	0.20
+ 3 yr prior	6.28	0.001	0.78	0.65	0.24

relationship. The first was the possibility that some other factor not consisered was affecting the growth of trees in the St. Clair River delta and the second was that the relationship of tree growth to climate was changing over time.

6.2 Twenty Year Response Functions

The 1925 to 1984 period was divided into 3 consecutive twenty year periods in order to investigate the suspected possibility that the relationship of the growth of red oak trees on Walpole Island to climate has changed over time. Individual response functions were developed for an early period (1925-44), a middle period (1945-64) and and a late period (1965-84). The first 14 amplitudes of the principal components matrix explained 97.5% , 98.0% and 98.2% of the total variation in the original climatic data for the early, middle and late periods respectively. A number of multiple regression equations were developed for each period but only equations with the same number of predictor amplitudes were used for the final analysis, In addition, because of the relatively short time periods involved, it was important to retain at least 10 residual degrees of freedom to insure that the regression results were not due to chance alone (Fritts,1976). The resultant response functions were based upon the best 6 amplitudes of the principal components matrix. When 3 years of prior growth indices were added to the regression equations exactly 10 residual degrees of freedom were attained. Table (5) shows the F-ratio, significance level, R^2, $\bar{R}^2$ and the first order autocorrelation of the residuals for each period for equations dealing with climatic variables alone and also for equations with up to 3 years of prior growth indices added as predictor variables.

TABLE (5) MULTIPLE REGRESSION RESULTS FOR THE THREE 20 YEAR RESPONSE FUNCTIONS

	F-ratio	Sig. Level	R	R^2	r of res.
1925-44					
Climate:	9.45	0.010	0.81	0.73	0.02
+ 1 yr prior	19.63	0.001	0.92	0.87	-0.49
+ 2 yr prior	15.78	0.001	0.92	0.86	-0.48
+ 3 yr prior	13.09	0.001	0.92	0.85	-0.46
1945-64					
Climate:	4.85	0.050	0.69	0.55	0.13
+1 yr prior	8.03	0.010	0.82	0.72	0.07
+ 2 yr prior	9.91	0.005	0.88	0.79	-0.18
+ 3 yr prior	8.15	0.005	0.88	0.77	-0.20
1965-84					
Climate:	2.31	0.500	0.52	0.29	0.38
+1 yr prior	5.90	0.025	0.77	0.64	0.18
+2 yr prior	4.74	0.025	0.78	0.62	0.15
+ 3 yr prior	7.45	0.005	0.87	0.75	0.05

The results of this analysis clearly show a decreasing trend in the sensitivity of tree growth to the climatic variables considered from the early period (X925-44) to the late period (1965-84). The F-ratio for regressions dealing with the 22 climatic degree-day and precipitation variables decreased from a value of 9.45 for the early period to a value of 4.85 for the middle period to a value of 2.31 for the late period. The same decreasing trend was evident when prior growth variables were added to the prediction equations. Coresponding significance levels related to each regression equation also show the decreasing trend. The R^2 values also show a similar decrease but the adjusted R^2 values ($\bar{R}^2$) for lost degrees of freedom show an even more dramatic decrease. First-order autocorrelation of the residuals were either negative or sufficiently low to indicate that autocorrelation was not a problem.

Figures (16-18) show the response functions for the 3 different periods based on the 22 climatic variables. An examination of these charts clearly indicates the changing nature of the relationship of tree growth to climate. Three aspects of this changing relationship are evident. The first relates to the decrease in the overall relative importance of the climatic variables through time. This is a reflection of the information contained in Table (5). The second deals with the change in direction of the relationship of growth to climate over time. In the early period, direct relationships are more common while in the later period this has changed to a prevalence of inverse relationships. The third aspect pertains ta changes in the relative importance of individual climatic variables to growth over time. For example, current August degree-days exerted significant influence on growth in the early period but were relatively insignificant during the latter 2 periods.

