

An aeropalynological study of metropolitan Toronto

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Abstract

This study uses 6 years of atmospheric pollen data to examine temporal variability of airborne pollen concentrations at various scales. Airborne pollen was collected from 1985 to 1990 with a Burkard trap, located 18 m above ground at Scarborough College, Toronto, Canada. Pollen season parameters are defined and summarized for all taxa in preparation for developing forecasting models. Annual totals of pollen concentration show great interannual variability. The highest coefficient of variation occurs in *Tsuga*, *Fraxinus*, *Betula* and *Fagus*, while the lowest in *Quercus* and *Ambrosia*. Some taxa show periodic cycles consistent with mast reproductive behaviour. In many studies, the start of the pollen season is defined as an arbitrary percentage of the annual sum. As a result, the start of the season cannot be identified until the season has passed. As well, due to large fluctuations in annual sum, start dates are more variable. This is not practical for the purposes of forecasting. In this study, the start of the pollen season is defined by a critical concentration threshold which signals the onset of the main pollen season in all years. These critical levels ranged from 2 to 60 grains/m³ for the abundant taxa. Interannual variation in the start of the season is approximately 20 days for tree taxa, 5 days for Poaceae, and 2 days for *Ambrosia*. For many plants, dehiscence is triggered at a critical level of accumulated degree-days. Since annual rates of temperature increase show great variation, there is also interannual variability in the onset of pollen release. Multi-year average pollen curves incorporate these differences in onset and may give an inaccurate representation of the pollen season in a typical year. This paper presents a method of aligning yearly pollen curves to reduce seasonal variation and more accurately represent both the average timing and magnitude of the pollen season. For some types, such as *Betula* and Poaceae, the resulting curves are positively skewed. Tree taxa, in general, exhibit a more symmetric pollen concentration curve. Aligned average pollen concentration curves are presented for Toronto in the form of a pollen calendar. In addition, phenological data for all common taxa are summarized. © 1997 Elsevier Science Ireland Ltd.

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1. Introduction

In recent decades, the incidence of asthma and allergies due to airborne biological material has increased both worldwide (Wüthrich, 1989; Arrighi, 1995), and in Canada (Bates and Baker-Anderson, 1987; Mao et al., 1987). Since information regarding the composition, timing, and abundance of airborne allergenic material is an essential tool for assessing exposures and developing effective avoidance strategies, general reports of pollen

occurrence should accurately represent the timing and abundance in a typical year.

The timing and prevalence of pollen in the air is the product of, (a) the distance to and amount of source vegetation present in the area; (b) the physiological factors affecting the timing, amount of flowering and rate of pollen release; and (c) the atmospheric conditions affecting pollen entrainment and dilution. Atmospheric pollen concentration is well known to be highly variable in both time and space. This characteristic prevails across many scales (e.g. hourly, seasonally, yearly and meters, kilometers and regions). For this reason, it is necessary to obtain several years of data

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before reporting average atmospheric pollen levels. Even after many years (decades possibly), additional data can change previous trends in pollen concentration.

This paper reports on the pollen content of the air of Metropolitan Toronto from 1985 to 1990. Previous studies of airborne pollen and fungal spores in Toronto used gravity sampling techniques that are now known to be quantitatively deficient (Dingle, 1957; Raynor, 1979); they identified few taxa, or were conducted for only 1–3 years (Detweiler and Hurst, 1930; LaRush, 1932; Collins-Williams and Best, 1955; Collins-Williams et al., 1973). The recent investigation by Cambon (1992) of cumulative weekly samples over a 2-year period provides a taxonomically detailed record of airborne pollen at four sites in southern Ontario, including Toronto. However, the methods used lack the temporal precision required for an analysis of allergenic pollen in relation to environmental conditions and human health. These studies identified the three main seasons of atmospheric pollen; spring-flowering trees, summer grasses, and fall ragweed.

Several pollen season parameters are of interest for the purpose of forecasting atmospheric pollen concentrations. These are the start, duration and magnitude of the season, and the shape of the pollen curve. The purpose of this study is to define these elements and report on their variability in preparation for developing forecasting models.

In anemophilous trees, pollen release is typically triggered at a certain level of accumulated degree days (i.e. temperature dependent) (Boyer, 1973; Frenguelli et al., 1991, 1992). In years when the rate of spring-time warming is greater, pollen release occurs sooner. To examine variation in the onset, the start of the pollen season must first be defined. Numerous approaches have been employed, many of which cannot identify the start date until the season has past (Mullenders, 1974; Pathirane, 1975; Lejoly-Gabriel, 1978; Nilsson and Persson, 1981; Frenguelli et al., 1991). For the purposes of forecasting atmospheric pollen concentrations, these methods are not practical since it is necessary to identify the start of the season immediately. In addition, methods that utilize a percentage of the annual sum to identify the start are in fact using different critical levels each year due to yearly differences in the annual sum. In this study, several years pollen data are examined to establish a consistent method of defining pollen season initiation and identify the start date immediately.

The seasonal progression of the pollen season, which often is a composite of a number of species, may show a consistent pattern from year to year for some types (Comtois and Sherknies, 1991). Yet, because of yearly variation in the timing of onset of

anthesis, pollen curves averaged over several years incorporate these differences in onset and thus several peaks occur when perhaps only one peak existed in each year. In essence, the true amplitude and morphology of each yearly pollen profile are masked. This is particularly true for tree taxa where pollination requires temperature dependent triggers to satisfy chilling requirements and the accumulation of heating for the release of dormancy and the onset of pollination. Variability in the onset of pollen release in strictly time dependent multi-year averages causes inaccurate representations of the timing, duration, and abundance of pollen for a typical year. In this study, I present a procedure of aligning annual curves in order to reduce apparent seasonal variability, elucidate the shape of the seasonal pollen curve, and report more accurately both the average timing and abundance of atmospheric pollen.

2. Geographic and floristic characteristics

The study area is located within the boundaries of Metropolitan Toronto, Ontario, Canada, 43° 40'N, 79° 23'W (Fig. 1). Metropolitan Toronto, located on the northern shore of Lake Ontario, lies within the transition between the deciduous (Carolinian) forest region and the mixed (Great Lakes–St. Lawrence) forest region (Soper and Heimburger, 1982; Rowe, 1972). The semi-natural woods in the area are dominated by roughly equal proportions of conifers—*Tsuga canadensis*, *Thuja occidentalis*, *Pinus* spp., *Picea* spp. and *Taxus canadensis*; and deciduous angiosperms—*Acer* spp., *Betula* spp., *Fagus grandifolia*, *Fraxinus* spp., *Ulmus americana*, *Populus* spp., *Salix* spp. and *Quercus* spp. In addition, many ornamental and horticultural trees and shrubs have been introduced. Toronto is peculiar among North American cities in that it is built on loosely consolidated Pleistocene sediments that erode easily, leaving several deep and wide river valleys (Chapman and Putnam, 1966). These valleys, being too unstable for construction, are maintained as semi-natural woodlands and parkland and hence act as source areas for tree pollen. Urban development in the area is extensive producing large expanses of transitory disturbed habitats that favour such weed species as the allergenically noxious ragweed (*Ambrosia*). Later stages of urbanization have produced widespread plantings of ornamental taxa along streets and in gardens. The combined effect of the distinctive geological setting of the city and its rapid residential, commercial, and industrial expansion at its periphery, produces a large conurbation with abundant source areas for airborne, often allergenic pollen.

