

Regional variations in grass pollen seasons in the UK, long-term trends and forecast models

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Summary

Background Three sites in the UK have daily records of pollen spanning several decades, giving the longest data sets worldwide. Previous research on London data revealed decreasing severity of grass pollen seasons. This is often taken as a model for the whole country but comparisons with Derby and Cardiff, in different regions of local climate and land-use, emphasize the need for regional studies.

Objective The grass pollen seasons were analysed for three contrasting long-term sites to provide regional insight into the changing incidence of hay fever.

Methods Pollen was monitored by volumetric instruments using standard techniques. Data have been taken from 1961 to 1993 to examine variation in grass pollen seasons in relation to land-use changes, cumulative temperatures and rainfall. Models were developed to predict total seasonal catches.

Results At Cardiff the annual counts and severity increased in the 1960s, declined in the 1970s and rose again in the 1980s. At Derby and London the annual counts and severity declined but at different rates. Start dates have tended to become earlier at Cardiff and Derby, but later at London. Trends in annual counts and severity are similar to changes in grassland areas but they cannot be accounted for entirely by these. Weather in spring and early summer has tended to become warmer but there are no sustained patterns in June and July. No trends are apparent in the rainfall records for these months. The maximum explanation ($r^2 \geq 95\%$) in forecast models was obtained using 10-day aggregates of weather.

Conclusion The contrasting patterns both in the pollen records and land-use changes between the three sites emphasize the need for regional data. The predictive models achieved a high degree of explanation enabling pollen season severity to be forecast with high confidence shortly before the start date.

Keywords: hay fever, aerobiology, grass pollen, long-term trends, forecast model

Clinical and Experimental Allergy, Vol. 29, pp. 347–356. Submitted 27 November 1997; revised 27 January 1998; accepted 11 March 1998.

Introduction

Three sites in the United Kingdom have daily average records of grass pollen concentrations spanning several decades, giving the longest continuous pollen data sets worldwide. Very few continuous records of pollen

monitoring exist over this duration anywhere in the world and the UK is the only country to have three such sites. Volumetric spore traps have been used to monitor daily average concentrations of airborne pollen at Cardiff since 1954, at Derby since 1969 and at London since 1961. The data sets provide an interesting opportunity to examine long-term trends in the pollen records in contrasting regions of one country.

Numerous papers have been published during the last

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decade concerning changes in the prevalence of seasonal allergic rhinitis in the UK. Most evidence indicates that notable increases have occurred [1–4] but the results from some research projects have shown no clear trends [e.g. 5]. Little attention has been given to trends in regional variations either for epidemiological aspects or aeroallergens. In an analysis of the long-term grass pollen data set for the London area [1,6] records showed that grass pollen concentrations have declined progressively since the 1960s. This posed a paradox, as the decreasing severity of pollen seasons occurred during a period when the prevalence of seasonal allergic rhinitis apparently increased. Moreover, there has been a tendency to assume that this pattern of change in the aeroallergen load has occurred throughout the whole of the UK [e.g. 7]. Considerable debate has been generated on the role of air pollutants in this scenario including possible interactions between aeroallergens and pollutants [8].

This paper presents a more detailed analysis of the London record together with further evidence available from the analysis of long-term pollen data sets in Derby and Cardiff, situated in regions of different local climate and land-use history than those in south east England. Records for daily grass pollen concentrations at the three sites have been examined to compare several aspects; namely the long-term trends in the total seasonal cumulative counts, the severity of the seasons in terms of the number of days with high counts and the start dates of the seasons. These aspects have been analysed in relation to changes in land-use and weather, particularly temperature and rainfall. The results show contrasting patterns both in the pollen records and land-use changes in the three regions and provide some insight into the changing incidence of seasonal allergic rhinitis in the UK. The different patterns highlight the importance of considering regional data in any analysis of environmental factors. In addition, empirical statistical models to forecast the severity of the seasons have been constructed from an analysis of the pollen data in relation to weather variables.

