

Cluster analysis of late Holocene pollen trends in Ontario

IAN D. CAMPBELL

Department of Botany, Royal Ontario Museum, 100 Queen's Park, Toronto, Ont., Canada M5S 2C6
and

Department of Botany, University of Toronto, Toronto, Ont., Canada M5S 1A1

AND

J. H. MCANDREWS

Department of Botany, Royal Ontario Museum, 100 Queen's Park, Toronto, Ont., Canada M5S 2C6
and

Department of Botany, University of Toronto, Toronto, Ont., Canada M5S 1A1

and

Department of Geology, University of Toronto, Toronto, Ont., Canada M5S 1A1

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Cluster analysis of Ontario pollen stratigraphies demonstrates similar regional successions during the past 1000 years. Seven character states qualitatively describe the behaviour of the pollen percentage trends for each taxon: 0, absent; 1, present with no visible trend but high noise; 2, rising through time; 3, falling through time; 4, rise–fall; 5, fall–rise; and 6, stable through time. The three similarity indices (S) used were of the form S equals the number of characters in agreement divided by the number of informative characters. The three clustering techniques used are single linkage, complete linkage, and unpaired weighted geometric mean analysis. Single linkage and unpaired weighted geometric mean analysis showed a north–south division with all three indices; complete linkage showed only rare local groupings with all three indices. The division between the two clusters falls just south of Lake Nipissing. All successions indicate climatic cooling; the clusters reflect southward movement of the centres of species abundances, particularly white pine. The method identifies regions of similar vegetation dynamics.

Key words: cluster analysis, forest dynamics, Holocene, Little Ice Age, Ontario, palynology.

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L'analyse des groupes appliqué aux tendances observés dans les diagrammes polliniques de l'Ontario délimite des régions de succession végétale des derniers 1000 ans. Sept états des caractères utilisés décrivent qualitativement les tendances des pourcentages polliniques des taxons: 0, absent; 1, présent; sans tendances définitives ou bruyant; 2, montant avec le temps; 3, descendant avec le temps; 4, montée–descente; 5, descente–montée; et 6, sans changement, faible niveau de bruit. Les trois indices de similarité (S) utilisés sont de la forme S est égal au nombre de caractères en accord divisé par le nombre de caractères informatifs. Les techniques de groupements utilisés sont à liens simples, complets, et selon l'association moyenne. Les liens simples et l'association moyenne démontrent une division nord–sud avec les trois indices; les liens complets ne trouve que de rares groupements locaux. La division entre les deux groupes tombe un peu au sud du Lac Nipissing. Toutes les successions indiquent un refroidissement climatique; les groupements reflètent un mouvement vers le sud des centres d'abondances des taxons, surtout le pin blanc. La méthode délimite les régions de dynamique forestière.

Mots clés : analyse de groupes, dynamiques forestières, Holocène, petit âge glaciaire, palynologie.

Introduction

Various paleoecological approaches have been used to produce "time-slice" maps of vegetation, climate, or modern analogues of pollen spectra (Davis *et al.* 1975; Delcourt and Delcourt 1987; Gaudreau and Webb 1985). Here we do not produce time-slice maps but maps of vegetation trends by considering pollen percentage variations through time. Specifically, only the direction of the trend shown by each tree pollen type is considered for Ontario pollen diagrams covering the period ca. A.D. 1000–1850. This approach facilitates a more process-oriented analysis of the pollen data by stressing regions of similar vegetation dynamic rather than similar vegetation composition.

Birks and Gordon (1985) and Birks (1986) summarized several numerical methods for the zonation, comparison, and correlation of pollen diagrams. The three comparative and (or) correlative methods are (i) zone-by-zone comparison, where

each pollen zone in each pollen percentage diagram is considered as a unit (within-zone trends are lost); (ii) combined scaling, where each sample (level) from the diagrams being compared is taken as a unit, and a cluster analysis is performed to link individual samples with similar samples in the other diagram(s); and (iii) sequence slotting, similar to combined scaling, but with some stratigraphic constraint.

Our method differs from those of Birks (1986) because the basic unit of comparison is the entire pollen diagram rather than the individual sample. In numerical taxonomy terms, the characters are the trends shown by each taxon in each pollen diagram, and the objective taxonomic units (OTUs) are the pollen diagrams themselves. The effects of sedimentation and basin morphology, which influence pollen spectra, are reduced both by considering the trends rather than just the relative abundance for each tree-pollen type and by the clustering, which identifies units of similar vegetation dynamic, with no interpretation occurring at the level of the individual diagram.

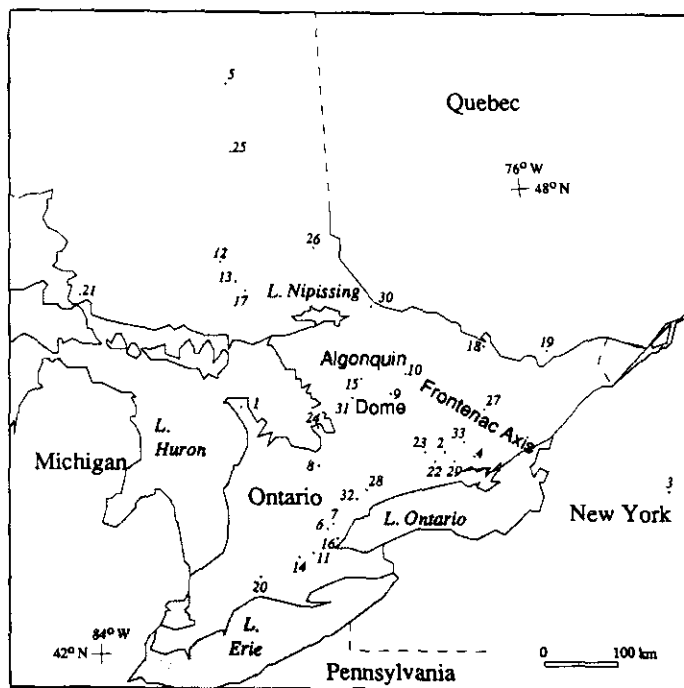


FIG. 1. Location map. (1) Shouldice Lake (McAndrews, unpublished). (2) Barry Lake (McAndrews 1984). (3) Clear Lake (Gajewski *et al.* 1987). (4) Johnston Lake (E. Woods, unpublished). (5) Crates Lake (Liu 1990). (6) Crawford Bog (Karrow 1987). (7) Crawford Lake (McAndrews and Boyko-Diakonow 1989). (8) Edward Lake (McAndrews 1981). (9) Emerson Pond (McAndrews, unpublished). (10) Found Lake (McAndrews 1981). (11) Hams Lake (Bennett 1987). (12) Jack Lake (Liu 1990). (13) Loon Lake (Liu 1978). (14) Maplehurst Lake (Mott and Farley-Gill 1978). (15) Mayflower Lake (Gold 1977). (16) Miller Lake (J. H. McAndrews, unpublished). (17) Nina Lake (Liu 1990). (18) Perch Lake (Boyko-Diakonow and Terasmae 1975). (19) Pink Lake (Mott and Farley-Gill 1981). (20) Pond Mills Pond (McAndrews 1981). (21) Quadrangle Lake (Terasmae 1967). (22) Rice Lake (McAndrews 1984). (23) Rice Marsh (McAndrews 1984). (24) Second Lake (Burden *et al.* 1986). (25) Lake Six (Liu 1990). (26) Three Pines Bog (J. H. McAndrews, unpublished). (27) Tonawa Lake (J. H. McAndrews, unpublished). (28) Van Nostrand Lake (McAndrews 1973). (29) Little Lake (J. H. McAndrews, unpublished). (30) Lac Bastien (Bennett 1987). (31) Nutt Lake (Bennett 1987). (32) Kelly Lake (I. D. Campbell, unpublished). (33) Oak Lake (J. H. McAndrews, unpublished).