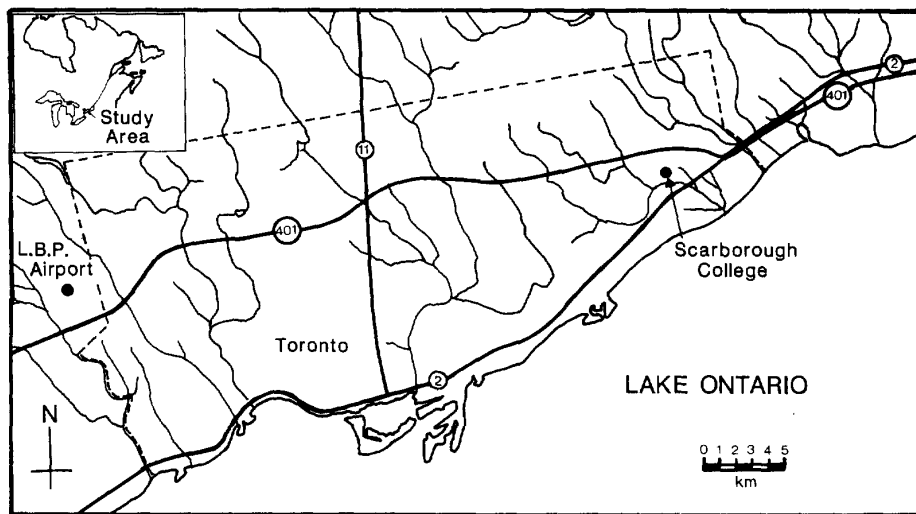


Fig. 1. Map of the Metropolitan Toronto area (dashed line) showing the pollen sampling station location at Scarborough College and meteorological station at Lester B. Pearson airport (L.B.P.).

3. Climate

The climate of Metropolitan Toronto is continental in nature but greatly modified by the Great Lakes (Auld et al., 1990). The annual temperature cycle results in four well defined seasons. Variations in temperature track changes in daylength which reach a maximum of 16 h at the summer solstice (Astronomical Almanac, 1989). Monthly precipitation amounts are one of the most predictable in the world with an average of 63 mm (Auld et al., 1990; Phillips, 1990). Winds are predominantly from the west, and weather systems pass rapidly, resulting in day to day weather variability. Wind speed and variability change seasonally with minimum values occurring during August. Locally, climatic conditions are heterogeneous and vary with land use, topography and distance from Lake Ontario (Auld et al., 1990). Meteorological data were obtained from the Atmospheric Environment Service for the meteorological station at Lester B. Pearson International Airport (Fig. 1).

4. Pollen sampling methods

Airborne pollen was sampled continuously (1985–1990) using a Burkard automatic volumetric pollen and spore trap located on the roof of Scarborough College, 18 m above ground (see Fig. 1). During this study, pollen samples were collected on melinex tape covered with a mixture of 9 parts vaseline to 1 part wax (white paraffin, melting point 68–74°C). Once exposed, tapes were cut into daily segments (48 mm long) and adhered to microscope slides using a thin film of gelvatol. A

solution of glycerol with lactophenol and a few drops of basic fuchsin was used as a mounting medium and stain. Microscopic counts ($\times 512$) of pollen grains along transverse traverses (perpendicular to the direction of movement of the drum) were made at 4-mm (2-h) intervals as suggested by K  p  l   (1981, 1984), K  p  l   and Penttinen (1981). Counts were converted to average daily concentration as number of grains/m³ of air.

5. Results

Table 1 lists the pollen taxa, with their common names, registered at Toronto. The listed taxa include plants native to the Great Lakes–St. Lawrence or Carolinian forest regions, and, in a few instances, introduced ornamental or cultivated species.

5.1. The yearly cycle

Average atmospheric pollen concentrations for all taxa are shown in Fig. 2. The yearly cycle begins in late March to early April, increases to a peak around mid-May, and decreases through mid June. The summer months of June and July are characterized by much lower pollen concentrations. Pollen concentrations begin to rise in mid August to a secondary peak in early September and then decrease throughout September and October toward the end of the pollen season. The winter months show very infrequent pollen occurrences. The three main seasonal contributors to atmospheric pollen concentrations are: spring flowering trees, summer grasses, and the fall flowering ragweed.

5.2. Yearly productivity

Total yearly pollen production of all taxa varies greatly from year to year (Fig. 3). In this study, productivity peaked during 1987 and 1989. Yearly pollen production

Table 1
List of pollen taxa registered at Toronto

Latin name	Common name
<i>Abies balsamea</i> (L.) Mill.	Balsam fir
<i>Acer</i> spp.	Maple
<i>Aesculus hippocastanum</i> L.	Horse chestnut
<i>Alnus</i> spp.	Alder
<i>Ambrosia</i> spp.	Ragweed
Apiaceae	Parsley family
<i>Artemisia</i> spp.	Wormwood
<i>Betula</i> spp.	Birch
Brassicaceae	Mustard family
<i>Carpinus caroliniana</i> Walt.	Hornbeam
<i>Ostrya virginiana</i> (Mill.) Kech	Ironwood
<i>Carya</i> spp.	Hickory
<i>Castanea</i> spp.	Chestnut
<i>Celtis occidentalis</i> L.	Hackberry
Chenopodiaceae	Lamb's quarters
Amaranthaceae	Pigweed
<i>Cornus</i> spp.	Dogwood
<i>Corylus</i> spp.	Hazelnut
Cupressaceae	Juniper/cedar
Cyperaceae	Sedge family
<i>Equisetum</i> spp.	Horsetail
Ericaceae	Heath family
<i>Fagus grandifolia</i> Ehrh.	American beech
<i>Fraxinus</i> spp.	Ash
<i>Iva</i> spp.	Marsh-elder
<i>Juglans</i> spp.	Walnut
Leguminosae	Pulse family
<i>Lycopodium</i> spp.	Club-moss
<i>Morus</i> spp.	Mulberry
<i>Picea</i> spp.	Spruce
<i>Pinus</i> spp.	Pine
<i>Plantago</i> spp.	Plantain
<i>Platanus occidentalis</i> L.	Sycamore
Poaceae	Grass family
<i>Populus</i> spp.	Poplar
<i>Prunus</i> spp.	Cherry
<i>Quercus</i> spp.	Oak
<i>Ranunculus</i> spp.	Buttercup
<i>Rhamnus</i> spp.	Buckthorn
<i>Rhus</i> spp.	Sumac
Rosaceae	Rose family
<i>Rumex</i> spp.	Dock or sorrel
<i>Salix</i> spp.	Willow
<i>Taxus</i> spp.	Yew
<i>Thalictrum</i> spp.	Meadow rue
<i>Tilia</i> spp.	Basswood
<i>Tsuga canadensis</i> (L.) Carr.	Hemlock
Tubuliflorae (Compositae)	Composite
<i>Typha</i> spp.	Cat-tail
<i>Ulmus</i> spp.	Elm
<i>Urtica</i> spp.	Nettle
<i>Viburnum</i> spp.	Arrow-wood
<i>Xanthium</i> spp.	Cocklebur
<i>Zea mays</i> L.	Corn

for individual taxa also show marked variation (Fig. 4), with high values recorded for different taxa in different years. Clearly, some taxa show greater variability from year to year than others. A coefficient of variation (the standard deviation divided by the mean) was calculated for the major taxa to examine the relative interannual variation irrespective of mean pollen productivity (Fig. 5). Those taxa with the highest variability are *Tsuga*, *Fraxinus*, *Betula* and *Fagus*; they vary by roughly 100% of their mean level. The least variable types are *Quercus* and *Ambrosia*.

