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The dendrochronological potential of modern yew (*Taxus baccata*) with special reference to yew from Hampton Court Palace, UK

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SUMMARY

Modern yew (*Taxus baccata*) is demonstrated to have considerable potential for dendrochronological use. A replicated 303 yr chronology has been formed from Hampton Court Palace yew and cross-matches well with a number of different tree species, including oak. Growth is positively correlated with rainfall but inversely related to late summer temperature. Range limits and present and prehistoric sources of yew are also briefly discussed, highlighting the future potential of yew to become the third major tree species for British dendrochronological study.

Key words: dendrochronology, yew, *Taxus baccata*, Hampton Court, response function.

INTRODUCTION

Tree-ring research in the British Isles differs from elsewhere in its overwhelming concern with one tree genus, the oak. This has arisen from the preponderance of oak timber artefacts and the apparent lack of other native tree species with suitable properties for dendrochronological study. Sampling of modern material (living trees) has been thought to provide only chronologies of 100 or 200 yr in length in the case of most British species. Studies have been conducted on beech, elm, ash, lime, alder and maple, among others, but it generally appears impossible to build a long-term chronology from these relatively short-lived species. The only other major candidate for tree-ring research in Britain has been the Scots pine, *Pinus sylvestris*, a species of importance over much of Europe (Hughes, 1987).

Yew is a long-lived species which could be useful for dendrochronology. It has been observed to contain up to 40 rings in 1 cm, and one yew in a Somerset churchyard was reported to show > 500 yr of continuous growth (Bowman, 1837). Present-day yews can measure up to 10.75 m in girth (Mitchell *et al.*, 1990). In Italy, although not commonly used as a building material, yew has also revealed long, continuous tree-ring counts where a single beam contained 441 rings (Bebber & Corona, 1986; Parsapajouh *et al.*, 1986). In comparison, even from British archaeological evidence oak has rarely been found > 400 yr old (Hillam, 1990).

Distribution

Taxus baccata is a western Atlantic species, characteristic of British rather than many continental woods (Ratcliffe, 1977). However, it has a wide range throughout Europe (Jalas & Suominen, 1973), and generally extends over the areas of central and western Europe where the climatic extremes in both winter and summer are not exceptional. In the south of its European range yew is largely a montane tree, whereas in the north (as in Britain, Ireland and Scandinavia) it grows at low altitudes and often in rugged locations. Tittensor (1980) shows the probable native distribution of yew in Britain and Ireland.

In Britain the yew is one of the few native conifers, along with juniper (*Juniperus communis*) and the Scots pine (*Pinus sylvestris*). It is particularly well suited to a mild oceanic climate and avoids all regions of strong winter frost (Godwin, 1975). Yew generally prefers humid soil, but also grows where groundwater levels are low in regions with an oceanic climate. In these regions any soil moisture shortage is offset by the high humidity of the air, or water from heavy rainfall. In mountainous areas yew grows mostly on the more shaded north-western or north-eastern slopes, where under deciduous or mixed stands it finds an ecological climate similar to the oceanic climate (Markiewicz, 1978). The yew is also strongly, though not exclusively, connected with calcareous soils.

Historic background

Historically it was generally thought that trunks of yews grew in a lop-sided manner according to aspect, slope of ground, shade and humidity, thereby producing a very asymmetrical trunk. Yew wood is characteristically extremely variable, dense and irregular, a fact which may have deterred dendrochronological study in the past. Another problematic feature of yew is that, while the wood has a very high resistance to decay, the heartwood of living yew has a tendency to rot: the heartwood of all yews >4.57 m in girth is thought to be rotten and hollow (Mitchell, 1972).

However, the yew has no known natural age limit, and it is thought that some living specimens may date back as far as the Neolithic period (Milner, 1992). For this reason many of the larger girthed trees are called ancient yews. Few ancient native yew woods survive today – Kingley Vale, on the chalklands of the South Downs in the UK, is one of the few examples of a yew wood in Europe. However, small stands of yew and many of the largest trees may be found in the churchyards and cemeteries of England and Wales (Wallace, 1992), and the parish churches of Britain provide a unique assemblage of the largest yews known in Europe (Denne, 1987).