The A.D. 1000–1850 time period in Ontario has several advantages. Firstly, this time interval is bounded by a conspicuous marker horizon in most Great Lakes region pollen diagrams, the rise of ragweed (*Ambrosia*) pollen (McAndrews 1988), which corresponds with vegetation changes due to Eurocanadian agriculture starting ca. 1850. This marker horizon, combined with available radiocarbon dates, allows good dating control. Secondly, new techniques have been developed that allow the collection and close-interval sampling of the upper metre of lake mud, which contains the record of the last 1000 years in most sites as well as the mud–water interface (Wright 1980; Saarnisto 1986). These advances in core recov-

ery techniques have permitted the development of a data base of pollen diagrams with fine-grained time resolution (close-interval sampling of varved sediment allows seasonal resolution; decadal resolution is the closest interval used in this study). Thirdly, historical records in Europe and worldwide proxy data provide a detailed and precise record of global climate fluctuations, such as the Little Ice Age (LIA), through this time interval (Ladurie 1971; Grove 1988).

Methods

Data codes

Percentage data for 17 arboreal taxa were used. To minimize local vegetation, topographic, and hydrological effects, and to most efficiently extract trends in the pollen data, the pollen diagrams were encoded subjectively using a single, seven-state variable for each arboreal taxon. The state codes correspond to the following: 0, pollen of the taxon absent or unlisted in the last 1000 years; 1, taxon present but with highly variable values and no discernable trend due to a high noise to signal ratio in the pollen diagram; 2, taxon percentage increasing; 3, taxon percentage decreasing; 4, taxon showing a distinct peak; 5, taxon showing a distinct trough; and 6, taxon with consistent percentages showing no overall change. Of the 48 diagrams from Ontario and adjacent New York and Quebec examined, 33 were selected for this analysis. Locations of the 33 pollen sites are shown in Fig. 1, and representative diagrams with the codes assigned to the pollen taxa are shown in Fig. 2.

Some diagrams were excluded from the cluster analysis because they lacked definite trends. A lack of definite trends was most often due to a high noise to signal ratio and appeared most frequently in sites where the sedimentology varied through the core. Another source of high noise was too large a sampling interval; diagrams having fewer than six samples in the period A.D. 1000–1850 were excluded for this reason. The inclusion of diagrams with an insufficient number of taxa coded in the range 2–6 resulted in too many ties in the similarity matrices. This problem was partly reduced by calculating similarity indices only for those pairs of diagrams where the denominators of the similarity indices were greater than 5. Pairs with smaller denominators were assigned similarities of 0, to prevent unjustified fusion of fundamentally nonsimilar diagrams in the cluster analysis. This eliminated several diagrams from consideration, by requiring a minimum information content. Of 48 published and unpublished diagrams collected after an initial assessment of their suitability for the analysis (preliminary requirements included a need for at least two radiocarbon or other dates, a minimum of eight arboreal species present, and a minimum of six samples in the A.D. 1000–1850 time period), 33 were found to have sufficient information content to be retained in the final analysis. Areas of the province not represented in the final 33 diagrams include the far southwest, the extreme east, a large portion of the north, and all of the western part of the province. Thirty-one of the 33 diagrams are from central and southern Ontario, with one additional diagram from New York state and one from Quebec.

Similarity indices

Standard Euclidean distance (or similarity) measures were unsatisfactory because they cannot adequately handle related but unrankable character states. We designed new similarity indices that took into account the complex relationships between variable states. Legendre and Legendre (1983) indicated that such "do-it-yourself" measures, first used by Estabrook and Rogers (1966), should be considered when (among other conditions) states are unordered or

FIG. 2. Sample pollen diagrams: (A) Nina Lake (17 on location map and in cluster analysis), (B) Found Lake (10), (C) Tonawa Lake (27), (D) Barry Lake (2), and (E) Crawford Lake (7). Upper portion of each diagram only is shown; all are redrawn from published or original data. The pollen sum includes the 17 tree pollen taxa shown, but not the herb *Ambrosia*, which marks the historic Eurocanadian land clearance near each site (shown by a horizontal line drawn across each diagram). The numbers following the species names are the codes used for the cluster analysis. See text for code meanings. Stipple shows 10× exaggeration curve.