5.3. Phenology

The rate of springtime warming, expressed as the cumulative sum of average daily temperatures above 5°C (growing degree-days), also varies from year to year (Fig. 6). Two years, 1988 and 1989, were significantly slower to warm. This delayed flowering as shown by curves of accumulated pollen concentration through the spring for two types, *Betula* and *Quercus* (Fig. 7). Fig. 7 illustrates the variability in the onset of pollination. For *Betula*, flowering initiation has varied by almost 4 weeks in the 6 years studied.

To study the variability in onset of pollination, the start of the season must first be defined. Frequently, early minor registrations are followed by a rapid rise in pollen concentration. Yearly pollen concentration curves for each taxon were examined graphically to determine the level that would clearly indicate the start of the main pollen season. For example, the threshold for *Populus*, determined to be an average daily concentration > 20 grains/m³ (Fig. 8), indicated the start of the main pollen season in all years. For some taxa, usually minor types, the best indication of the season's start was when the first pollen grains were recorded. Occasionally single grain occurrences were found outside the season (e.g. *Plantago*) which are thought to occur from reintraintment. When this occurred, the start was determined as the first day pollen grains were found in continuous or near continuous occurrence. Table 2 contains the results of the start date criteria determination, the average start date, and the range of earliest and latest start dates for all taxa.

Threshold atmospheric pollen concentrations, that signalled the onset of the pollen season, were determined for the abundant types, and ranged from 2 to 60 pollen grains/m³ of air. The concentration threshold, when applied to the aligned average curve of the taxon, represented a range of 1–15% of the average annual sum. Spring tree taxa exhibited the greatest variability in start dates, ranging up to 20 days between years. Poaceae initiation varied by 5 days, and *Ambrosia* by only 2 days, in start date between years. Other herbaceous taxa such as *Thalictrum* and *Artemisia* exhibited a wide range in start dates, but this may be due to low, sporadic registrations.

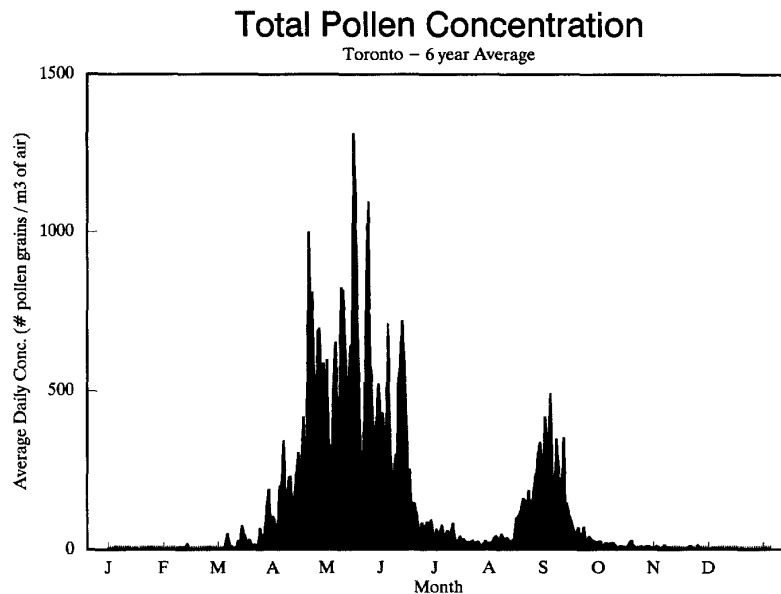


Fig. 2. Total atmospheric pollen concentration, averaged for the 6 years 1985–1990, at Toronto, Ontario.

Pollen season duration, defined as the time from the start date to the last day the start date criteria were observed, was shortest for tree taxa such as *Acer*, *Carpinus/Ostrya*, *Picea*, and *Tsuga* and lasted < 15 days. In general, the pollen season of other tree taxa averaged roughly 30 days in duration. Seasons for most other taxa lasted greater than 53 days.

Since the pollen season varies in time, multi-year time-dependent averages are not representative of pollen occurrence in any given year. For example, the five year average curve for *Acer* (Fig. 9a) shows numerous seasonal peaks. The cumulative frequency curve shows bimodal flowering events in each year, with each peak being variable in timing (Fig. 9b). The result of averaging all years is that yearly peak periods may be averaged over non peak times in other years thus creating a

complicated average curve. In order to better characterize the seasonal trend, pollen curves from each year were matched with the pollen curves of other years and then averaged. For *Acer*, each yearly pollen curve was cut between the bimodal peaks and each half moved to each peak's average start date. The five year average was then calculated on the adjusted data (Fig. 9c). For some types, this adjustment greatly simplified the seasonal average curve, however, for *Acer*, temporal variation is still present. A second approach identified the two dates of peak concentration for *Acer* in each year. Again the curves were moved to the average peak date in each case, and the five year averages calculated. Now two clear peaks are evident in the average curve (Fig. 9d). Peak atmospheric concentrations changed from 90 pollen grains/m³ per peak in the time dependent average (Fig. 9a) to 90 and 300 pollen grains/m³, respectively in the peak date aligned average (Fig. 9d). For other types, usually minor constituents, it was uncertain whether any alignment was of benefit, in which case a straight (time-dependent) average was taken. Table 2 summarizes phenological dates, as well as peak values, and method of aligning the data, for each regularly registered taxon. Dates of peak concentration using aligned data were determined. They show a seasonal progression with sufficient spacing of peak dates and few overlaps.

Absolute peak concentrations show order of magnitude differences between types. Five taxa—*Ambrosia*, *Betula*, Cupressaceae, *Pinus* and *Quercus*—had single day pollen concentrations that reached the thousands. Even minor types whose aligned (usually time aver-

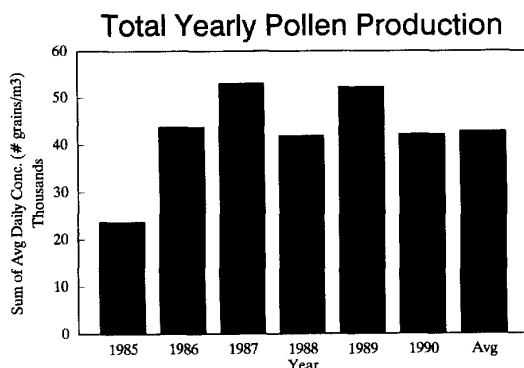


Fig. 3. Yearly pollen production, from the sum of average daily concentrations of all taxa, plotted for each year and the total average.