Hampton Court Palace

In July 1993 an avenue of yew trees was removed from the grounds of Hampton Court Palace, as part of a plan to reconstruct a 17th century design for the Privy Garden. The trees were reported to be all that remained of 197 yews planted between 1700 and 1703 as part of a baroque parterre garden. The yew trees were thought to have been clipped and maintained in an obelisk shape *c.* 2.4 m high until at least 1736 (Boulding, 1992). Clipping ceased *c.* 1764, when Capability Brown was appointed Surveyor to His Majesty's Gardens and Waters at Hampton Court (Clifford, 1992), and although it was resumed in 1919–20 in order to tidy the trees, their obelisk shape was not restored (T. Goth, Hampton Court Palace, pers. comm.).

MATERIALS AND METHODS

Fourteen complete cross sections of different yew trees (*Taxus baccata* L.) were obtained. The sections were 5–10 cm thick and were taken from approx. 1 m above ground level. These sections were air-dried, sanded and polished. A numbering system created by Travers Morgan (pers. comm.), previously used on plant location maps at the Privy Garden site for Hampton Court Palace, was adopted for labelling the yew samples. Girth measurements were recorded for an additional 30 yew trees from the Privy Garden site at Hampton Court, at a height of 60 cm above ground level. This sample height is generally recommended for measuring ancient yew trees (A. Meredith, pers. comm.), and was used because the trees sampled had already been felled.

Table 1. *Species chronologies available from Kew, UK*

Species	Common name	No. of trees	Chronology (yr)
Quercus spp.	Oak	8	121
Carya cordiformis	Bitternut hickory	6	138
Castanea spp.	Chestnut	3	198
Fagus sylvatica	Beech	3	199
Pinus nigra	Black pine	1	126

The growth ring widths were measured to an accuracy of 0.01 mm and processed on software written and developed by Ian Tyers, formerly of the Museum of London Archaeological Service (Tyers, 1990). In view of the availability of entire yew cross-sections and the yew's reputed asymmetrical growth, four radii were measured along lobes aligned closest to the north, south, east and west orientations. As two of the samples were hollow, only 12 of the 14 tree sections could be measured along all four orientations. Matches were confirmed visually using ring-width plots, which also served as a useful check for possible ring counting errors and for missing rings. The ring widths from each tree were compared with each other, then with those of the other trees from the site, by a process of cross-matching (Baillie & Pilcher, 1973).

Climate and site data

The meteorological station at Kew is only 9 km from the Hampton Court Palace site, and provides a weather record which is one of the longest series available anywhere in the world. Monthly precipitation and temperature data extend from 1872–1994, while yearly total rainfall records extend back to 1697. This provided a rare opportunity to examine the long-term effect of monthly temperature and precipitation on yew through response functions.

Precipitation and temperature data from September of the year prior to growth, to October in the year concurrent with growth, were used in the response-function analysis. This 14-month range included the autumn months in England, and provided coverage of the variable ends of both prior and current growing seasons. To examine the stability of the response function, 40-yr overlapping periods were also selected, spanning the range of response data available. Five equally spaced segments, overlapping one another by half, were selected for comparison (1873–1912, 1893–1932, 1913–52, 1933–72 and 1963–92).

The raw measurements of the tree-ring data were detrended in two steps and autocorrelation was removed using the program ARSTAN (Holmes *et al.*, 1986). The resulting data were averaged and a site chronology obtained. Pointer years were selected from the residual chronology, rings of at least 1.5 SD from the mean were selected as narrow- or wide-ring pointer years.

The cambium in conifers has been stated to lose its ability to react and reduce growth abruptly after the age of *c*. 50 yr (Schweingruber, 1986). This possible effect was examined on two additional chronologies. A chronology 'MHPYUN' was created from the eight mean yew chronologies of the trees germinated close to 1808, whereas 'MHPOLD' contained the six older trees germinated close to 1726.

Both Hampton Court Palace gardens and Kew are relatively flat sites, with a thin layer of top soil (pH 6.5 at Hampton Court) overlying sand and gravel river terraces. The sites, on the west of the major conurbation of London, experience the same high, tidal-influenced water table that exists at the edge of the Thames. Mean soil-moisture deficits for the 'growing season' (May–August) have been estimated using the monthly Kew data and the Penman–Meteorological Office model (Wales-Smith, 1980). The average soil-moisture deficit over the 4 month period (May–August) was used as an index of both drought severity and very wet soil during the growing season (Wigley & Atkinson, 1977).