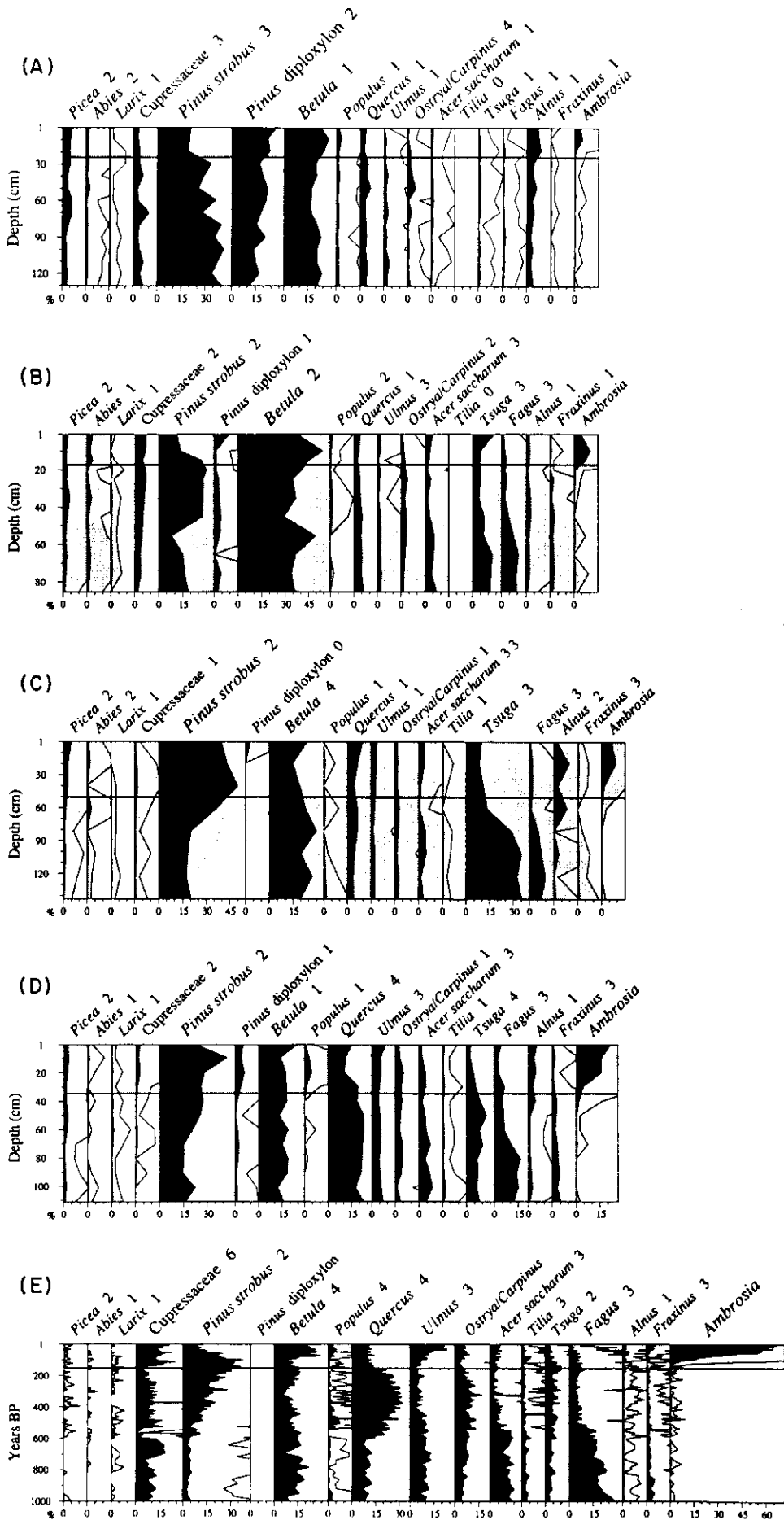


TABLE 1. Matrices of numerator and denominator values for similarity indices

Char. state	Index 1							Index 2							Index 3						
	0	1	2	3	4	5	6	0	1	2	3	4	5	6	0	1	2	3	4	5	6
Numerator																					
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	0.5
2	0	0	1	0	0	0	0	0	0	1	0	0.5	0.5	0	0	0	1	0	0.5	0.5	0
3	0	0	0	1	0	0	0	0	0	0	1	0.5	0.5	0	0	0	0	1	0.5	0.5	0
4	0	0	0	0	1	0	0	0	0	0	0.5	0.5	1	0	0.5	0	0.5	0.5	1	0	0.5
5	0	0	0	0	0	1	0	0	0	0.5	0.5	0	1	0.5	0	0.5	0.5	0.5	0	1	0.5
6	0	0	0	0	0	0	1	0	0	0	0	0.5	0.5	1	0	0.5	0	0	0.5	0.5	1
Denominator																					
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	0.5	0.5	0.5
2	0	0	1	1	0	0	0	0	0	1	1	0.5	0.5	1	0	0.5	1	1	0.5	0.5	1
3	0	0	1	1	0	0	0	0	0	1	1	0.5	0.5	1	0	0.5	1	1	0.5	0.5	1
4	0	0	0	0	1	1	0	0	0	0.5	0.5	1	1	0.5	0	0.5	0.5	0.5	1	1	0.5
5	0	0	0	0	1	1	0	0	0	0.5	0.5	1	1	0.5	0	0.5	0.5	0.5	1	1	0.5
6	0	0	0	0	0	0	1	0	0	1	1	0.5	0.5	1	0	0.5	1	1	0.5	0.5	1

NOTE: To read the contribution of a given taxon to a given comparison, find the code for that taxon in the first pollen diagram across the top of the desired index, and in the second diagram down the left side for both the numerator and the denominator. Reading across and down will give the contributions of that taxon.

partially ordered, but states coded differently nevertheless partly resemble each other. Because they depend on the subjective evaluation of the information content of the various character states, three such indices were used.

The numerators and denominators for each of these indices are presented in Table 1. All of the indices are of the form

$$[1] S = \frac{\text{no. of characters in agreement}}{\text{no. of informative characters}}$$

The first index is conservative. Agreement is declared only for character states assigned to definite trends, and only when those trends are a precise match. Character states 0 (absent) and 1 (noise) never contribute to either the numerator or the denominator. Furthermore, only certain pairings of trends are considered informative and contribute to the denominator. States 2 (rising) and 3 (falling) indicate adequate detail and lack of noise in both diagrams, so that there is a potential for a match in the pollen trends if there is a match in the vegetation trends; they therefore contribute to the denominator when one or the other is present in both diagrams for the same species. States 4 (peak) and 5 (trough) are similarly potential matches and contribute to the denominator when one or the other is present in both diagrams. Other imperfect matches are considered to be uninformative; for example, a rising trend (code 2) paired with a peak (code 4) is not considered to carry information relating to the similarity or dissimilarity of the diagrams. Although it may seem that they are different trends and therefore carry information indicating a dissimilarity, not all of these diagrams have equal resolution; a peak in one diagram may be either a rise or a fall in another diagram owing to a different sampling interval. Similarly, state 6 (no trend but low noise to signal ratio) is considered comparable only to itself, owing to the unusually low noise to signal ratio required to recognize this state.

The second index is more generous, recognizing that any trend is change. Partial agreements are recognized for nonperfect matches involving a peak or trough in one diagram and a rise, fall, or no change in the other diagram. States 0 (absent) and 1 (noise) are still excluded from consideration.

The third index is the most generous in its allowance of partial similarities owing to differing resolutions in each pair of diagrams. It allows partial similarities for matches involving a peak, trough, or no change, when paired with state 1 (noise). The assumption justifying this is that it is likely, when only a few samples cover the relevant time interval, to select samples from a peaking or troughing sequence such that the pollen curve will resemble only noise; also, the recognition of a taxon showing no change through time requires an exceptionally detailed diagram with unusually consistent percentages for the taxon under consideration.

For an ideal data set, the only index used would assign similarity in the numerator only for perfect matches and dissimilarity in the denominator for all others, because all diagrams would be constructed with very high resolution and very low noise levels. Also, the state 1 (noise) would be unnecessary. Here, the first index operates by assigning similarity only where there is a demonstrated similarity. The second and third indices increasingly assign similarity where there is simply no definite dissimilarity. It is the variability of the pollen curves (noise) and the uneven temporal resolution of the diagrams that require the creation of the intermediate, nonsimilar, and non-dissimilar states exploited by the other two indices.

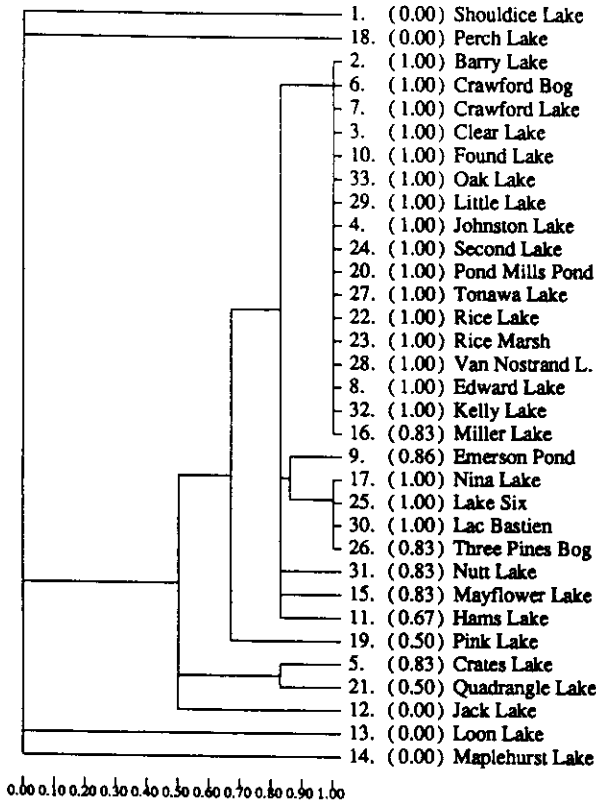
Clusters were constructed using the SAHN program of NTSYS-pc (Rohlf 1988). Single linkage, complete linkage, and unpaired weighted geometric mean analysis (UPGMA) were used with each of the three similarity indices.