F I GURE (16) RESPONSE FUNCT I ON 1925-44

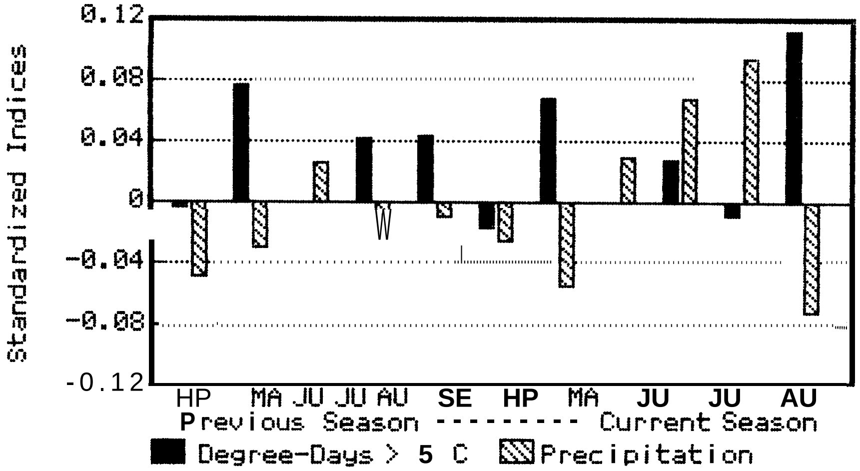
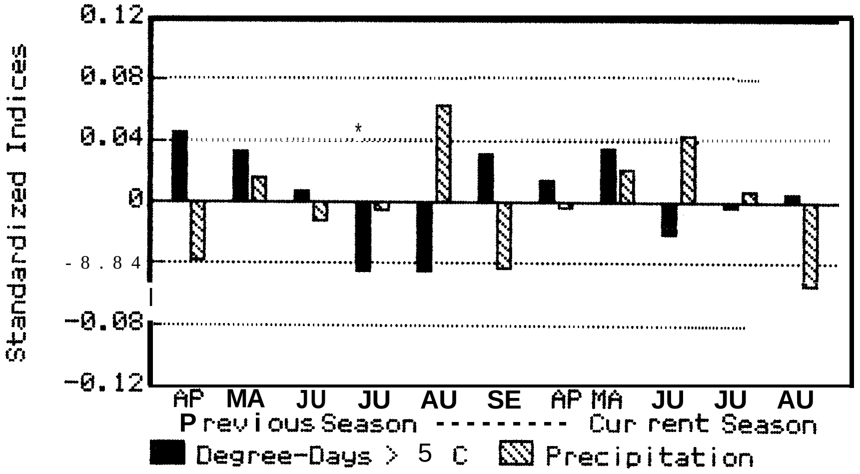
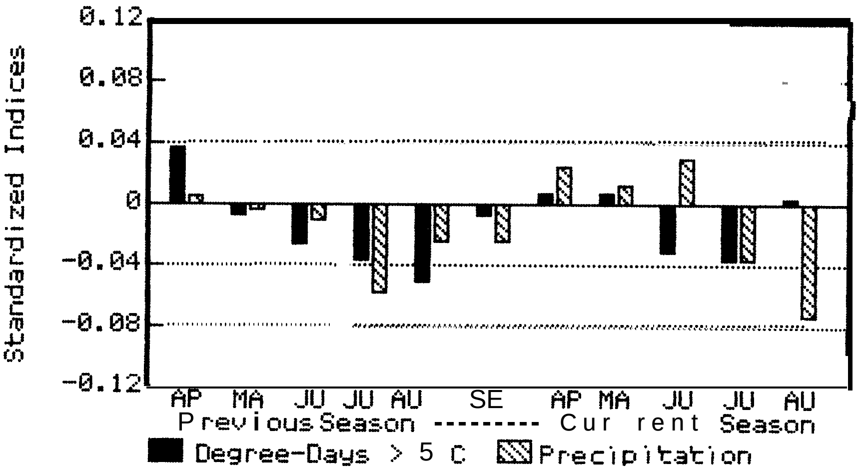


FIGURE (17) RESPONSE FUNCTION 1945-64



F I GURE (18) RESPONSE FUNCTION 1 'X5-84



Also, the relationship of current April precipitation changes from an inverse relationship in the early period ta relatively little importance in the middle period to a direct relationship in the later period.

6.3 Climatic Change and Tree Age Tests

It was assumed that the relationship of tree growth to climate would remain constant if all other factors remained the same. The observed changing relationship inferred that environmental conditions have changed aver the 60 year period. The monthly climatic data were tested far homogeneity between periods ta determine whether climatic change might have been responsible far the changing relationship. In addition, trees of different age classes were tested ta determine if older and younger trees reacted differently ta the same climatic: conditions.

Changes in the climate of the Northern Hemisphere during this century have been well documented (Budyko,1977). A warming trend began in the 1920's and peaked in the 1940's. There has been a cooling trend since that time. Precipitation changes during this century are more difficult to determine because of the regional nature of that variable,, Diaz and Quayle (1980)found that for eastern North America as a whole there has been generally more precipitation but less variability since 1955 than in the 30 years prior ta that.