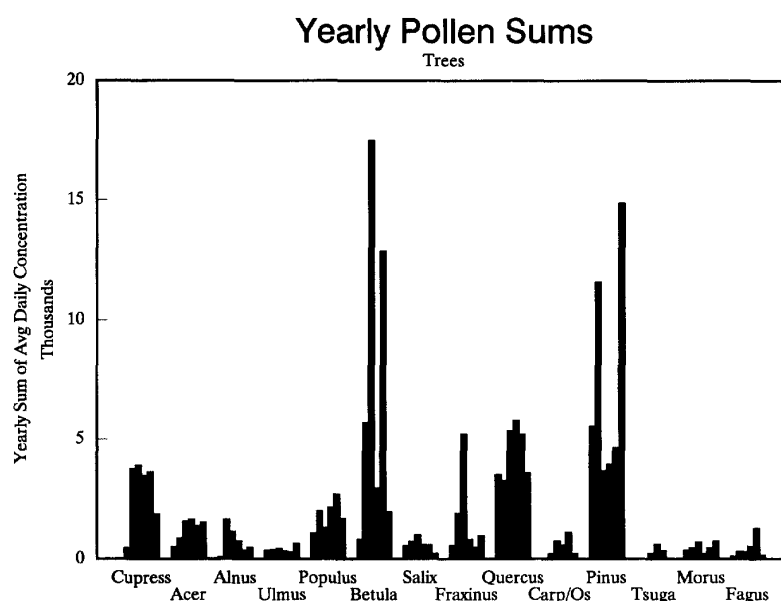


Fig. 4. Yearly histograms (1985–1990: left to right) of the pollen sums for selected tree taxa at Toronto. Some taxa names are abbreviated.

aged) peak concentration was low (i.e. < 50 grains/m³), reached substantial single day pollen concentration levels. Large differences between taxa also occurred in average yearly sums and aligned peak concentrations. The greatest airborne concentrations were produced by *Pinus*, *Betula*, *Ambrosia*, *Quercus*, Cupressaceae and Poaceae.

5.4. Pollen calendar

Aligned average atmospheric pollen curves (Table 2) are shown as a pollen calendar for Toronto (Fig. 10). Taxa are ordered according to their peak date. Fig. 10 illustrates the seasonal progression of flowering of the various taxa along with their percent contribution to the total pollen catch. The three taxa which most often incite allergic symptoms in Toronto, in order of allergenicity are *Ambrosia*, *Betula*, and Poaceae, (Knight, 1990; pers. commun.) (Fig. 11). Average seasonal pollen curves over time show positively (or right) skewed distributions in the case of *Betula* and Poaceae, and a nearly symmetrical curve for *Ambrosia*.

Tree pollen seasons are known to be shorter in duration, and higher in peak atmospheric concentrations than herbaceous taxa. In order to examine the general biology of flowering in anemophilous trees over time, pollen concentrations are standardized to allow comparison of all tree taxa. Daily average aligned pollen counts (Fig. 10) were converted to percent of the average yearly sum. The peak of each curve was aligned with the peaks of all other tree taxa, and all taxa then averaged. The resulting tree pollen curve (Fig. 12)

illustrates a smoothed, general form of seasonal atmospheric tree pollen concentration. For tree taxa in general, $> 20\%$ of the total catch is released on the peak day of pollination of the taxon. The 10-day period surrounding the peak accounts for approximately 60% of the total pollen catch. The shape of the curve is more or less symmetrical.

6. Discussion

There is a yearly cycle in the reproduction of anemophilous plants. Trees pollinate early in the season using reproductive structures set during the preceding growing season. Once warm spring temperatures occur, developmental processes finish and anthesis occurs. In contrast, plants that must initiate reproductive structures or generate entire new individuals each year, such as Poaceae and *Ambrosia*, flower later in the growing season due to lengthy developmental processes.

Variations in yearly pollen production, as sensed by airborne pollen samples, are the result of the population density of a particular taxon, overall community health, and the prevailing climate prior to and during the pollen season (Hyde, 1952). In addition, some trees undergo intrinsic genetic cycles of reproduction called mast cycling (Silvertown, 1982). Large yearly fluctuations in fruit set are frequently seen in anemophilous trees, and seem to be accompanied by large fluctuations in pollen production (Hyde, 1955). It has been shown here that coniferous and boreal taxa (*Pinus*, *Betula*, *Alnus*) and temperate species (*Tsuga*, *Fraxinus* and

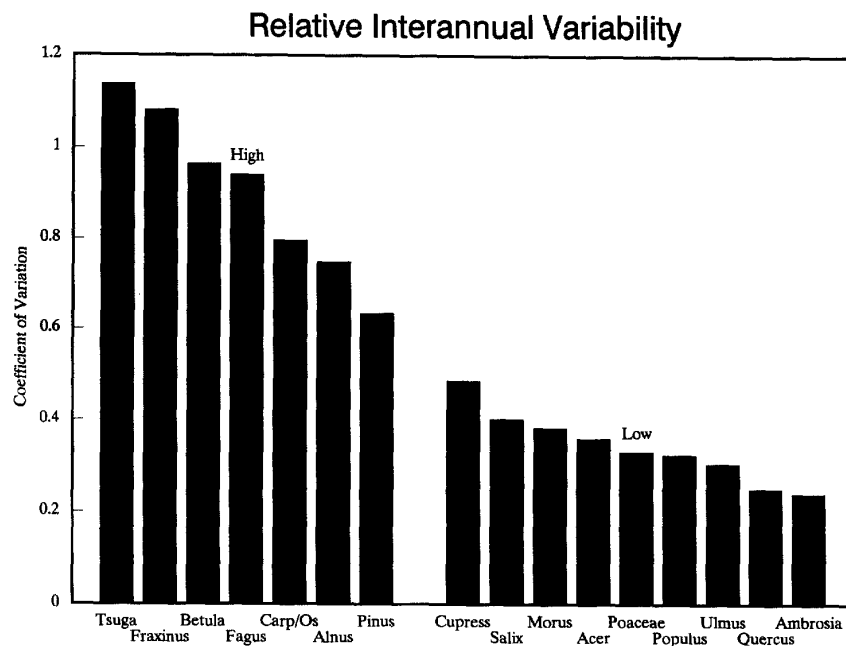


Fig. 5. Relative interannual variability expressed as the coefficient of variation for 1985–1990. Taxa that vary by more than 50% of their mean level are considered highly variable. Some names abbreviated.

Fagus) exhibit a high degree of interannual variability in pollen production. Pollen productivity in this study supports evidence of cycles of high productivity found for *Betula* at 2-year intervals (Nilsson and Persson, 1981; Atkinson and Larson, 1990; Spieksma et al., 1995) and *Pinus* at 3–4 year intervals (Atkinson and Larson, 1990). Pollen productivity of tree taxa is influenced by climatic conditions, such as temperature and rainfall, of the preceding year when reproductive primordia are forming (Solomon, 1979; Fairley and Batchelder, 1986). However, high yearly pollen productivity is not synchronous among taxa indicating species specific responses (Hyde, 1956). Adverse meteorological conditions within a pollen season can decrease atmospheric concentrations significantly regardless of the total pollen production commitment and may partly explain lack of concordance of high productivity years among taxa. It is conceivable that longer-term cycles exist in pollen productivity for some taxa, thus emphasizing the need for long term databases on pollen production in order to elucidate stable pollen-vegetation relationships.