Results

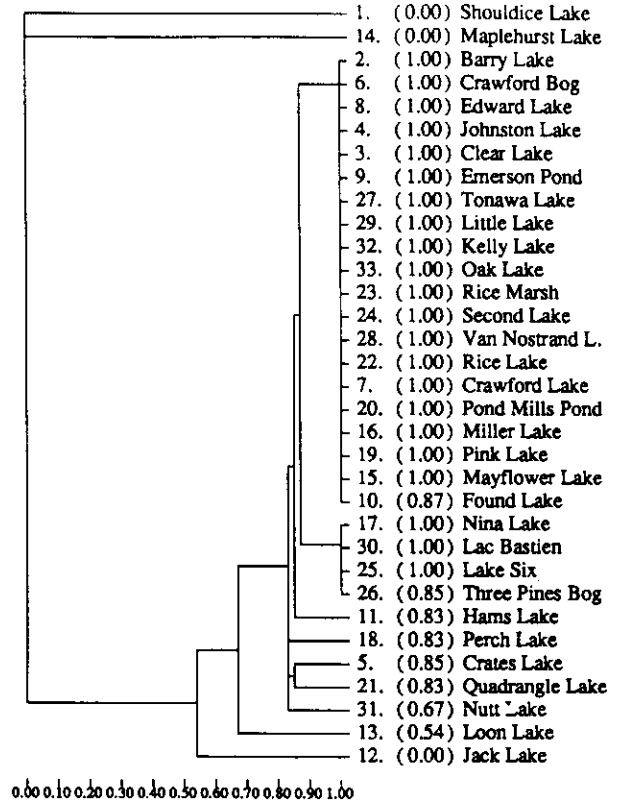
Analyses are presented in Fig. 3. Ties are common in cluster analyses of both binary and multiple-state data owing to their discontinuous nature, which forces the similarity indices into one of a finite number of categories. Although the NTSYS-pc program handles a small number of ties in a data set to be clustered, it cannot handle the larger number of ties generated by this data set. Fortunately, the main structure of the tied

FIG. 3. Twelve dendrograms produced by three clustering methods and three similarity indices. Complete link with all three indices and UPGMA with index 1 produced an overwhelming number of ties; only the first dendrogram is shown for each. Index 3 consistently produces more structured dendrograms, as does UPGMA clustering. UPGMA and index 3 combined produce the most structured dendrograms and the fewest ties. The two tied dendrograms produced this way differ only in the order of linking of Miller Lake and Second Lake to otherwise identical clusters.

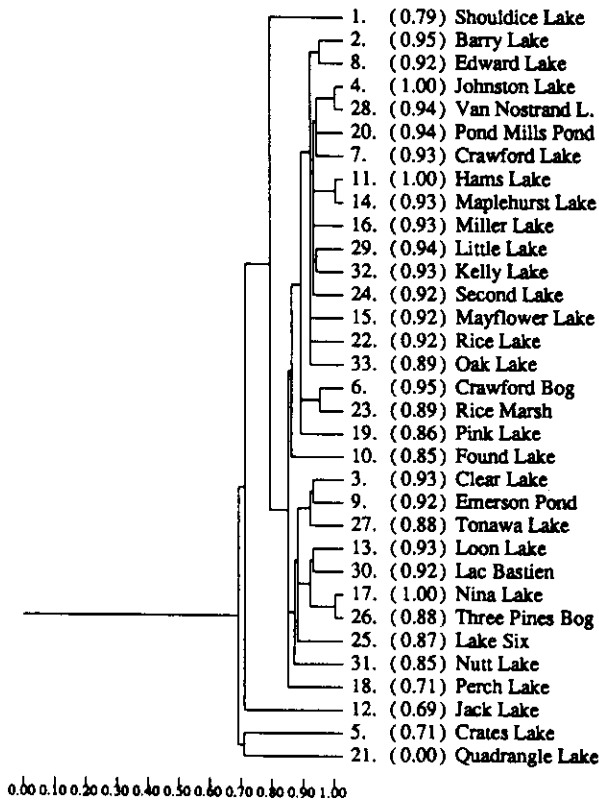
(A) Single link. Statistic 1. NTSYS.



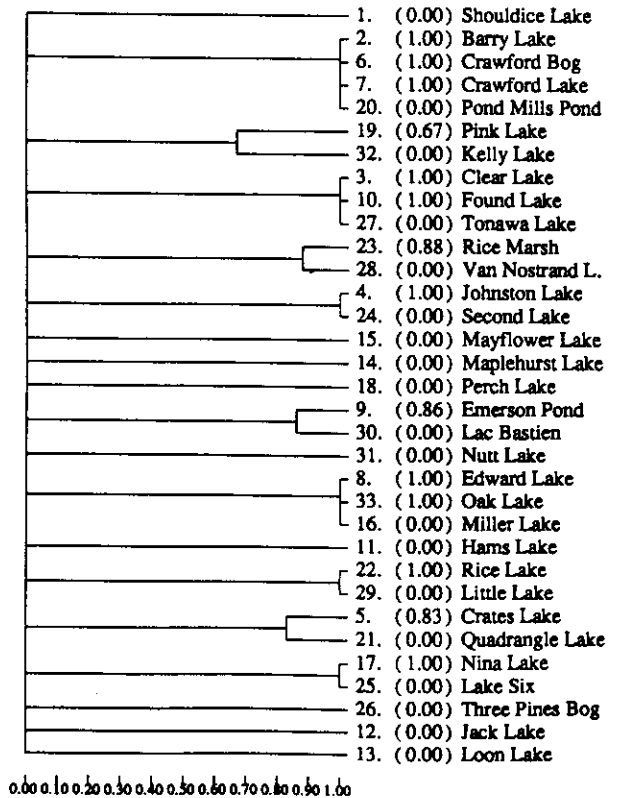
(B) Single link. Statistic 2. NTSYS.



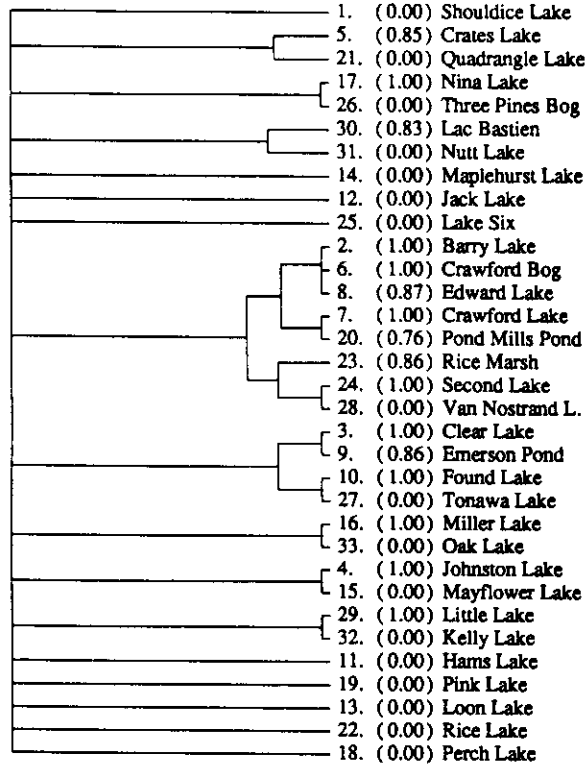
(C) Single link. Statistic 3. NTSYS.



(D) Complete link. Statistic 1. NTSYS.

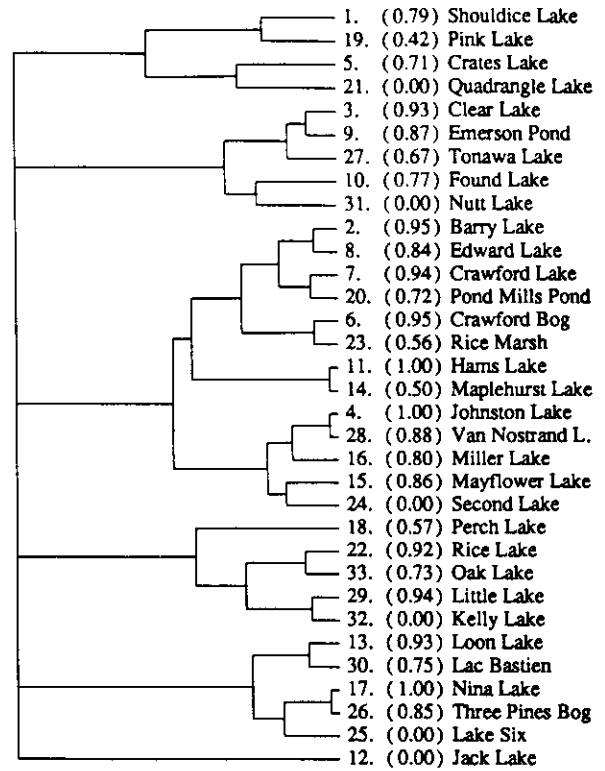


(E) Complete link. Statistic 2. NTSYS.