Statistical F-tests and t-tests were employed to test whether the variance and means, respectively, of the monthly climatic data for the three periods used in the study were similar. Table (6) shows the results of

TABLE (6) MONTHS WHEN SIGNIFICANT DIFFERENCES WERE FOUND IN THE VARIANCES OR MEANS OF DEGREE-DAY (D) OR PRECIPITATION (P) DATA BETWEEN THE THREE PERIODS

	Early - Middle	Early - Late	Middle - Late
*	July (P;t,F)	July (D;t) April (P;F) August (P;t,F)	July (P;t,F) August (P;t,F)
**	July (P;t)	July (D;t)	July (P;F)

Early Period = 1925-44
Middle Period = 1945-64
Late Period = 1965-84

* $P < 0.005$ ** $P < 0.05$

F or t denote the use of F-test or t-test, respectively the climatic data test. Twelve months were tested, April to September for each of the degree-day and precipitation data sets. Months when significant differences were found in the variances or means of the data are given at two levels of significance. At the higher level of significance, the greatest differences were found between the early and late periods with one month for degree-days and 2 months for precipitation displaying significant differences. Two months were significantly different between the middle and late periods and only one month between the early and middle periods. When the significance level was lowered only one month, July, proved to be significantly different between all 3 periods.

The oldest tree used in the mean chronology was 90 years while the youngest was 51 years with a mean age of about 66 years, not much older than the 60 year period used to develop the response functions. It was felt that the observed decrease in sensitivity of tree growth to climate might be related to the increasing age of the trees. Tree age-climate tests were conducted to determine if such a relationship existed.

Two separate chronologies were developed to test the nature of the relationship. Ring-width indices for the oldest 5 trees and from 5 of the younger trees were selected from the sample of individual ring-width chronologies and separately merged to form a mean cronology of older trees and a mean chronology of younger trees. The older trees selected were trees 2, 3, 6, 8 and 12 and the younger trees selected were trees 1, 7, 10, 11 and 14. The ages of these trees were seen in Table (1). The mean age of the younger tree chronology was exactly 60 years while the mean age of the older tree chronology was about 20 years older at 78 years.

Response functions were developed for the same 3 periods as previously outlined and the same degwe-day and precipitation variables yet based on an older and a younger tree chronology for each period. Prior growth was not used as a predictor variable because prior growth indices for the 2 separate chronologies were not the same and their inclusion would present difficulties in making accurate comparisons. In addition, the low number of trees used in the merging technique did not reduce the autocorrelation due to competition with other trees. The best 9 amplitudes of the principal components matrix were used to derive the response functions, thus retaining 10 residual degrees of freedom.

Table (7) shows the multiple regression results for the relationship of the climatic variables to the growth of older and younger trees for the 3 periods. This table clearly shows that tree chronologies of differing ages are reacting to the same climatic variables in a similar manner. Italso shows that wtien the 2 chronologies are assessed at similar stages of their growth they can be seen to be reacting differently to climate. The decrease in the sensitivity of growth to climate, as previously seen, is still quite evident. The relationship is so low for the older trees in the late period that it is insignificant,, The adjusted R^2 value for the younger trees in the late period is also quite law. There does not appear to be any significant difference in the relationship of climate to either older or younger trees in any particular period.

All statistics pertaining to each period for the 2 types of trees are very similar. The older trees are slightly more sensitive to

TABLE (7) MULTIPLE REGRESSION RESULTS FOR THE RELATIONSHIP OF CLIMATIC VARIABLES TO THE GROWTH OF OLDER AND YOUNGER TREES

	F-ratio	Sig. Level	R^2	$\bar{R}^2$	r of res.
1925-44					
Old Trees	8.07	0.005	0.88	0.77	-0.22
Young Trees	6.67	0.005	0.86	0.73	-0.26
1945-64					
Old Trees	3.23	0.050	0.74	0.51	0.05
Young Trees	2.77	0.100	0.71	0.46	0.19
1965-84					
Old Trees	0.73	-----	0.40	-0.15	0.35
Young Trees	1.29	0.500	0.54	0.12	0.25

climate than are the younger trees for both the early and middle periods. In addition, the older trees of the early period are, on average, the same age as the younger trees of the middle period, from 20 to 40 years, and the older trees of the middle period are, on average, the same age as the younger trees of the late period, 40 to 60 years. The reduction in the variation in ring-width explained for trees at similar growth stages, based on the adjusted R values, is 31% from the late to the middle period and a further 39% from the middle period to the late period.

6.4 Response Functions with Additional Climatic Variables

The changer; in the relationship of tree growth to climatic variables inferred that environmental conditions which affect growth have changed during the past 60 yearns. The inclusion of further climatic and climatically related variables was felt to be necessary in order to validate or explain the observed relationships. Lake and river level data have been successfully correlated with the growth of trees (Stockton and Fritts, 1973; Cook and Jacoby, 1983). Fluctuations in Lake St. Clair levels might be responsible for variations in the growth of natural vegetation on the delta. In addition, variations in sunshine amounts were felt ta be important to alterations in the photosynthetic process (Fritts,1976).