The implications of high interannual variability in terms of allergy are that dose exposure is obviously not the same from year to year. Patients complaining that 'this is a bad year' may in fact be exposed to significantly more pollen than in other years (e.g. Comtois and Gagnon, 1988). Also, atopic individuals must first become sensitized to an allergen through exposure. Most years for trees may be highly sensitizing years for

atopic individuals. The effect may not be seen until the following year when the individual reacts more severely to a lower pollen exposure.

Average yearly pollen sums and percentages of total pollen catch are a reflection of relative plant abundance in the surrounding vegetation. Relative percentages are not directly translated into plant abundance values due to differential pollen production, and differences in pollen dispersal between taxa. Typically *Pinus* and *Betula* are over-represented relative to their abundance in the surrounding vegetation. Cambon (1992) compared atmospheric pollen samples with regional floristic characteristics in a transect through Ontario and found that atmospheric pollen composition qualitatively matched floristic changes in vegetation zones. Urban development modifies the relative composition of the natural vegetation by the introduction of ornamental species (Sukopp and Werner, 1983) and changes in relative abundances due to land use practices, thus complications arise when making comparisons between urban pollen concentrations and modern pollen vegetation studies.

Pollen concentrations at the beginning of the season for a particular taxon are low and sporadic before a marked increase occurs (Fig. 8). It is assumed that the large surge in pollen concentration is due to the coordinated flowering of populations in the study area. Earlier registrations may be caused by numerous factors. For example, Metropolitan Toronto has several deep and wide river valleys where heat accumulation de-

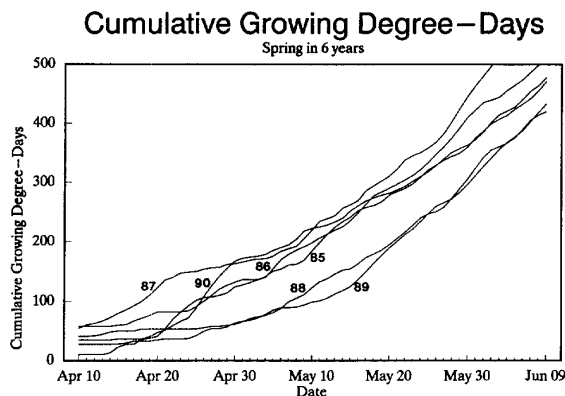


Fig. 6. Springtime warming at Toronto in the 6 years as shown by the rate of increase of cumulative growing degree days $> 5^{\circ}\text{C}$.

depends on the direction of slope exposure. Also, the climate over Metropolitan Toronto is heavily influenced by moderating lake effects, in particular the distance

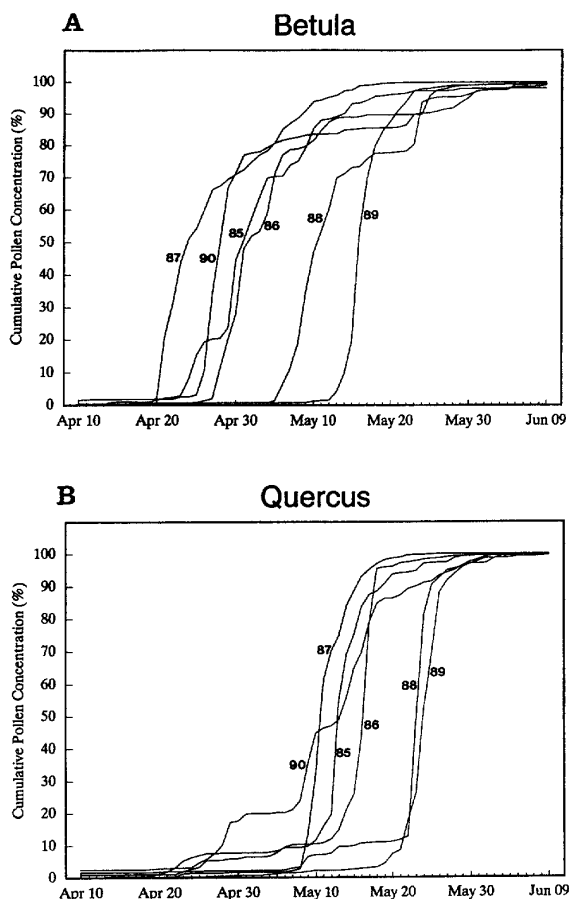


Fig. 7. Cumulative pollen concentration curves for (A) *Betula* and (B) *Quercus* for each of the 6 years at Toronto.

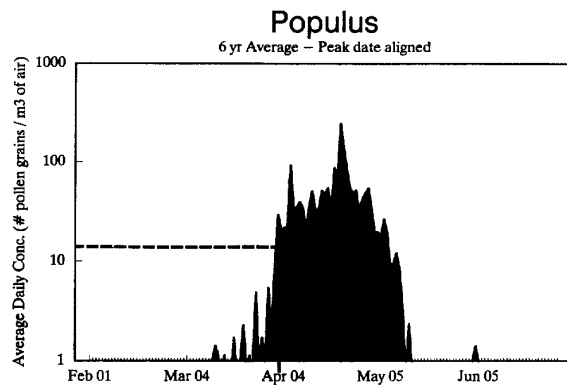


Fig. 8. Pollen concentration curve for *Populus* illustrating early minor registrations. A critical concentration was determined (20 grains/ m^3 ; dashed line) that indicates the start of the pollen season on April 4.

from Lake Ontario. These microclimatic differences cause deviations in the onset of flowering between local areas (Jackson, 1966). These early registrations may also be due to the long distance influx of pollen from earlier flowering populations in southern areas, ecotypic variations in flowering time, or peculiarities of flowering physiology for particular taxa.

Early minor registrations in atmospheric pollen concentration occur for many taxa. Taxon specific criteria are defined to establish the start of the pollen season and to circumvent early minor registrations. Other investigations use criteria that define pollen seasons after they have passed (e.g. Mullenders, 1974). In this study, the start date criterion is not based on the annual sum, therefore the same atmospheric concentration defines the start in every year. Since the determination of a threshold level is subjective, it is desirable to examine several years of data to establish the atmospheric concentration that clearly indicates the start of the season for a particular taxon. This level can be continuously updated with additional data until it stabilizes and no change occurs in subsequent years. Many studies use a set level (e.g. 1% or 5% of the annual sum) to indicate the start of the season for all taxa, however, this assignment is arbitrary rather than objective. Also, because early minor registrations are more prevalent for some taxa than others, it is reasonable to assign different critical levels to different taxa. In this study, critical levels represented from 1% to 15% of the annual sum, however most of this difference is due to great variation in annual sum between taxa. Since the critical level of atmospheric concentrations are related to the prevalence of the taxon in the area, these determinations are location specific.