Methods

Pollen monitoring

Pollen concentrations in the air were monitored using standard Volumetric Spore Traps of the Hirst design on roofs between 9 and 29 m above ground level in the city centres of Cardiff, Derby and London. The data collection at the three sites employed standardized techniques now adopted by the British Aerobiology Federation for use by the National Pollen Network [9]. Data for this study were taken from 1961 onwards to facilitate inter-site comparisons. Daily average concentrations of grass pollen were

calculated as grains per cubic metre of air sampled. Grass pollen is not differentiated to species level for routine pollen counts performed by light microscopy as the grains from nearly all species are virtually identical morphologically. Due to this, the grass pollen counts are an amalgam of pollen from many types of grass. In the UK there are about 150 grass species of which about 12 contribute most pollen to the airborne catch. This is partly because of their widespread distributions and partly because they release comparatively large amounts of pollen per plant. It is important to note that the species spectrum of grasses in the vegetation is likely to differ between regions. The species exhibit differences in phenology as well as in tolerance to environmental factors. In particular, some species respond to long photoperiods and so require the longer days of late spring to initiate flowering, whereas other species are day neutral and will initiate flowering in response to warmth irrespective of day length.

Site descriptions

The three sites are located in different regions of local climate within the broad mid-latitude temperate western margin type [10]. Although the sites are urban they differ in the size of the surrounding built up areas and the land-use of the rural environs.

Cardiff, (51° 29' N, 3° 10' W) on the coastal plain of south Wales, is subject to a strong maritime influence. From 1962 to 1993 the pollen trap was situated on the roof of the University of Wales, in the centre of Cardiff 13 m above ground level, 3.5 km from the Bristol Channel and 2.5 km from the nearest rural area. The local climate here is wetter with milder winters, cooler summers and less sunshine than at the other two sites. Meteorological data for the analysis was obtained from Cardiff airport, at Rhoose, 14.5 km SW of the pollen monitoring site. The 30 year rainfall records show an annual average total of 1065 mm, with 180 days per annum having more than 0.25 mm. At Derby, situated in central England (52° 55' N 1° 28' W) the location of the pollen monitoring station altered twice within the city centre during the period 1969–1993, with a change in height from 9 to 10 m above ground level. Statistical analysis (analysis of variance) of the data set showed that the results could be treated as one population. The meteorological data were obtained from weather stations situated between 0.5 km and 2.2 km from the sites used for pollen sampling. The Derby pollen monitoring sites are approximately 2.3 km from the surrounding rural areas. Derby has a drier climate than Cardiff with a 30 year annual average rainfall of 764 mm and 178 days per annum receiving over 0.25 mm rain. The inland location produces a larger range of temperatures, with colder winters and warmer summers than at

Cardiff, although the differences in monthly average temperatures between the two sites are only a few degrees.

In London (50° 42'N, 0°18'W) the pollen trap was located on the roof of St Mary's Hospital, Paddington in central London from 1961 to 1990, 29 m above ground level and 15 km from the nearest rural area. Meteorological data for the study was obtained from St James' Park within central London and also from sites outside the conurbation (Heathrow 21 km to the west and Rothamsted, near Harpenden 39 km to the north) as these give a better representation of conditions in the grass pollen source areas and are especially useful in statistical models to predict the start dates of seasons [6]. Central London experiences a drier climate than the other two sites, with 30 year annual average rainfall of 593 mm, and 153 days per annum having more than 0.25 mm rain. There is a tendency for summer rain to be heavier than that in winter. Temperature profiles are similar to those at Derby but are modified by the effects of the urban climate. This is especially noticeable in summer when monthly averages tend to be a few degrees above those for the other two sites [12].

Land use

The most pertinent aspect of rural land-use is the extent of grassland areas around the sites during the 30 year study period. Information about grassland trends in the vicinities of the sites was obtained from the Agricultural Statistics for England and Wales June returns [13] for land within a radius of approximately 40 km around sites, (giving catchment zones of a diameter of 80 km). This information is included as illustrative of the main differences occurring and is not intended to define quantitative changes in source strengths. This is partly because it is not possible to determine the exact extent of the catchment zones for each of the traps as this differs with prevailing weather. Also the grassland category is not limited to flowering grass nor does not include cereal crops. No information is available for annual percentages of grassland areas flowering in each region although figures for hay production in the UK showed a fall of 54% between 1969 and 1989. The area under cereal crops was not considered to be as important as the area under grassland because pollen from cereals tends to be larger than that from ordinary grasses, and has a more limited dispersal pattern. In the case of the Cardiff site, data from the across the Bristol Channel was included as the prevailing wind direction is from the south west and grass pollen from the area across the estuary could contribute to the catch under certain weather conditions.