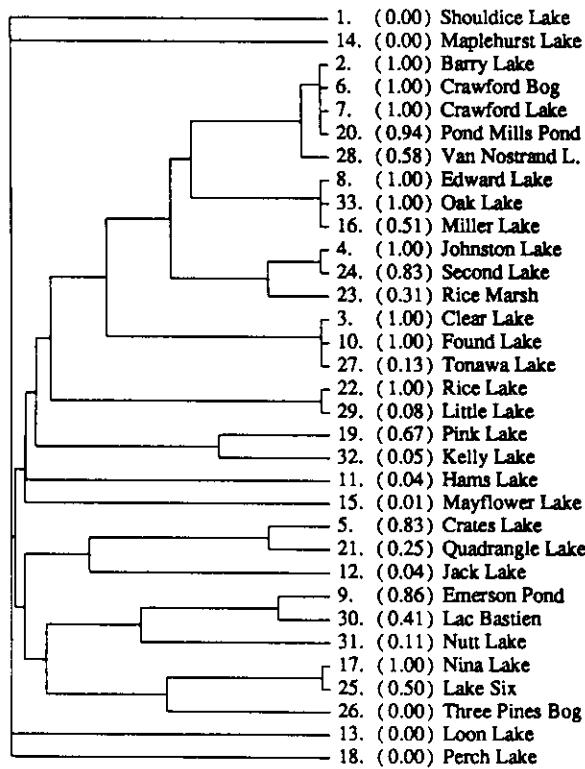
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00

(F) Complete link. Statistic 3. NTSYS.



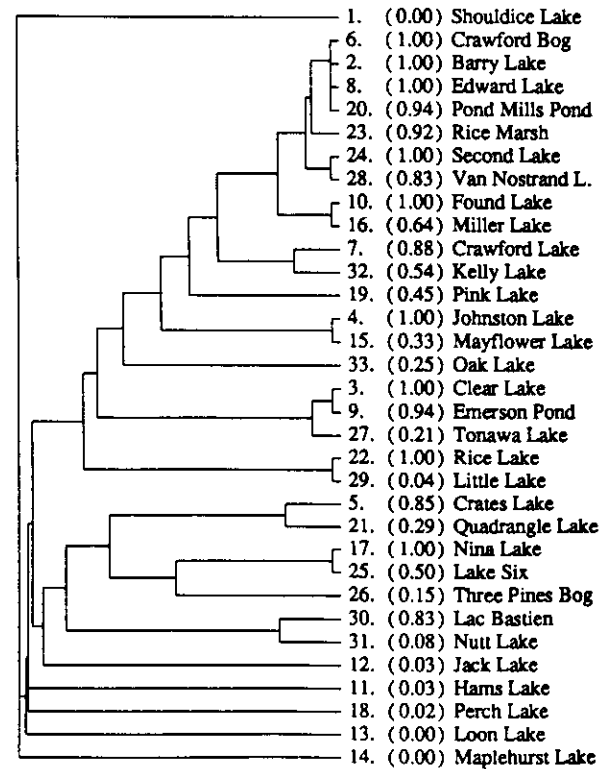
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00

(G) UPGMA. Statistic 1. NTSYS.



0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00

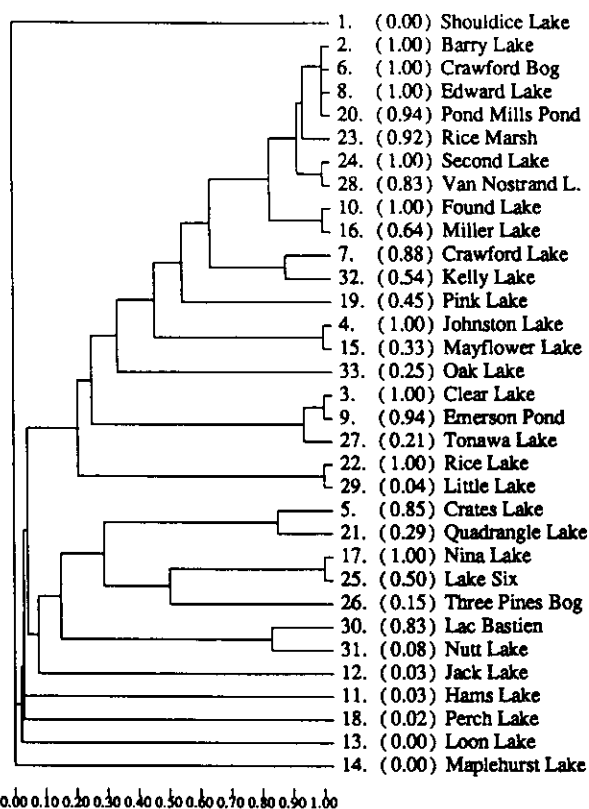
(H) UPGMA. Statistic 2, tree 1. NTSYS.



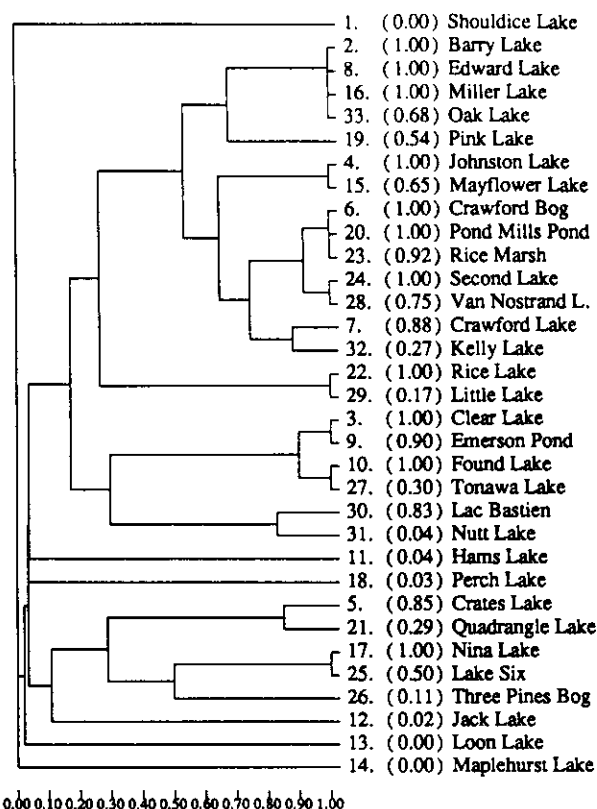
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00

FIG. 3 (continued)

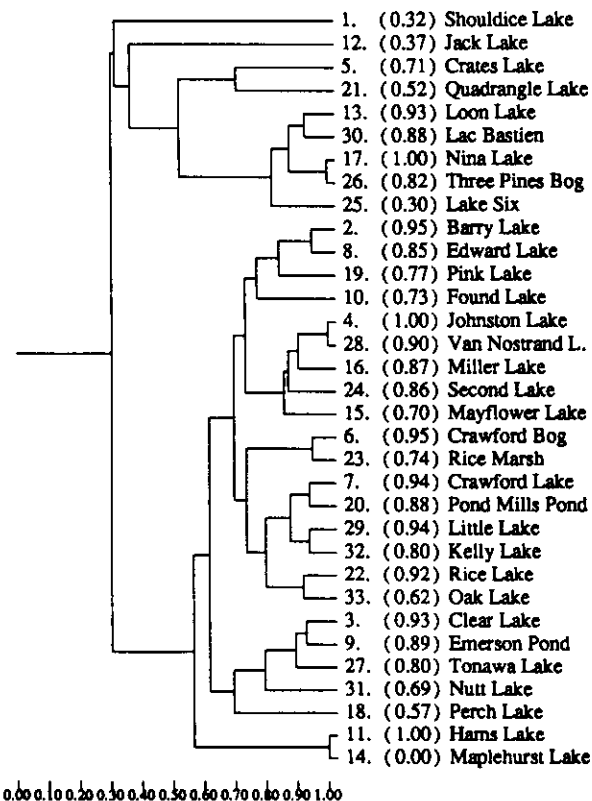
(I) UPGMA. Statistic 2, tree 2. NTSYS.