Inter-species cross-dating

Inter-species cross-matching could be particularly important in the dating of a new chronology, and may have long-term implications in the future dendrochronology of yew. As there have been few studies exploring the potential of inter-species cross-matching, data available from Kew (Cutler *et al.*, 1992; M. C. Bridge, pers. comm.) were used in an initial assessment. Five tree-species chronologies were created from the Kew raw data measurements for comparison with Hampton Court yew (Table 1).

The rainfall data from Kew were obtained for 1872–1987 (Kew tree-ring data end at 1987 due to the loss of trees in a storm of that year). All of the tree species chronologies examined in this paper were also edited to this period to aid comparison. Editing had the added advantage of cutting off the variable early growth years from the majority of the chronologies.

RESULTS

A 303 yr modern chronology based on the 14 yew trees from Hampton Court was established, called 'HPYEW92'. The mean annual radial increment over the whole observation period was 1.08 mm with a mean sensitivity of 0.23, which is relatively high especially in comparison with oak (mean sensitivity is a measure of the variation between successive years of tree-ring widths; it ranges from 0.0 to 1.0,

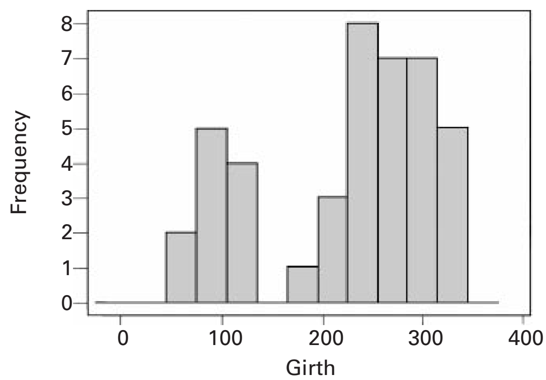

Fig. 1. Distribution of girth measurements (in cm) taken from Hampton Court yews.

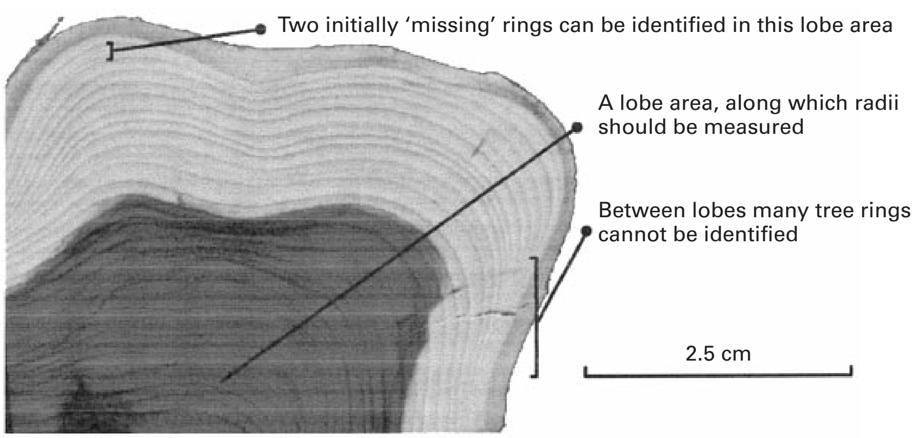

Fig. 2. Sanded cross-section of yew showing how partly 'missing' rings can be identified on radii measured along lobe areas.