While the absolute date of onset of the pollen season for each type varies from year to year, the order of taxa shows little variation (Hyde, 1956; Bricchi et al., 1995). Tree taxa in particular vary greatly in onset due to the

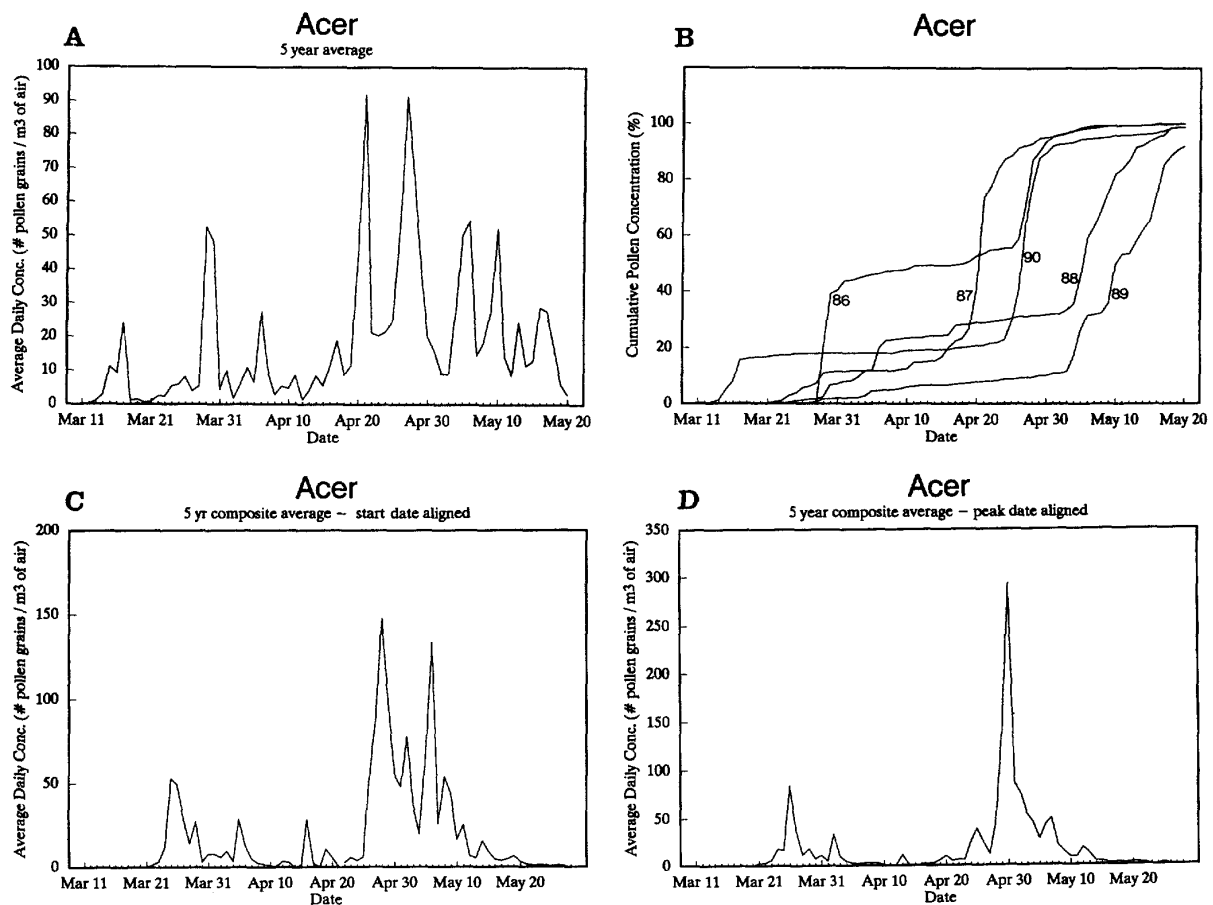


Fig. 9. (A) Five year (1986–1990) average pollen concentration for *Acer*. (B) Cumulative pollen concentration showing bi-modal occurrence. (C) Start date aligned average pollen concentration. (D) Peak date aligned average pollen concentration.

temperature-sensitive nature of the triggering of pollination (Boyer, 1973; Frenguelli et al., 1991, 1992). The alignment of pollen curves between years reduces the variation in onset due to differences in the rate of springtime warming, and gives a more accurate representation of the amplitude and trend of seasonal atmospheric concentrations. Taxa whose optimum alignment was achieved using the start date, such as *Fagus* and *Juglans*, might indicate that the developmental processes from the pollination onset to the seasonal peak are highly canalized, and that once the criteria for anthesis are met, the commitment to the progression of pollination, and hence the peak pollen period, is assured.

Start dates for flowering in spring tree taxa have been evaluated to determine threshold values of accumulated temperature necessary to initiate pollination. These values are then used to predict the start of the pollen season in future years (Andersen, 1991; Frenguelli et al., 1991, 1992; Spiekma et al., 1995). Other methods

of predicting pollen season initiation include cumulated activity models and time-linkages between taxa (Larsson, 1993; Bricchi et al., 1995). Comparison of dates of first flowering in Ottawa (400 km NE of Toronto) (Bassett et al., 1961) with pollen season start in this study reveals that flowering commences, on average, 10–15 days earlier at Toronto.

Flowering phenology studies are often based on the timing of first flowering due to the ease of objective determinations. The date of peak atmospheric pollen concentration may be a more appropriate ecological indicator of the processes affecting flowering time particularly for anemophilous tree species. For anemophilous species, the coordination of male and female function is of prime importance. Highly coordinated, short duration, pollen concentration peaks are necessary in order to avoid gametic wastage (Rabinowitz et al., 1981) and maintain sufficient atmospheric concentration to ensure successful fertilizations (Solomon, 1979). Temperature-sensitive tree taxa that