Data analysis

Three main aspects of the pollen records were examined at each site. Annual cumulative counts were calculated from

the summation of daily average pollen concentrations. These were then smoothed by expressing them as 5 year running means. The severity of the season was assessed as the number of days on which the daily average grass pollen concentrations exceeded subjective thresholds of 50 grains/m³, 100 grains/m³ and 150 grains/m³. The start of the grass pollen season was determined as the date on which the cumulative daily grass pollen concentration reached a figure of 75 grains. A delimited start is necessary because typically a period of very low concentrations occurs in late spring due to early flowering species before the main pollination time, beginning in late May or June [14,15]. Analysis of grass pollen seasons in many locations of the UK [16] has shown that the cumulative count 75 threshold can be taken as a good indicator of the time when the main pollen season is beginning. These features of the pollen records were analysed in relation to cumulative temperatures above 5.5°C compiled from daily averages, precipitation and changes in grass land areas.

Results

Total seasonal cumulative counts and severity of the seasons

Cardiff. The cumulative annual grass pollen catch has differed markedly, ranging from a maximum of 12 407 grains in 1971 to a minimum of 2190 grains in 1976. Totals for June exceed those for July except in 6 years in which June temperatures were below the long-term averages (namely 1962, 1972, 1979, 1985, 1990 and 1991). Running means for annual totals (Fig. 1) show a cyclic fluctuation over the three decades. In the 1960s there was an increase followed by a decline in the 1970s and another rise again during the 1980s. Since then the annual totals have remained

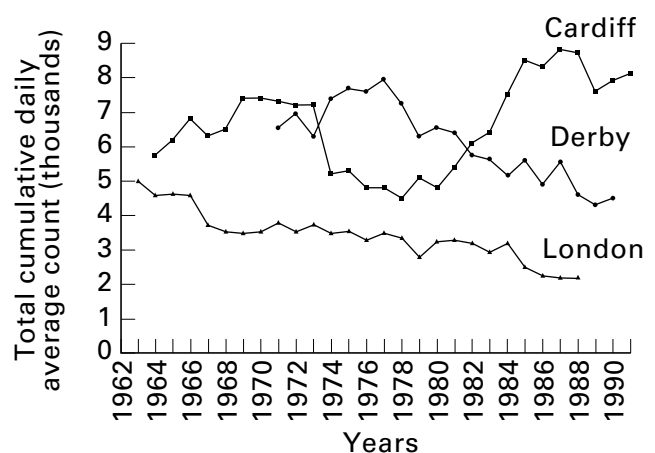
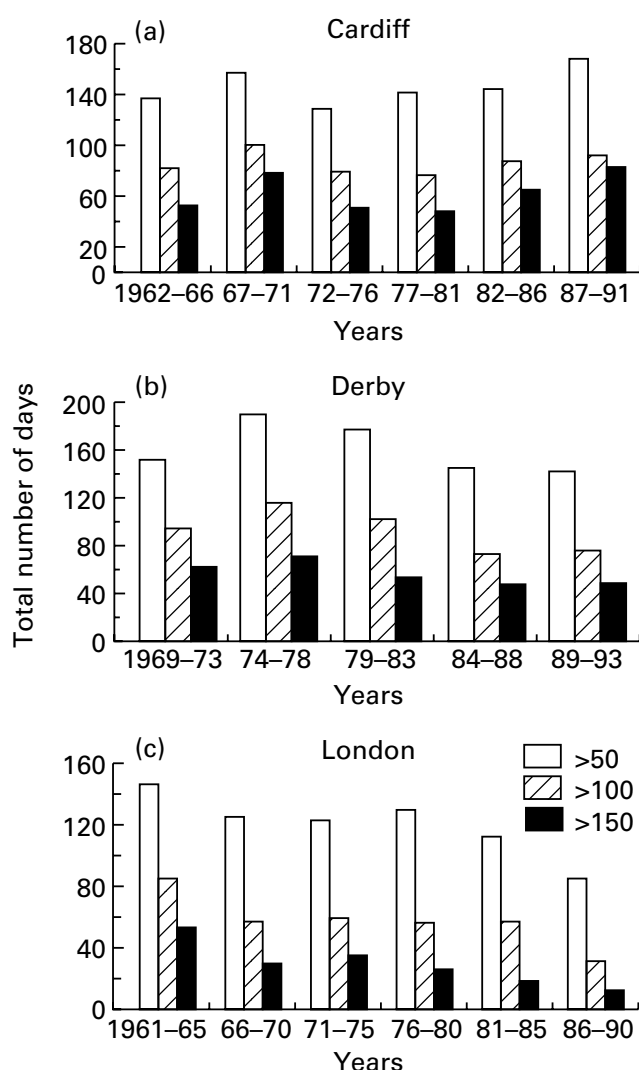


Fig. 1. Five year running means of cumulative yearly grass pollen counts.