(J) UPGMA. Statistic 2, tree 3. NTSYS.



(K) UPGMA. Statistic 3, tree 1. NTSYS.



(L) UPGMA. Statistic 3, tree 2. NTSYS.

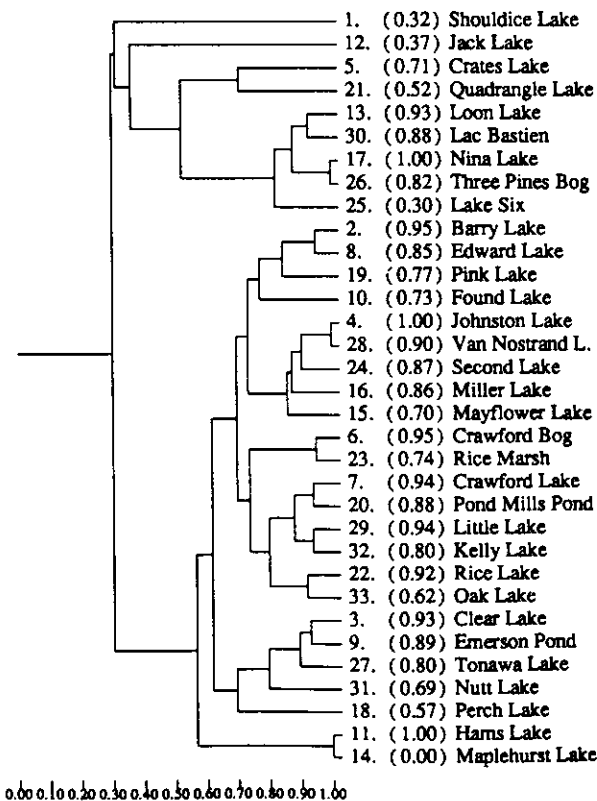


FIG. 3 (concluded)

dendrograms is similar; only the dendrograms found by NTSYS-PC in the first attempt (i.e., before the program crashed) are presented here for most combinations of methods and similarity indices.

Figure 4 shows the mapped summaries of the dendrograms presented in Fig. 3. The groups were defined by drawing a line across each dendrogram; the level at which the line was drawn was arbitrarily selected to yield several clusters for mapping. There is a north-south division in most cases. The Algonquin Dome and Frontenac Axis, a crystalline bedrock feature forming a region of relatively high elevations and shallow soils from the Algonquin Park area southeast through Kingston, Ont. and into New York state, also shows as a recurring, though poorly sampled, region on several of the cluster maps.

Seven of the 12 dendrograms presented here agree with the clusters shown in Fig. 4K. The diagrams that are excluded from all clusters on this map are: Shouldice Lake (1), Jack Lake (12), Loon Lake (13), Perch Lake (18), Nutt Lake (31), Hams Lake (11), and Maplehurst Lake (14). These exclusions mostly reflect the lower temporal resolution or higher noise levels found in these diagrams.

Some of these link preferentially to one cluster or another, without doing so in more than half the dendrograms; for instance, Hams Lake and Maplehurst Lake frequently link with each other at a fairly low level in the dendrograms, and one or the other sometimes links with another diagram from the southern group; neither of these two ever links with a site north of Lake Nipissing. Jack Lake links once with the northwestern group; Loon Lake links once with the Algonquin Dome - Frontenac Axis group and twice with the northeastern group. Shouldice Lake links only once, with Pink Lake (19) in Quebec north of Ottawa. Nutt Lake links with the larger northern group or the southern group with equal frequency, each way in 6 of the 12 dendrograms; its isolation on the summary map may therefore be due to the transitional nature of the forest dynamic in this area.

The consistent major groupings across clustering methods and similarity measures suggests that the clusters reflect "forest dynamic regions," not simply random groupings. Furthermore, some of the clusters separate sites from geographic near neighbours and link them to more distant sites (these cases will be discussed further in the next section).

Paleoecological interpretation

The phytogeographic boundary between the northern and southern groups of similar vegetation dynamics is slightly south of Lake Nipissing. This corresponds approximately to the latitudinal peak abundance of white pine in Ontario (Delcourt *et al.* 1984). South of this line, the most commonly recurring trends are reduction in beech pollen percentages followed by an increase in white pine pollen percentages. Several diagrams show an intervening peak in oak, elm, or another species.

North of this line, white pine commonly declines, with an increase in spruce or jack and red pine percentages. Where present, the intervening peak is most often birch or poplar.