Response functions were developed for the three consecutive 20 year periods as previously outlined. Standardised variables describing total monthly bright sunshine hours and mean monthly Lake St. Clair levels were employed in addition to the degree-day and precipitation variables. Eleven sunshine variables for April to September of the prior growing season and for

April to August of the current growing season were added. Lake level variables for June of the prior growing season and June of the current growing season were also added for a total of 35 independent variables. Only two lake level variables were used because of the high seasonal correlation of monthly lake level data. June levels were used because they represented the best correlations with the dependent variable. It was assumed that the relative importance of June lake levels in the ensuing response functions would be indicative of the importance of lake levels for the entire growing season.

The first 14 amplitudes of the principal components matrix explained 94.8% , 95.3% and 96.0% of the total variation in the data set for the early, middle and late periods, respectively. The resultant response functions were again based upon the best 6 amplitudes. Ten residual degrees of freedom were retained when 3 years of prior growth indices were added as predictor variables. Table (8) shows the multiple regression results, with the sunshine and lake level data added, for the 3 consecutive 20 year periods. The same decrease in the relationship of tree growth to climate which was evident in the 3 original response functions, as seen in Table (5), still applies. However, the F-ratio for climate variables alone for the early period has increased significantly over that seen in Table (5), from 9.45 and a 0.01 significance level to 15.05 and a 0.001 significance level. The F-ratios for the middle period pertaining to climatic variables alone have remained about the same while those for the late period have shown a rise fram 2.31 and a 0.50 significance level in Table (5) to 4.68 and a 0.05 significance level with sunshine and lake level variables added. The same relationships persist when up to 3 years of prior growth variables are added.

TABLE (8) MULTIPLE REGRESSION RESULTS FOR THE
THREE 20 YEAR RESPONSE FUNCTIONS WITH
SUNSHINE AND LAKE LEVEL DATA

	F-ratio	Sig. Level	R^2	$\bar{R}^2$	r of res.
1925-44					
Climate:	15.05	0.005	0.87	0.82	-0.48
+ 1 yr prior	14.25	0.001	0.89	0.83	-0.49
+ 2 yr prior	12.60	0.001	0.90	0.83	-0.46
+ 3 yr prior	10.29	0.001	0.90	0.81	-0.56
1945-64					
Climate:	4.71	0.050	0.68	0.54	0.12
+ 1 yr prior	7.49	0.010	0.81	0.71	-0.14
+ 2 yr prior	6.23	0.010	0.82	0.69	-0.16
+ 3 yr prim	5.18	0.025	0.82	0.66	-0.22
1965-84					
Climate:	4.68	0.050	0.68	0.54	0.28
+ 1 yr prior	7.74	0.010	0.82	0.71	0.16
+ 2 yr prior	6.25	0.010	0.82	0.69	0.20
+ 3 yr prior	5.55	0.010	0.83	0.68	0.05

Figures (19-21) show the response functions for the degree-day, precipitation, sunshine and lake level data for the early, middle and late periods, respectively. The upper portions of each chart, which deal with the relative importance of the degree-day and precipitation variables, are quite similar to the coresponding response functions seen in Figures (16-18). The lower portions of each chart, which deal with the relative importance of the sunshine and lake level data, also display the decrease in the relative imortance of each variable from the early period to the late period when both sunshine and lake levels have become relatively unimportant. There is no marked change in the direction of the relationship of the sunshine and lake level variables to growth over time as there was with the degree-day and precipitation variables. Lake levels show an inverse relationship with growth except during the prior season in the middle period. There is however a marked change in the importance of individual variables over time. For example, June and July sunshine had an inverse relationship to growth in the early period and a direct relationship in the middle and late period.

6.4.1 Climatic Change and free Age Tests

The same climatic change tree age tests were conducted for the additional sunshine and lake level variables. Table (9) shows the months where significant differences were found in the variances or means of the sunshine or lake level data between the three periods. Seven months were tested, April to September for sunshine and the month of June for lake levels. June and July sunshine were different between the early and middle periods and April and June sunshine were different between the middle and late periods at the higher significance level. In addition, lake levels were