Table 1. Change in the area of grassland around Cardiff 1961–1991 (total area of grassland in acres).

Region	1961	1970	1977	1991	% change 1970–1991	% change 1961–1991
Glamorgan, (Mid, West and South)	298 552	222 267	246 701	238 426	+7	–20
Gwent	260 019	162 248	176 965	174 778	+7	–32
Somerset	N/A	353 828	465 687	519 448	+47	N/A
Devon	N/A	898 483	977 307	1 017 296	+19	N/A
TOTAL	N/A	1 637 826	1 866 660	1 949 948	+19	N/A

**Fig. 2.** Severity of grass pollen seasons shown as the number of days when average concentrations were above thresholds expressed as grains per cubic metre of air.

relatively constant. This follows the broad changes in grassland amounts (Table 1). The severity of the seasons reflects the total count trend (Fig. 2a). The 1960s had 129 days with counts >150, the 1970s had 99 days with >150 and the 1980s had 147 days with counts >150.

Derby. At Derby the annual cumulative daily average pollen counts show a general decline over the 24 year period (Fig. 1) but the decrease was not as smooth as in the case of London. In Derby the grass pollen counts increased during the period 1969 to 1976 but then declined from 1976 onwards. The range of differences in totals extends from 9515 in 1976 to 2818 in 1990. Totals for July exceeded those for June in 9 years, more than for London and Cardiff (namely 1971, 1972, 1974, 1977, 1980, 1981, 1983, 1985 and 1991). Apart from 1983 when June temperatures were near normal, the July maxima years were ones in which the June temperatures were below the long-term average. The severity of the seasons (Fig. 2b) has declined from 147 days > 150 grains/m³ in the 1970s, to 96 days in the 1980s. Land use records show that around Derby grassland acreage increased from 1970 to 1980 but decreased by 1990, representing a fall in acreage of 7% over this decade (Table 2). The 5 year running means for grass pollen totals increased during the 1970s but thereafter continued to fall.

London. The London record shows a distinct trend for a decrease in the annual cumulative totals over the period, with a range from 8210 in 1964 to 940 in 1981. The decline is most distinct in the 60s but is sustained through the 1970s and 1980s (Fig. 1). Totals for June exceed those for July except in years with cool June weather (1972, 1974, 1977, 1979, 1983 and 1995). The severity of the season has followed the decline in total pollen counts (Fig. 2c). In the decade of the 1960s there were 81 days with counts > 150 grains/m³, in the 1970s there were 59 days > 150 grains/m³, and in the 1980s only 29 >150 grains/m³.

Table 2. Change in the area of grassland around Derby 1961–1990 (total area of grassland in acres).

Region	1969	1980	1990	% change 1980–90	% change 1969–90
Derbyshire	358 273	365 076	350 268	–4	–2
Nottinghamshire	97 405	108 685	84 578	–22	–13
Staffordshire	293 289	339 008	333 205	–1	+12
Leicestershire	193 009	246 190	214 165	–13	+10
Total	941 976	1 058 959	982 216	–7	+4

Start of the grass pollen season

Cardiff. The range of differences in start days during the period 1962 to 1993 was 37 days with the mean start date occurring at 139 days from 1 January (i.e. 19 May). The years which had the earliest starts (1963, 1974, 1976, 1980, 1984, 1991, 1993) all had relatively warm springs, and years with late starts characteristically had cool, dry springs. Overall there is a weak trend towards earlier start dates (Fig. 3).

Derby. The range in the difference in start dates from 1969 to 1992 was 25 days with the mean start date at 148 days from 1 January (i.e. 28 May). Earlier start dates were associated with higher temperatures in the early months of the year. There is a trend towards earlier start dates (Fig. 3)

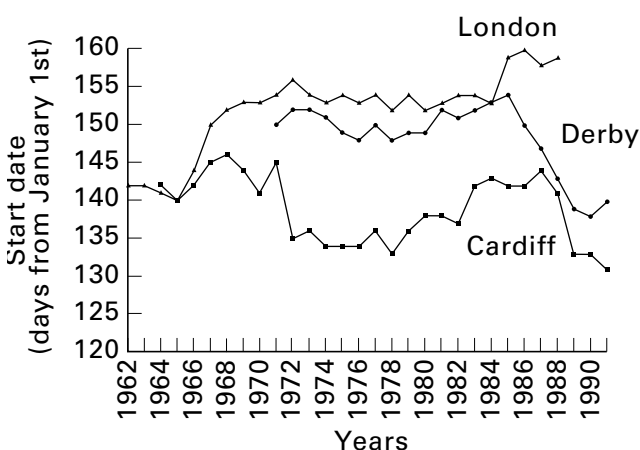
London. Start dates between 1961 and 1990 differed by 39 days with the mean start date at 151 days from 1 January (i.e. 31 May). There is a trend towards later start dates (Fig. 3).