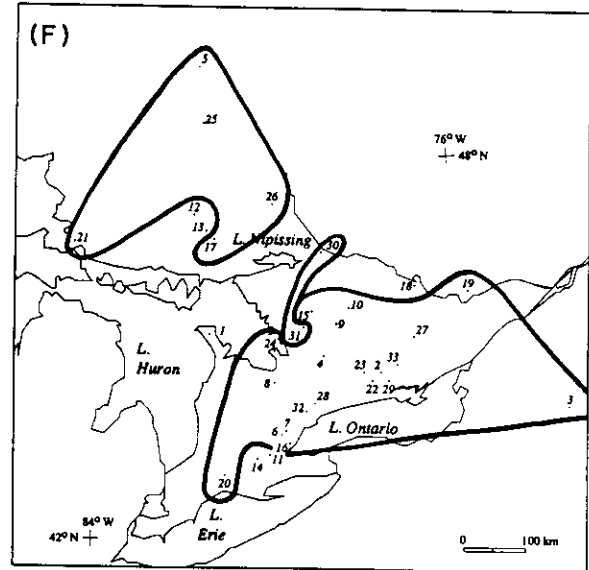
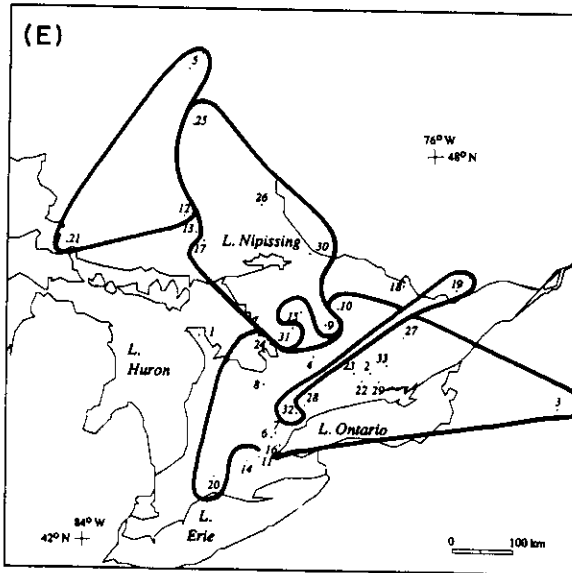
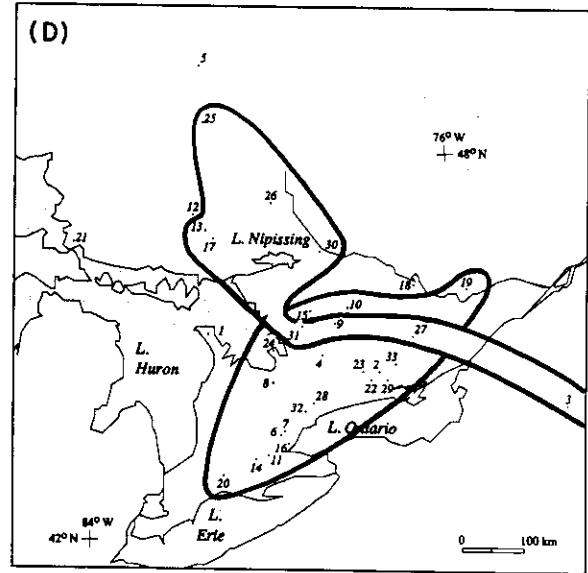
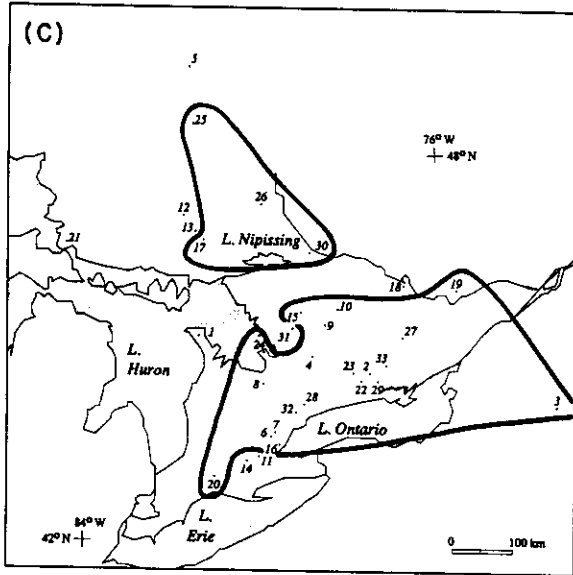
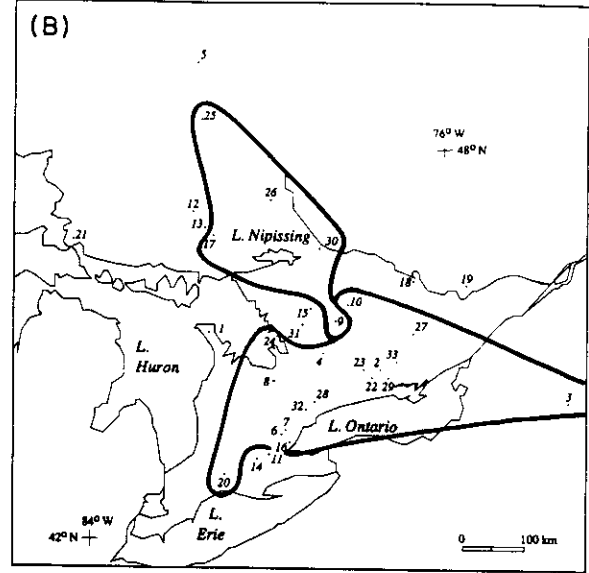
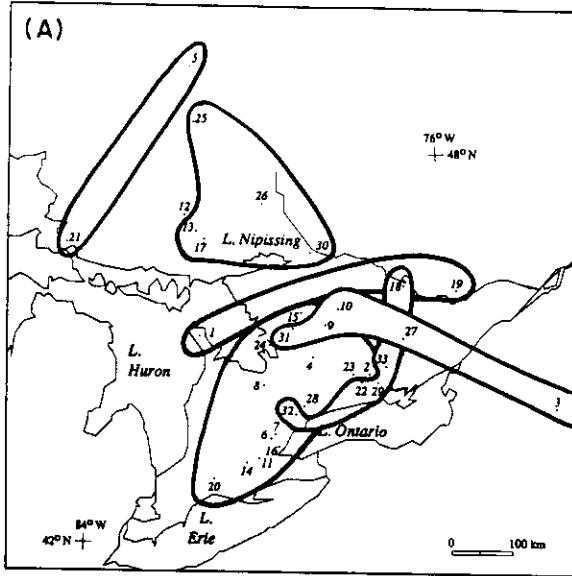
The Little Ice Age (LIA) spanned A.D. 1450-1850; it was an apparently worldwide cool period (Ladurie 1971; Grove 1988). It can be thought of as the culmination of the Neoboreal cooling, which started in the mid-Holocene. In most places, including Ontario and the adjacent United States, mean annual temperatures started declining ca. A.D. 1250, crossing below the 1931-1960 normal (30-year mean) temperature ca. A.D. 1450, and rebounding above this threshold after A.D. 1850 (Cermack 1971; Ladurie 1971; Bernabo 1981; Gajewski *et al.* 1987; Grove 1988). Mean annual temperatures 1-2°C below the 1931-1960 normal occurred in the late 1700s.

Tree abundances are in part a function of temperature (Ritchie 1987), and climate change is the only mechanism likely to have affected so many species across such a large territory. The vegetation dynamics shown in these pollen diagrams can be accounted for by the cooling of the LIA. Cooling caused a contraction of the northern range of most temperate species and perhaps a southward expansion for many boreal taxa. Beech, which reaches its northern limit just south of Lake Nipissing (Fowells 1965), declined in abundance in this, the northern part of its range. If the response of beech populations took the form of higher mortality rates for mature beech trees (possibly also with decreased seeding and establishment), then other species would increase in the more frequent canopy gaps, with reduced competition from beech seedlings in these gaps. White pine, which is most abundant just to the north of the limit of beech (Delcourt *et al.* 1984), had its climatic optimum shifted southwards by 70-140 km (corresponding to a decrease of 1-2°C in mean annual temperature). In the interval between the reduction of beech and the increase of white pine, other species, such as oak, birch, poplar, elm, and ironwood, mostly already common (for good seed-source) and slightly less shade-tolerant than beech (to take advantage of the increased frequency of canopy gaps), had a brief "bloom."

In the north, the decline of white pine was also caused by climatic cooling (and perhaps an attendant decrease in fire frequency), producing a southward shift of its centre of abundance. By analogy with modern transects across the Frontenac Axis (Beschel *et al.* 1962), white pine would probably have suffered most on wet sites and survived best on mesic sites. Spruce and jack and (or) red pine, the forest dominants, began to replace white pine, with an intermediate peak of the early-successional birch and poplar.

In all of the northern diagrams, as well as in some of the southern diagrams, at least some of the vegetation trends had been in progress for hundreds or thousands of years prior to the A.D. 1000 time limit of this study. Since the Neoboreal cooling started approximately 5000 years ago, in the mid-Holocene, it is hardly surprising to find that the vegetation response to the LIA was a continuation of its response to the longer term cooling of which the LIA was a part. What dis-

FIG. 4. Mapped summaries of the clusters defined by the cluster analyses. Complete link with indices 1 and 2 not shown owing to the lack of structure. (A) Complete link with index 3 (cutoff linkage value 0.40). (B) Single link with index 1 (cutoff linkage value 0.85). (C) Single link with index 2 (cutoff linkage value 0.90). (D) single link with index 3 (cutoff linkage value 0.85). (E) UPGMA with index 1 (cutoff linkage value 0.10). (F) UPGMA with index 2, tied dendrograms 1 and 2 (cutoff linkage value 0.20). (G) UPGMA with index 2, dendrogram 3 (cutoff linkage value 0.20). (H) UPGMA with index 3, dendrograms 1 and 2 (cutoff linkage value 0.35). (I) Groupings admitted by all 12 dendrograms presented here, using the same cutoffs as were used for the maps of the individual dendrograms (the cutoffs for complete link index 1 and index 2, not mapped owing to the large number of small clusters formed, were 0.50). (J) Groupings admitted by 10 of 12 dendrograms (cutoffs as for I). (K) Groupings admitted by 7 of 12 dendrograms (cutoffs as for I).