FIGURE (9) RESPONSE FUNCTION 1925-44

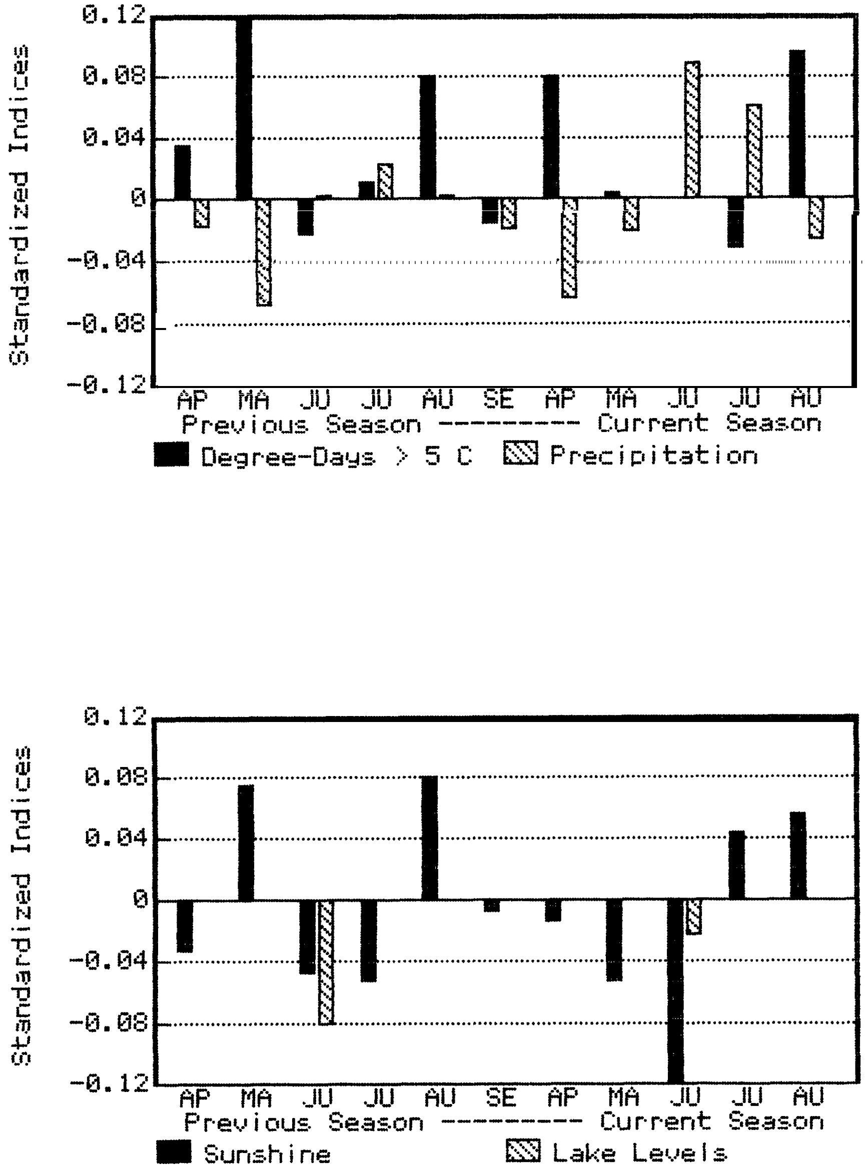
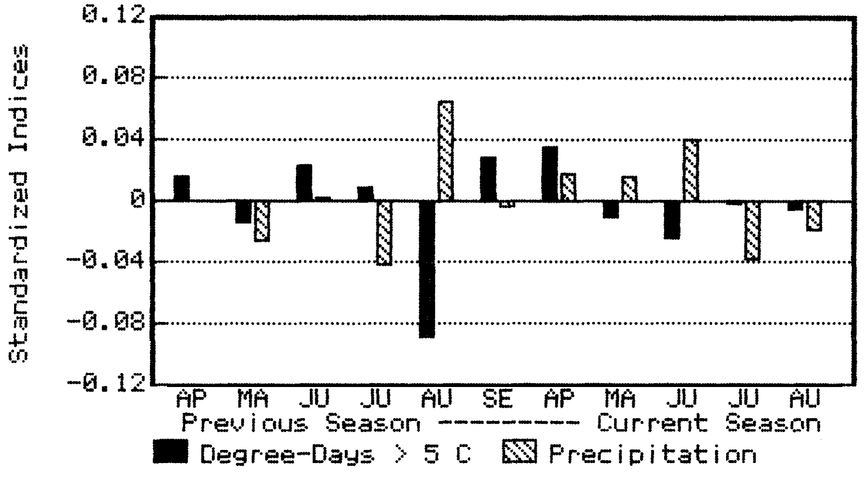