Grassland areas

The broad trends in total pollen catches at Cardiff reflect some of the general changes in the amounts of grassland in

the surrounding regions over the 30 years (Table 1). In the counties around Cardiff grassland acreage had decreased by 1970 but showed a marked increase by 1977 which was sustained through into 1991 by which time the acreage under grassland was 19% higher than it had been in 1970. In comparison, the 5 year running means for grass pollen totals at Cardiff showed a similar fall during the 1970s and then rose again during the 1980s to reach higher levels than had been recorded during the 1960s. Although the trends in cumulative grass pollen counts and severity of seasons show some similarity to those for the grassland areas they cannot be accounted for entirely by these land-use changes. The area under cereals around Cardiff fell by 10 % between 1970 and 1990, however the area under cereals was only 18% of that under grass in 1970 and 14% of that under grass in 1990 [13].

At Derby the main trends in seasonal catches and the severity of the season show a general relationship to the changing grassland acreages. In the surrounding region the area of grassland increased until the late 1970s and then decreased (Table 2). The area under cereals rose by 3.5% between 1970 and 1990 but remained at a constant level with respect to grassland at 55% [13]. Similarly in London the decline in total grass pollen catches matches the general trends in grassland areas of the region (Table 3) in which there was an overall decline of 35 % with the greatest rate of change occurring in the 1960s. The area under cereals around London was higher than at either of the other two sites and was 154% of the area under grass in 1970 and 163% in 1990, but showed a fall of 9.4% between 1970 and 1990 [13]. However, both in the cases of Derby and London the decline in grass pollen catch is greater than the decrease in grassland area. This is especially notable at Derby where there has been a 4% rise in the grassland area overall during the study period.

**Fig. 3.** Five year running means of start dates for the grass pollen season.

Trends in weather variables

Previous research has shown that the most important climatic variables influencing the broad features of grass pollen seasons are temperatures and precipitation [11]. The effects of other factors such as sunshine hours, relative

Table 3. Change in the area of grassland around London 1961–1990 (total area of grassland in acres).

Region	1961	1970	1980	1990	% change 1970–90	% change 1961–90
North West (Bucks and 1 Herts)	231 406	187 928	159 094	148 284	–21	–36
North East (Essex and 1 Herts)	202 294	137 516	117 024	101 442	–26	–50
South West (Hamps and Surrey)	324 761	223 559	216 658	227 033	+1	–30
South East (Kent)	239 732	203 160	181 278	167 758	–17	–30
TOTAL	998 193	752 163	674 054	644 517	–14	–35

humidity, atmospheric stability and wind speed are important for daily variations in pollen counts but they are auto correlated with the two main variables and are less significant on an annual basis. The effects of temperature and precipitation on grass pollen seasons can be exerted from mid winter onwards. For example, soil temperatures in late winter and early spring will influence the start of grass growth. Temperature and rainfall profiles through the spring and early summer will influence net productivity and hence pollen production, then subsequently heading times, anthesis and pollen dispersal.

Preseason weather

Analysis of cumulative temperatures over the 30 year period shows a trend towards notable warming over the last decade especially in the months of February and March at all three sites. Considerable fluctuations featured in the rainfall records for these months but there were no sustained trends [18]. Similarly no trends were discernible for temperatures in April but at Derby the rainfall 5 year running means show a trend to drier weather in recent years.

Warmer weather in early months of the year would encourage grass growth, with early maturation of flowers in thermal response species. This would generate a long period of low counts at the beginning of the season before the onset of the main grass flowering period. This pattern is evident in the cumulative curves of pollen counts in years with warm weather early in the year and is likely to become more frequent if the trend towards warming is sustained [19,11]