Table 2
Table of phenological values

Taxa	Start defined (grains/m ³ or mm/dd)	Avg date of start (mm/dd)	Earliest start (mm/dd)	Latest start (mm/dd)	Duration (days)	Absolute peak conc (grains/m ³)	Avg yearly sum (grains/m ³)	Aligned by	Aligned peak conc (grains/ m ³)	Aligned peak date (mm/dd)
<i>Abies</i>	*	04/29	04/24	05/13	24	8	13	Ave	1	05/05
<i>Acer</i> 1	> 10	03/24	03/14	03/29	10	177	337	Peak	60	03/26
<i>Acer</i> 2	> 20	04/26	04/11	05/04	12	515	1014	Peak	300	04/30
<i>Aesculus</i>	*	05/23	05/09	06/13	25	4	7	Ave	1	05/24
<i>Alnus</i>	> 5	03/25	03/15	04/05	67	475	761	Peak	223	04/19
<i>Ambrosia</i>	> 30	08/14	08/12	08/14	44	1258	6773	Ave	473	09/02
<i>Apiaceae</i>	* / 07/09	07/22	07/18	07/25	57	10	39	Ave	2	08/14
<i>Artemisia</i>	* / 07/01	07/27	07/03	08/19	14	14	50	Ave	4	09/07
<i>Betula</i>	> 10	04/27	04/19	05/05	32	4271	6965	Peak	1636	05/02
Brassicaceae 1	*	04/18	04/07	04/26	32	7	11	Ave	1	05/05
Brassicaceae 2	* / 05/30	06/18	06/14	06/25	24	8	7	Ave	1	07/13
<i>Carpinus</i> / <i>Ostrya</i>	> 10	05/01	04/21	05/13	14	400	504	Peak	123	05/02
<i>Carya</i>	> 2/04/10	04/29	04/17	05/10	46	31	115	Peak	19	05/20
<i>Celtis</i>	*	05/03	04/25	05/19	19	32	31	Ave	5	05/21
<i>Cheno/Am</i>	* / 06/30	07/08	07/03	07/19	101	22	199	Ave	7	08/16
<i>Cornus</i>	*	05/15	04/29	06/02	37	6	12	Ave	1	05/16
<i>Corylus</i>	*	04/06	03/15	05/14	40	82	48	Ave	14	04/10
Cupressaceae	* / 03/20	03/23	03/22	03/25	90	1412	2854	Peaks	551	04/22
Cyperaceae	*	04/30	04/19	05/14	28	13	55	Ave	4	05/07
<i>Equisetum</i>	*	04/20	04/16	04/26	28	7	20	Ave	2	05/01
<i>Fagus</i>	> 10	05/03	04/22	05/17	23	202	456	Start	70	05/09
<i>Fraxinus</i>	> 15	04/30	04/20	05/17	25	748	1670	Start	179	05/16
<i>Juglans</i>	* / 03/27	05/12	05/09	05/19	29	72	140	Start	23	06/01
<i>Morus</i>	> 15	05/09	04/28	05/25	25	107	507	Ave	34	05/28
<i>Picea</i>	> 10	05/23	05/05	06/09	11	215	383	Ave	45	05/30
<i>Pinus</i>	> 40	05/20	05/12	05/27	33	2534	7381	Peak	1467	06/08
<i>Plantago</i>	*	05/22	05/09	06/02	121	14	94	Ave	3	08/04
<i>Platanus</i>	*	04/29	04/17	05/20	30	31	42	Peak	13	05/13
Poaceae	> 10	05/29	05/26	05/31	53	233	1878	Ave	70	06/12
<i>Populus</i>	> 20	04/04	03/29	04/13	28	348	1830	Peak	246	04/22
<i>Prunus</i>	> 6	05/21	05/11	06/04	25	30	84	Ave	8	06/04
<i>Quercus</i>	> 60	05/04	04/23	05/19	21	2088	4453	Peak	1298	05/16

Table 2 (continued)

Taxa	Start defined (grains/m ³ or mm/dd)	Avg date of start (mm/dd)	Earliest start (mm/dd)	Latest start (mm/dd)	Duration (days)	Absolute peak conc (grains/m ³)	Avg yearly sum (grains/m ³)	Aligned by	Aligned peak conc (grains/ m ³)	Aligned peak date (mm/dd)
Rosaceae	*	05/10	04/29	05/23	63	65	102	Ave	15	06/01
<i>Rumex</i>	*	05/07	04/15	05/29	89	11	69	Ave	3	05/30
<i>Salix</i>	> 10	04/21	04/11	04/19	29	225	627	Peak	91	05/04
<i>Taxus</i>	> 5	04/04	03/30	04/09	30	73	97	Ave	25	04/09
<i>Thalictrum</i>	*06/15	07/19	06/28	08/25	67	3	20	Ave	1	09/05
<i>Tilia</i>	*06/11	06/27	06/23	07/04	26	10	27	Ave	2	07/09
<i>Tsuga</i>	> 5	05/18	05/10	05/23	12	207	221	Peak	75	05/21
<i>Typha</i>	> 5	06/21	06/18	06/28	25	53	236	Ave	17	07/10
<i>Ulmus</i>	> 10	03/12	02/13	03/27	45	201	412	Peak	111	04/08
<i>Urtica</i>	*06/29	07/17	07/04	07/31	51	117	258	Peak	58	08/08

Start of the season defined as:

*, the occurrence of the first pollen grain.

*07/01, the first occurrence of pollen after the date indicated.

> 10 grains/m³, the pollen concentration level that determines the start date.

> 2 grains/m³/04/10, the pollen concentration level that determines the start date after a particular date.

Duration, the duration of the pollen season is calculated from the start date to the last day the start date criteria were observed.

Absolute peak conc, absolute highest peak concentration found on one day of all 6 years.

Avg yearly sum, the 6-year average of the annual sum of average daily concentration.

Aligned by, method of aligning the data.

Aligned peak conc, the average peak concentration once the data has been aligned.

Aligned peak date, the date of the aligned peak concentration.

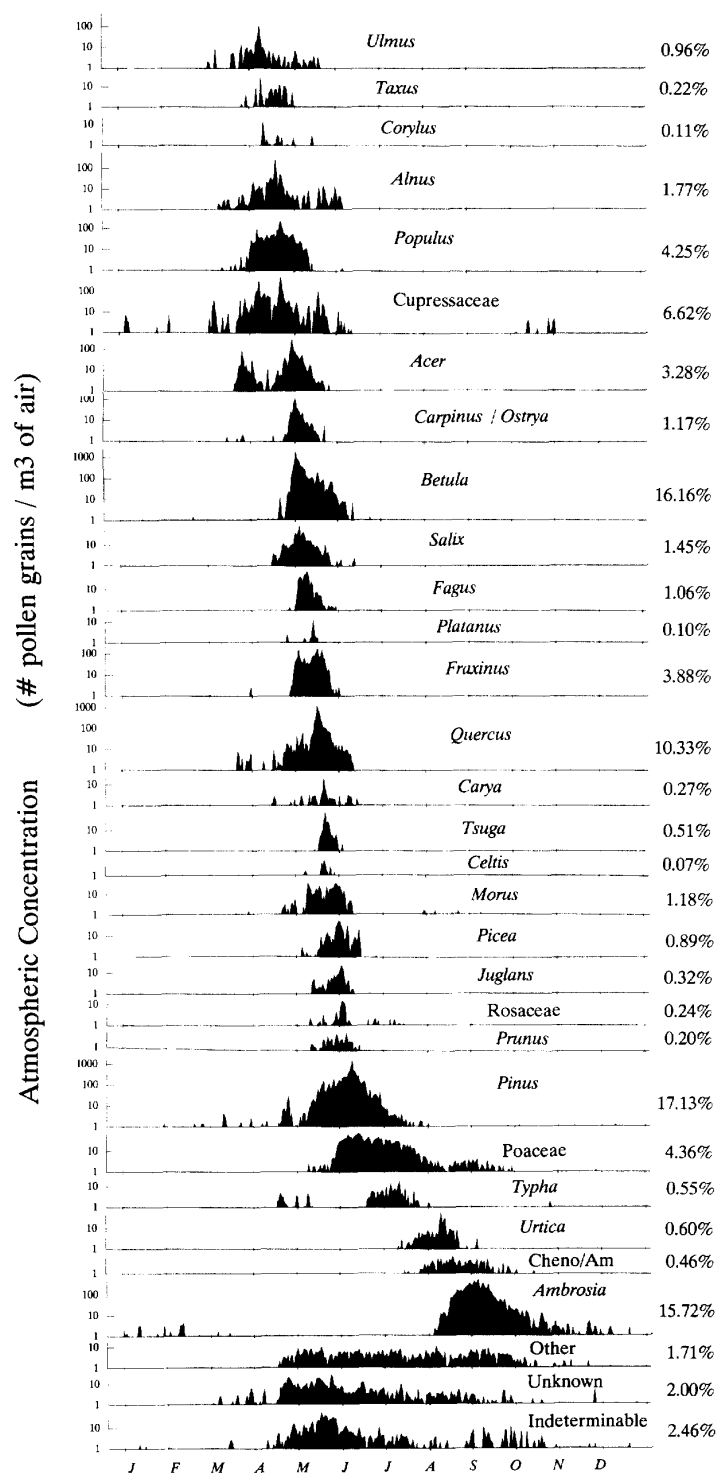


Fig. 10. Pollen calendar for taxa registered at Toronto (log scale). Pollen concentration curves are aligned according to Table 2. Taxa are ordered according to the peak date. Percent of total pollen catch is indicated for each type.

pollinate in the highly variable conditions of the spring, can stall flowering, once started, until optimum atmospheric conditions for maximum airborne pollen concentration are available. For this reason, start dates may not be the best indicator of processes affecting pollination in wind pollinated species.