FIGURE (20) RESPONSE FUNCTION 1945-64



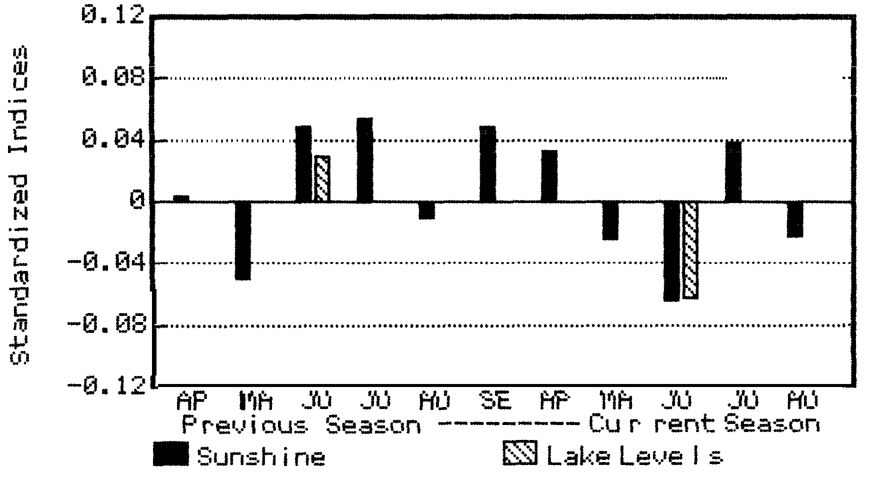
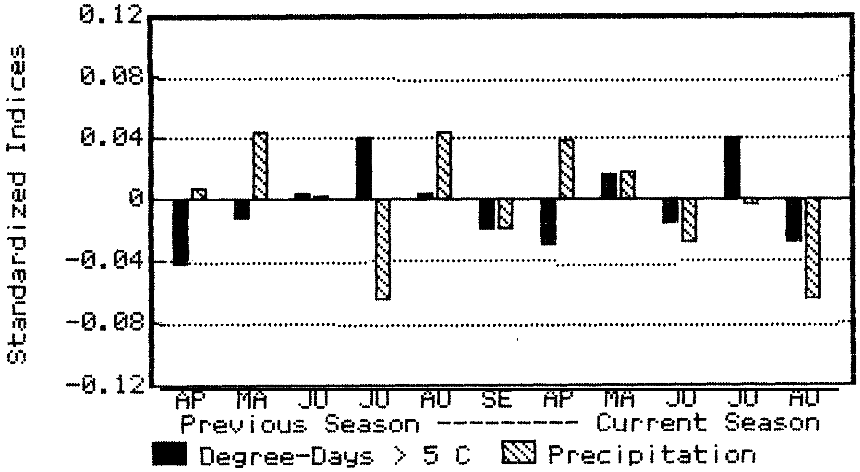
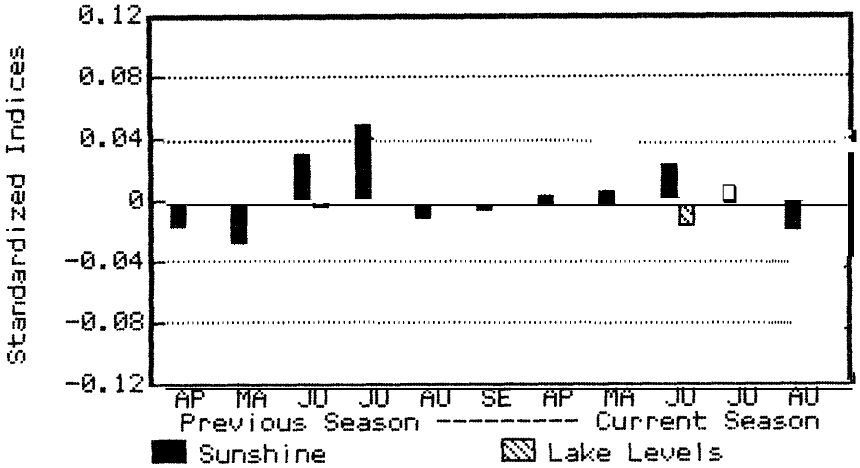


FIGURE (21) RESPONSE FUNCTION 1965-84





TABLE(9) MONTHS WHEN SIGNIFICANT DIFFERENCES WERE FOUND IN THE VARIANCES OR MEANS OF SUNSHINE (S) OR LAKE LEVEL (L) DATA BETWEEN THE THREE PERIODS

Early - Middle	Early - Late	Middle - Late
* June (S;t) July (S;t) June (L;t)	* June (L;t)	* April (S;t) June (S;t) June (L;t)
	** June (L;t)	

Early Period = 1925-44
Middle Period = 1945-64
Late Period = 1965-84

$* P < 0.005$ $** P < 0.05$

F or t denote the use of F-test or t-test, respectively significantly different between all 3 periods at this level. Only lake levels between the early and late periods were different at the lower significance level. By referring to Table (6) and Table (9) a total of 19 months were tested for 3 periods for a total of 57 comparisons. At the higher significance level (0.005), 13 months proved to be different? while at the lower level (0.05) only 4 months proved to be different.