Weather at the start and through the season. Temperatures and rainfall during April and May are important in influencing heading times of flowers and the start of anthesis. The over-riding influence of these variables continues through June and July for the release of pollen and its dispersal from the plants. In the weather records at the three sites some recent changes are clearly evident for the months of April and May but not for June and July. For

example, at Cardiff cumulative temperatures in May have tended to be higher since 1988 than in the preceding years of the data set. All the Mays since 1988 have had cumulative temperatures above the long-term mean and the three warmest Mays of the data set have occurred in this period. In contrast, the cumulative temperatures for the months of June and July show a lot of fluctuations but no clear patterns. Similarly, in the rainfall records for June and July there are no clear trends. At Derby, 5 year running means of cumulative temperatures show distinct trends towards increases in the months of May since 1984, and to a much weaker level also in July but not in June. In the case of London, cumulative temperatures in May indicate a trend towards warming since 1985, following a general cooling since 1969. No patterns feature in the records for June months. In contrast several cycles of warmer and cooler Julys occur over 7–8 year periods in the data set since 1961. The latest of these is a tendency to warming since 1984. There are no discernible patterns in rainfall over recent years that relate to the observed trends in pollen seasons.

Discussion

Trends in the cumulative catches of grass pollen over the 24–30 year period differ between the three sites. At Derby and London there has been a general decline in the totals but the rates of decrease differ, whereas at Cardiff the record is more varied and shows a fluctuation leading to a recent increase that is not entirely explained by increases in the amount of local sources. The differences between the patterns in the Cardiff pollen record and the trends in grassland amounts could result from several factors. For example, grass pollen may be transported across the Bristol channel from Cornwall, Somerset and Devon by south westerly winds, augmenting the local catch. Long distance transport of pollen has been reported previously for several locations, for example in Sweden [20].

The trends in pollen count decline at Derby and London follow the main trends in grassland amounts round the sites, but the annual cumulative grass pollen catches declined

more than the areas of grassland during the 1980s. The possible reasons for this are well documented elsewhere [11] but in summary, include changes in agricultural practice from hay making to silage which resulted in a 54% decrease in production of hay between 1969 and 1989, a change in seed mix from *Dactylis glomerata* to *Lolium perenne*, the introduction of 'set-aside', which in the years from 1990 to 1995 increased in the UK from 72 000 hectares to 633 000 ha [13], the growth of the urban areas so that pollen sources are further from the traps and increases of pollution exerting more stress on plants resulting in decreased pollen production.

Analysis of the daily temperature and rainfall records for the months of January through to the end of July at the three sites shows relationships between weather and annual variations in start dates and severity but reveals no patterns that would account for the observed sustained trends in pollen seasons. Regional trends in total grass pollen appear to relate primarily to changes in agricultural practice rather than trends in weather conditions. The large differences apparent between the patterns in the pollen count data at the three different sites around the country highlight the need to consider regional aeroallergen data in epidemiological studies. Extrapolation of the results from one monitoring site is valid only within that biogeographical and land use area.

Predicting the annual cumulative totals of grass pollen

Statistical approach. Accurate predictive models of pollen season characteristics are useful not only for allergists, and for physicians conducting clinical trials but also for others such as pharmaceutical companies and the Health Care Industry for marketing and stocking hay fever treatments. Various approaches have been used including empirical regression, indicator species and phenological relationships to environmental factors [e.g. 21–23]. In the majority of cases the predictive power of the models has been limited by the short data sets available and the consequently small number of observations. Previous work on the London data set [11] achieved a 66% explanation of variation in annual cumulative totals over 20 years working with monthly aggregates of temperature and precipitation variables built into a multiple regression model. Additional variables such as wind speed and direction, sunshine hours and relative humidity did not add significantly to the explanation achieved probably because they are auto correlated with the key variables of temperature and precipitation.

In the current analyses empirical models were developed using multiple regression [24]. Various approaches were tried including 5, 10 and 30 day aggregates of weather variables. The greatest accuracy was achieved using ten day aggregates of cumulative daily temperatures above 5.5°C

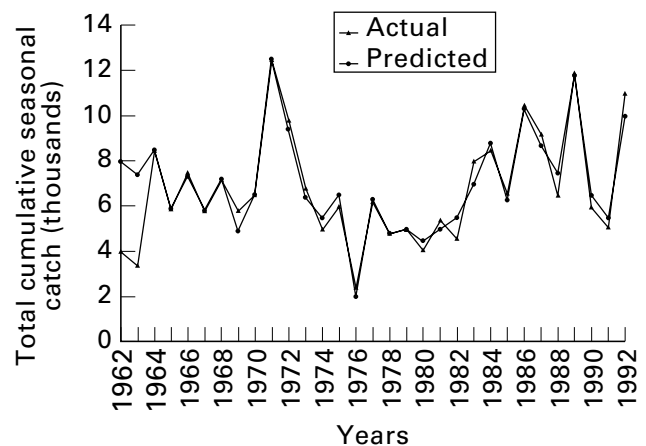


Fig. 4. Seasonal cumulative grass pollen catches at Cardiff; actual results against predicted values.