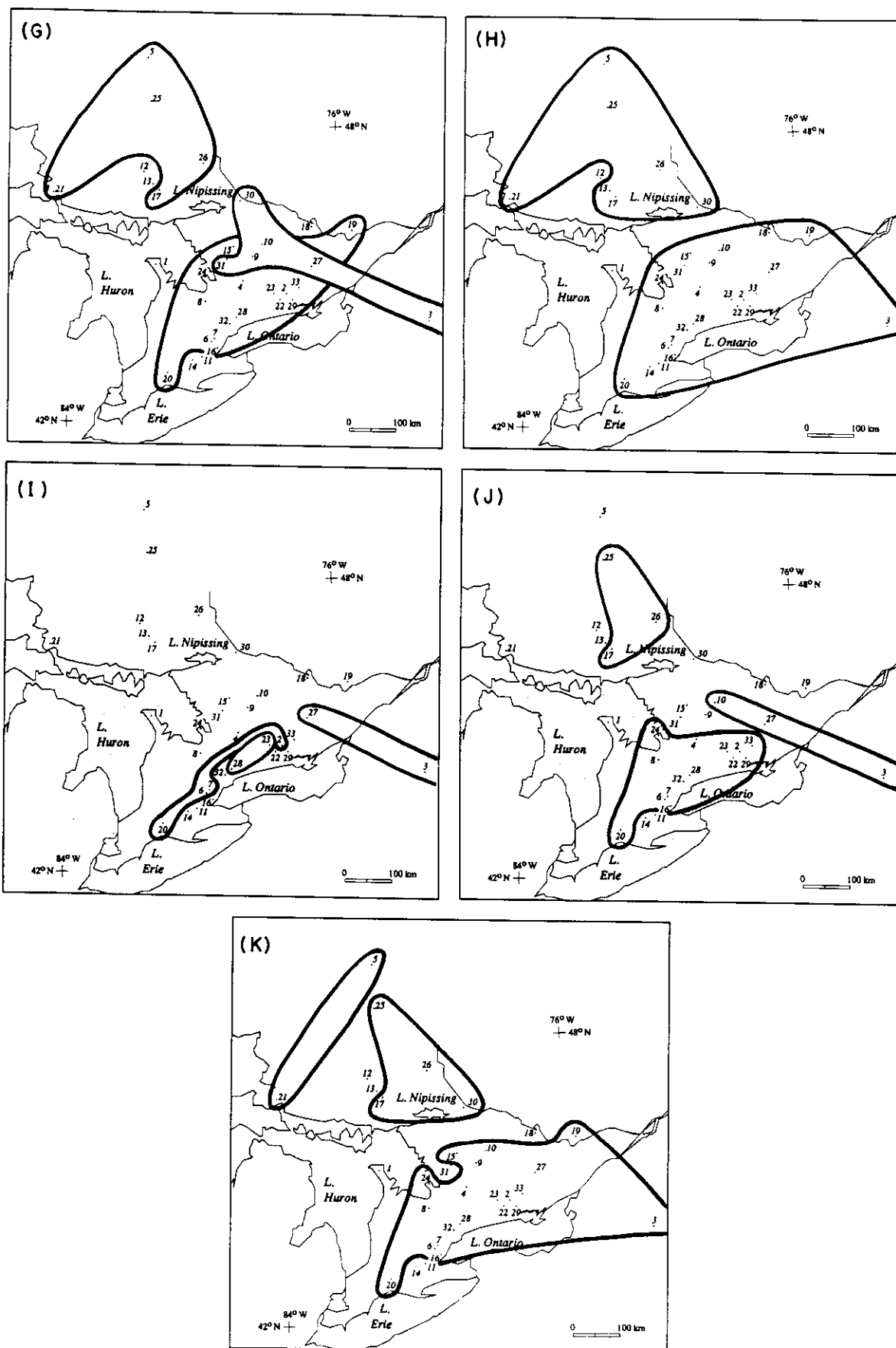


FIG. 4 (concluded)

tinguished the LIA from this general cooling trend was the rapidity of the cooling, sufficient to cause the peaks of intermediate-successional species like oak and pine in southern Ontario. A less rapid cooling of equal magnitude might have caused a beech decline, but perhaps without the rapidity required to open sufficient canopy gaps to cause a peak in intermediate successional species. The lack of a peak of intermediate successional species in the northern part of the area may simply be due to the relatively short fire-rotation period in the north, which prevents the most shade-tolerant species from becoming dominant; in effect, the dominant species are intermediate-successional, with the forest prevented from achieving a late-successional composition by the fire rotation.

Separation of near neighbouring sites requires further discussion. The linking of Lac Bastien (30) with the northern, rather than the southern group, could be due to its position near the centre of abundance of white pine. The separation of Crates Lake (5) and Quadrangle Lake (21) from the rest of the northern sites is explained by the decline in spruce (*Picea*) at both sites, followed by the rise of ironwood and (or) blue beech (*Ostrya-Carpinus*) and birch (*Betula*). This also suggests an increase in frequency of canopy gap formation but without the increase in spruce found throughout the rest of the northern region. Crates Lake is near the centre of abundance of spruce (Delcourt *et al.* 1984), so its failure to rise there could be due to climatic cooling.

The Frontenac Axis is poorly sampled in this study. Only Tonawa Lake (27) in Ontario joins with three or four lakes on the Algonquin dome and Clear Pond (3) in the Adirondacks. These sites form a discrete cluster on some of the dendrograms. The Frontenac Axis, Algonquin Dome, and Adirondacks share several characteristics, including shallow soils, abundant crystalline bedrock, rough terrain, and a generally higher altitude (therefore cooler climate) than the surrounding terrain (Chapman and Putnam 1984).

Davis and Botkin (1985) suggest that only relatively few pollen sites on good soil might carry a detectable signal from the LIA. This is not the case in the mixed forest of southern Ontario, where virtually every closely sampled pollen site shows a signal. This vegetation dynamic has been variously ascribed to Indian agriculture (McAndrews 1988; McAndrews and Boyko-Diakonow 1989) and to the LIA (Boyko-Diakonow and Terasmae 1975; McAndrews 1988; Campbell and Campbell 1989). Indian agriculture is an unlikely candidate, since the northern limit of prehistoric maize agriculture in Ontario lies along the southern edge of the Canadian Shield, well to the south of Lake Nipissing. However, the consistency with which this signal occurs throughout southern Ontario and with which a contemporaneous signal ascribable to the LIA occurs in northern Ontario, suggests that detecting the LIA in most Ontario pollen sites is largely a matter of sufficiently close interval sampling of the pollen cores, with time intervals on the order of decades.

Conclusions

The clustering of pollen diagrams delimits regions of past vegetation dynamics. It provides information similar to that found on time-slice maps of pollen abundances (or maps of interpreted vegetation or climate), but it emphasizes vegetation dynamics. This in turn facilitates discussion of the physical and ecological processes driving the dynamics at the level of forest regions. This method of data summarization requires a

relatively high geographic density of detailed, well-dated pollen diagrams, with temporal resolution suited to the time scale of the dynamic under investigation. The study of LIA Ontario presented here provides a critical starting point for a broader scale study covering the last 1000 years in northeastern North America.

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