Table (10) shows the multiple regression results for the relationship of climatic variables, with the addition of sunshine and lake level data, to the growth of older and younger trees. The same older and younger five tree chronologies were used as in Table (7) for the degree-day and precipitation variables. The same decrease in sensitivity to climate from the early to the late period is still quite evident. However, the older trees for each period are slightly more sensitive to climate than are the younger trees. The difference in sensitivity between older and younger trees also decreases through the 3 periods. Trees at similar stages of growth are reacting quite differently to climate as they did in Table (7).

TABLE (10) MULTIPLE REGRESSION RESULTS FOR THE RELATIONSHIP OF CLIMATIC VARIABLES INCLUDING SUNSHINE AND LAKE LEVEL DATA TO THE GROWTH OF OLDER AND YOUNGER TREES

	F-ratio	Sig. Level	R^2	R	r of res.
1925-44					
Old Trees	16.97	0.001	0.94	0.88	-0.30
Young Trees	7.32	0.005	0.07	0.75	-0.25
1945-64					
Old Trees	3.33	0.050	0.75	0.53	-0.01
Young Trees	1.74	0.500	0.61	0.26	0.40
1965-84					
Old Trees	1.83	0.500	0.62	0.28	0.35
Young Trees	1.40	0.500	0.56	0.16	0.38

7. DISCUSSION

The relationship of tree growth to climate should remain constant through time if all other extraneous factors remain the same. The growth response of red oak trees from Walpole Island in the St. Clair River delta has been related, by multivariate regression techniques, to climatic and climatically related variables. The observed relationship of tree growth to climate has been seen to change through 3 consecutive 20 year periods beginning in 1925. The largest change occurred sometime after 1945 with a significant reduction in the sensitivity of growth to climate. This infers that environmental conditions have changed during that period. There are a number of possible explanations, some of which have been tested for and some of which cannot be tested for at present.

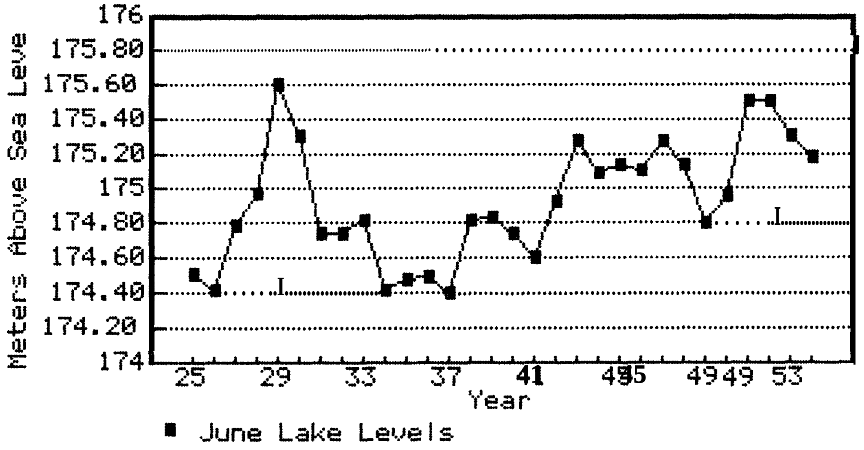
One possible explanation is climatic change during the past 60 years. Climatic data tests were conducted and it has been shown that significant changes have occurred. The cooling climate of the northern hemisphere since about 1940 likely accounts for the differences in July degree-days between the early and late periods as seen in Table (6). Significant precipitation and sunshine differences also occurred between all 3 periods as seen in Tables (6) and (9). Normally, these variables are negatively correlated and if differences occur in one then differences can be expected in the other. At a slightly lower level of significance, only the differences between the early and late period appear to stand out. This is because of the significant degree-day and lake level differences.

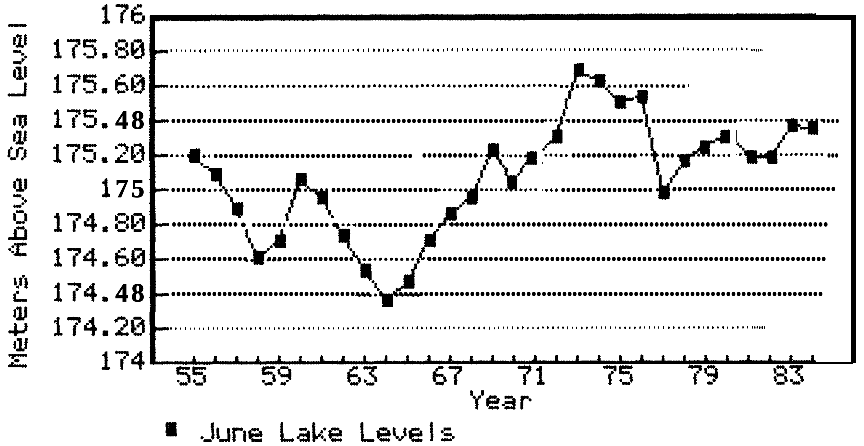
Climate does not appear to have changed enough from the early to the middle period or from the middle to the late period to alter the tree growth-climate relationship. It may have changed enough from the early to the late period to alter this relationship. Therefore, comparisons **between the early** and late periods should be interpreted cautiously. Since the greatest difference in the tree growth-climate relationship occurred between the early and middle periods it can be assumed that some other environmental variable besides climate has been affecting tree growth.