and precipitation. Variables were compiled retrospectively from 31 July to 1 January. Most grass pollen is dispersed in June and July so weather from the start of August exerts little effect on the final pollen sum. The first 7 months of each year include the key times that influence the growth of the grasses after the winter, the initiation of flowering and production of pollen, and the pollen release and dispersal. Annual cumulative grass pollen counts were square rooted in order to create a normal distribution for multiple stepwise regression analysis. The models were constructed with the intention of using long range weather forecasts for the June and July aggregate variables so that the cumulative totals for the season could be predicted before or near the start date. Individual models were developed for each of the three sites for the data sets up to 1993 then tested on data for the years 1994 and 1996 as examples.

Cardiff. Preliminary analysis (analysis of variance) of the grass pollen data set from Cardiff confirmed that it could be treated as one population. A multiple regression model was developed to achieve a level of 96.6% explanation using the variables as shown in eq. 1. The most significant variables are rainfall in June and accumulated temperatures in May; these two variables on their own give 53% of the explanation. In comparison with the other two sites, rainfall is more important at Cardiff. This is probably a function of the coastal location that gives rise to more equable temperatures than at the inland sites. Actual annual counts for the study period are compared to those predicted from the model on Fig. 4. The average error is 11.53% reducing to 5.6% if 1962 and 1963 are excluded.

$$\begin{aligned} &\text{Square root of cumulative catch for the season} \\ &= 41.997 + 0.434a + 0.267b - 1.68c - 0.151d + 0.638e \\ &\quad + 0.348f + 0.157g + 0.3290h - 0.35j + 0.18k \end{aligned} \quad (1)$$

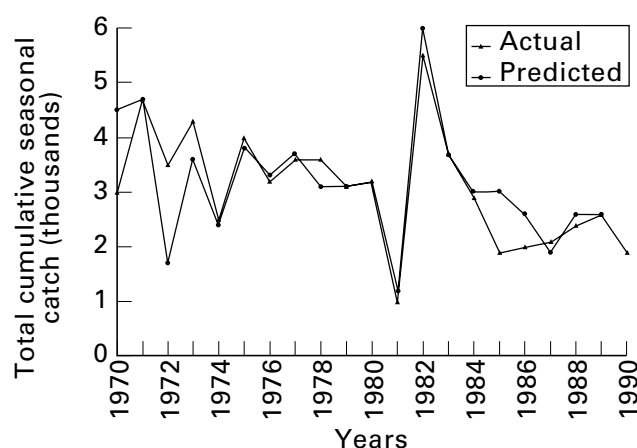


Fig. 5. Seasonal cumulative grass pollen catches at Derby; actual results against predicted values.

a = total rainfall June 2–11
 b = cum temp 13–22 May
 c = cum temp 22 Feb.–3 March
 d = total rainfall 4–13 March
 e = actual start date (sum 75)
 f = cum temp 23 April–2 May
 g = total rainfall 23 April–2 May
 h = cum temp 3–12 May
 j = total rainfall 13–22 Jan
 k = total rainfall 12–21 Feb.
 $r^2 = 96.6$
 $P < 0.001$

Derby. In the case of Derby cumulative temperatures were more important than rainfall. The model developed to predict total seasonal catch achieved 98% level of explanation using the variables shown in Eq 2. Predictions could not be made for 1969, 1970 and 1971 due to a lack of temperature data. The average error is 10.2% with the main differences occurring in 1981 and 1988 following a particularly wet period at the end of March in both of these years (Fig. 5).

$$\begin{aligned} &\text{Square root of cumulative catch for season} \\ &= 83.582 - 0.48a + 0.642b - 0.733c + 0.371d \\ &\quad - 0.35e - 0.503f \end{aligned} \quad (2)$$

a = cum temp 14–23 March
 b = total rainfall 3–12 May
 c = total rainfall 24 March–2 April
 d = cum temp 13–22 April
 e = cum temp 3–12 April
 f = cum temp 23 Jan–1 Feb.
 $r^2 = 98\%$
 $P < 0.001$

London. The data from the 1960s was excluded from the modelling as the pollen counts were notably higher in this decade and not relevant to the current situation. Analysis of variance showed that this data was different to that of the 1970s and 1980s and therefore the data could not be treated as one population. A 91.5 % level of explanation was achieved using a regression with the actual start date (sum75), cumulated temperatures and total rainfall at Heathrow for the periods shown in Eq (3). Weather data from Heathrow gave significantly more explanation than data from Rothamsted or St James' Park. Heathrow is closer to the pollen monitoring site than Rothamsted and is likely to share weather features with Paddington as it lies to the south west, the prevailing wind direction. These aspects are important in predicting the cumulative catches but would be less relevant to models of the start dates.