Clinically significant threshold values of atmospheric pollen concentration to elicit allergic responses have been determined in the three main seasons to be 8–21 grains/m³ for spring tree taxa, 4–12 grains/m³ for the

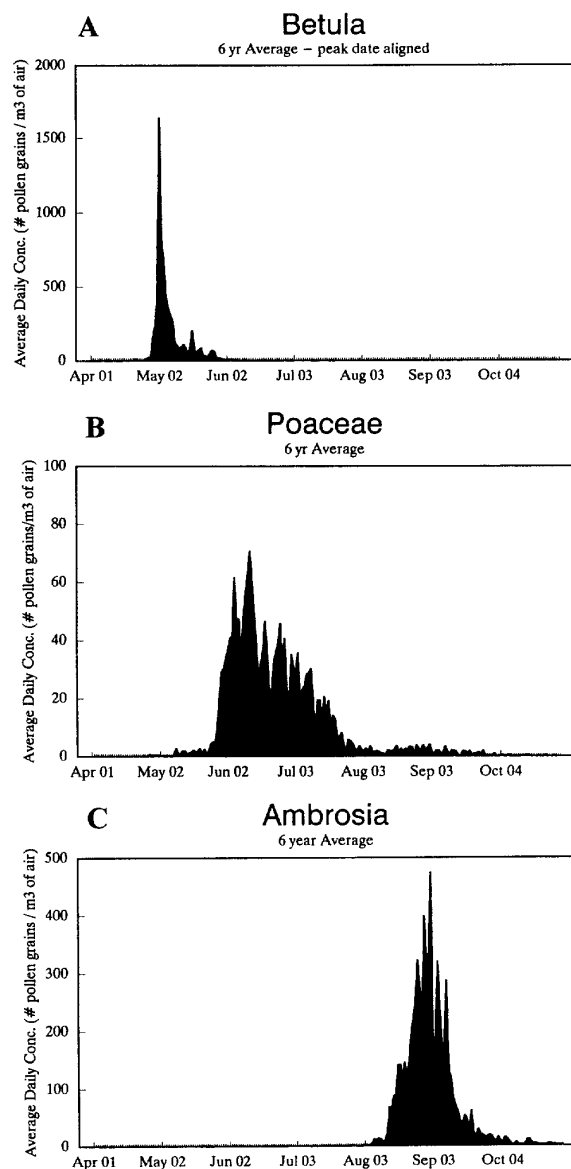


Fig. 11. Six year average pollen concentration curves for the three most allergenic taxa at Toronto, (A) *Betula*, (B) *Poaceae*, (C) *Ambrosia*.

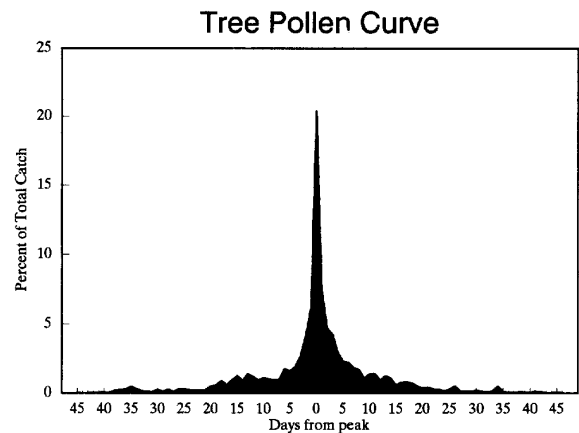


Fig. 12. Average pollen concentration of all tree taxa, expressed as a percent of the total and aligned according to peak date. Greater than 20% of the total is registered on the peak day and 60% over the 10-day period surrounding the peak.

grass season, and 1–3 grains/m³ for *Ambrosia* based on a representative sample of patients in Montreal (Comtois and Gagnon, 1988). Start date criteria established in this study in general match the clinical threshold values for trees and grass, however, are well above those for *Ambrosia*.

Daily pollen concentrations > 500 grains/m³ are intermittent but typical, particularly in the tree season, and likely pose significant problems for moderately or even slightly allergic individuals. Predictive models developed using average peak values have difficulty estimating absolute peak concentrations. Pollen counts reported as five or ten day running averages greatly smooth over peak periods and fail to show the real character of short-term pollen concentrations as do strictly time-dependant averages of several years. Comtois and Sherknies (1991) found that many taxa do not maintain a constant pollen curve each year, therefore the amplitude and morphology of the pollen profile are difficult to determine. Alignment of pollen concentration curves, and subsequent averaging, presents a more accurate representation of both pollen occurrence over time and atmospheric levels normally observed.

Average pollen concentration curves smooth out yearly differences in day to day pollen concentrations due to the influences of meteorological conditions affecting dehiscence and transport. With accurate alignment of many years of data, the actual progression of flowering through the season, due to the reproductive biology of the taxa, can be visualized. The shape of the pollination curve, with relative height and narrowness of peaks, is determined by the pollination biology of the species. For *Ambrosia*, the seasonal trend in pollen concentration appears symmetrical. While tree taxa in general appear to have symmetrical curves, there are

differences in the shape of pollination curves for individual taxa. *Betula* and *Poaceae*, for example, have positively skewed pollination curves where slower declines occur. The longer tailing out of pollen concentration may be due to the recirculation of previously released pollen (O'Rourke, 1990) and these pollen concentration curves may not perfectly represent flowering curves which could be more symmetrical.

The three curves at the bottom of the pollen calendar, 'Other', 'Unknown' and 'Indeterminable' represent minor registrations of other taxa, pollen grains of unknown identity, and grains which were in an unidentifiable condition, respectively. For completeness, it is important to include these categories in aerobiological investigations, as they are in palaeopalynology, and I suggest this practise be adopted in all future aerobiological reports.

In summary, pollen concentrations show variability over several different scales. It is clear that in order to predict atmospheric pollen concentrations, a forecasting model must be able to accurately predict interannual pollen productivity, variations in the start of pollination, the seasonal trend in pollination, and day to day deviations from the seasonal trend due to meteorological conditions. The establishment of start date criteria and the alignment of pollen curves to give more accurate averages are critical as a first step toward this endeavour.

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