The past 60 years spans a period of both extremely high, and low, lake and thus river and groundwater levels. Figure (22) shows Lake St. Clair levels for the period 1925-84. Lake levels were quite low during thhe early period and quite high during the late period. The middle period had both high and low levels but was characterized by a general increasing trend. The response functions for all climatic variables, as seen in Figures (19-21) show that, with only one exception, significant inverse relationships exist between lake levels and tree growth but this relationship decreased in its relative importance t hrough time. A comparison of Figure (22) with the mean chronology in Figure (12) visually confirms this relationship. Lake levels were significantly different between all three periods as seen in Table (9). The rise in lake levels from the early period to the late period may have been partially responsible for a decrease in sensitivity of tree growth to climate in a delta environment.

Another possible explanation is **that the trees sampled for the study were of a very young age** during the earlier 1925-44 period. **Tree age-**climate tests were devised under the assumption that younger trees were more sensitive to climate than **older trees. It was found that a chronology of** five

F IGURE (22) LAKE ST. CLAIR LEVELS





trees that were, on average? 20 years older than a chronology of younger trees dislayed a slightly higher sensitivity to the climatic variables. In addition? trees of similar age groupings reacted differently to the same climatic variables of different periods;. The age distribution of the Walpole Island trees does not appear to have any distinct climatically related information.

A final explanation which cannot be tested for at present is that air pollution, either by itself or in combination with other factors, has changed the relationship of tree growth to climate. Numerous studies have shown that both point-source and nonpoint-source levels of various types of air pollutants have had negative effects on the growth of trees (Vins, 1970; Polge, 1970; Parker et. al., 1974; Lawhon and Woods, 1976; McClenahen, 1978; Mann et. al., 1980; McLaughlin et. al., 1980). The relationship of various air pollutants to the growth of trees through multiple regression analyses have also shown the negative effect on growth (Phillips et. al., 1977a,1977b; Fox and Nash, 1980; Johnson et. al,1981). Response function analysis has been applied to infer the negative effects of air pollutants on the growth of trees; in eastern North America (Ashby and Fritts, 1972; Puckett, 1982).

The metabolic processes and photosynthetic capacity of trees can be severely inhibited by toxic substances in the air. Continued exposure to such substances for a number of years would cause a gradual decline in ring width (Fritts, 1976). An examination of the mean chronology in Figure (12) shows a decline in standardized ring-width beginning in the early 1940's. This was followed by stable growth through the late 1950's and early 1960's.

Since the mid 1960's there has been a steady decline in standardized ring-width. This general decline in ring-width beginning in the 1940's coresponds with increases in atmospheric pollutants in eastern North America. As previously mentioned, the St. Clair River delta is situated on the eastern side of Lake St. Clair. Prevailing westerly winds during the growing season pass over the large industrial and residential complex of Detroit, Michigan and Windsor? Ontario immediately before passing over Lake St. Clair and the delta. Ashby and Fritts (1972) have related the reduction in tree growth in northern Illinois-Indiana during the 1940's to high levels of smoke-haze directly upwind in Chicago.

The response function developed for Walpole Island red oak trees for the 40 year period from 1945-84 showed similar statistical properties to that developed by Ashby and Fritts (1972) for white oak trees with similar climatic variables. Puckett (1982) found an increasing sensitivity of the growth of pitch pine, white pine and chestnut oak in southeastern New York to temperature and precipitation variables during the 20th century. The periods used in that study were slightly different than those used in this study, the first being 1901-20, the second 1926-45 and the third 1954-73. The significant increase in sensitivity to climate occurred between the second and third periods. This was about the same as the significant decrease in sensitivity to climate found in this study. Acid rain and chronic low-level air pollution were felt to be the primary causes of the observed increased sensitivity to climate in that study. This study has not entirely discarded the changes in climate, especially the climatically related lake levels, as having no effect on the observed decrease in the relationship of tree growth to climate. The combination of increasing lake levels and increasing low-levels of chronic air pollution seem to be the most plausible explanation far a subdued relationship with climate. Unfortunately, there are no long-term air quality observations in the entire region with which to substantiate this suspected relationship.

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