In London variations in temperatures during the dispersal period were a greater influence on total catch than differences in rainfall. It was found that temperatures in late spring and in the third week of June were critical. The actual start date is important, as seasons that start late tend to have lower total catches ($r = 0.639$, $P < 0.01$). The average error is 13.3% but this is inflated by large percentage errors that occurred in the predictions for 1970 and 1972, probably arising from the abnormal weather patterns in June of these years.

$$\begin{aligned} &\text{Square root of Cumulative catch for the season} \\ &= 246.413 - 1.266a - 0.372b - 0.204c - 0.152d \end{aligned} \quad (3)$$

a = actual start date (sum 75)
 b = cum temp 24 March–2 April
 c = Total rainfall 2–11 Feb.
 d = cum. temp 12–21 June
 $r^2 = 91.5\%$
 $P < 0.001$

Region	1961	1970	1980	1990	% change 1970–90
Cardiff		1 637 826	1 866 660	1 949 948	+19
Derby		942 076	1 058 959	982 216	+4
London	998 183	752 163	674 054	664 517	–14

Table 4. Summary of grassland changes around Cardiff, Derby and London.

Table 5. Actual and predicted cumulative grass pollen catches at Cardiff, Derby and London for 1994 and 1996.

Site	1994		1996	
	Actual	Predicted	Actual	Predicted
Cardiff	4940	5581	4926	5665
Derby	5367	5873	3816	4288
London	1559	1720	1359	1514

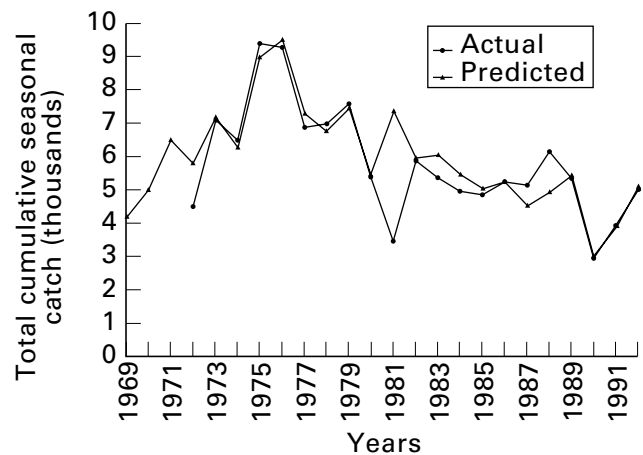
Testing the models

The models were tested on data for the 1994 and 1996 seasons as examples. The results gave predicted sums within 15% of the actual amounts for Derby and Cardiff and within 10% for London (Table 5). The predictions can be made during May if forecast weather variables are entered into the model. In this way the cumulative grass pollen sum for the season may be forecast shortly before the start date to give a useful indication of the severity in comparison with other years.

Conclusions

The forecast models have achieved a high percentage of explanation within the data sets and have proved to be effective in subsequent years. The models stress the differing importance of the variables that influence the total catch at the three sites. For example, rainfall is more important at Cardiff and temperature more important at Derby. The models have the advantage of an empirical base that has monitored the biological response of the various species to variations in climate over the study period. However, in all three cases the most accurate predictions can be made in years when weather patterns are near the mean condition. Extremes of temperature and rainfall represent isolated cases that may not be duplicated or matched within the data set. In current forecasting the progress of the weather variables is monitored to assess deviations from the norm so that predictions can be assigned confidence limits.

The high percentage explanation achieved in the cumulative sum models derives partly from the fact that the weather at the time of flowering of individual grass species is not as important as for start dates. The total catch takes into account all species through the season irrespective of when they flower. The models combine estimates of pollen production with potential dispersal throughout the season. The timing of the peak period is not forecast by this technique but could be incorporated later. In their present form the models serve as a useful basis for forecasting severity at a relatively early stage in the year. If current

**Fig. 6.** Seasonal cumulative grass pollen catches at London; actual results against predicted values.

climatic shifts continue the models can be modified by including data from more recent years and omitting that from the earlier ones. In this way the biological response can be tracked through empirical modelling.

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