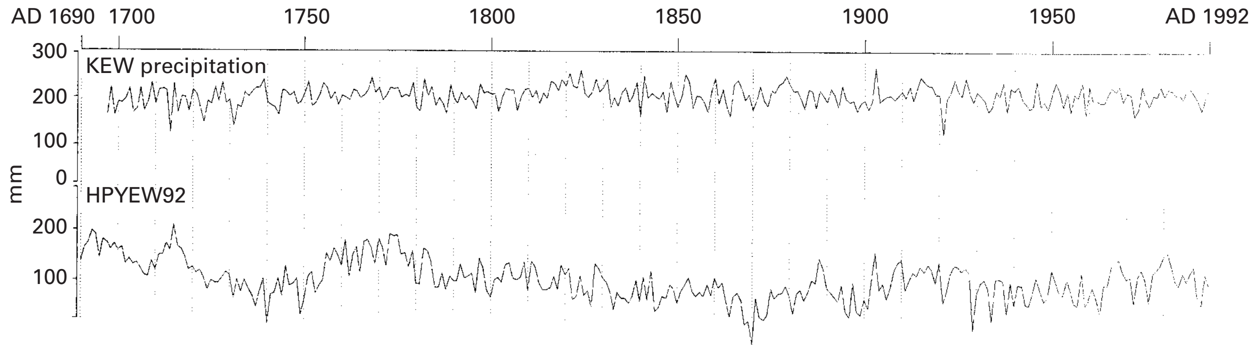

Fig. 3. Indices plot: Kew rainfall and HPYEW92 master chronology.

larger values indicating greater variability). A pith date obtained from 60 cm above the ground represents the age of the tree at that height, not necessarily the absolute age of the tree or the year of its germination (Telewski & Lynch, 1991). However the age range of the tree sections (between 90 and 303 yr), reveals a wide range in the planting dates. Of the 14 tree sections measured, 12 extended to the pith and were used to calculate an age regression equation from the tree's girth measurements:

$$\text{AGE} = 17.8 + 1.08 \times \text{GIRTH (in cm)} \quad (\text{SD} = 31.0)$$

The girth measurements of all yew trees measured at the site are compared in Fig. 1, which indicates at least two distinct yew tree age groups with considerable variation in girth within each.

The initial measurement of tree sections revealed a problem whereby radii from the same section were found to be affected by locally missing rings (i.e. those visible around only part of the circumference). Extremely narrow rings, initially missed, could be identified by a characteristic previously seen as a problem in measuring conifers. Lobate growth (Ward *et al.*, 1987), where a single ring varies in width around the circumference of the section, is characteristic of yew and makes extremely narrow or partly missing rings more clearly visible on the lobe of some parts of each section (Fig. 2).

Missing rings could generally be identified on one of the four radii measured on each section. A series of seven narrow rings between 1896 and 1938 were amongst the most difficult to identify, particularly the successive narrow-ring years of 1921 and 1922. Comparison of several radii measured along the lobes was necessary to obtain an accurate ring sequence for a single section. Good statistical and visual comparisons between the yew and rainfall data (Fig. 3) strongly suggest that the initial measuring problem of missing rings was overcome. The yew chronology was compared against the 298 yr (1697–1994) rainfall data for Kew by cross-matching, and produced a 9.88 t value. The yew chronology HPYEW92 also cross-matched significantly against a number of generally established oak chronologies (Table 2).

The average response function for the yew chronology HPYEW92 is seen in Fig. 4. Precipitation, particularly in the months February–July, had a positive effect on yew growth. Temperature also influences growth positively, as is clearly evident early in the year (January and February) and in late summer (October), which is probably indicative of the extended growing season.

High temperature has a negative influence on growth; this generally occurs in the summer months and is particularly evident in July. Low temperatures in January and February correspond with narrow rings, whereas milder temperatures are shown to be associated with wider rings. Higher temperatures in early spring probably give rise to an early resumption of metabolic activity, thus enabling an earlier resumption of growth. Relatively high temperatures in summer (particularly June) appear to inhibit growth and the formation of wide rings, which is consistent with the evidence from the late-wood growth rates of all conifer species (from cool humid regions) where they are limited by summer temperatures (Schweingruber, 1986). Therefore a high summer temperature generally gives rise to a narrow annual tree ring, depending on the positive effect of precipitation.

A comparison of mean young (MHPYUN) and old (MHPOLD) yew chronologies, edited to similar periods (1872–1992), displayed little variation in mean annual radial increment or mean sensitivity values. The only significant difference in the comparison of the two chronologies is seen in the response functions, where the older tree chronology

Table 2. *Cross-matching of the yew chronology HPYEW92 against several established oak chronologies*

Chronology	Reference	t
GIERTZ 2	(Siebenlist–Kerner, 1978)	5.72
SOTTERLY	(Briffa *et al.*, 1986)	5.08
WINCHESTER	(Barefoot, 1975)	4.76
OXON 93	(D. Miles, pers. comm.)	4.60

HPYEW92, a 303 yr modern chronology based on 14 yew trees from Hampton Court, UK.

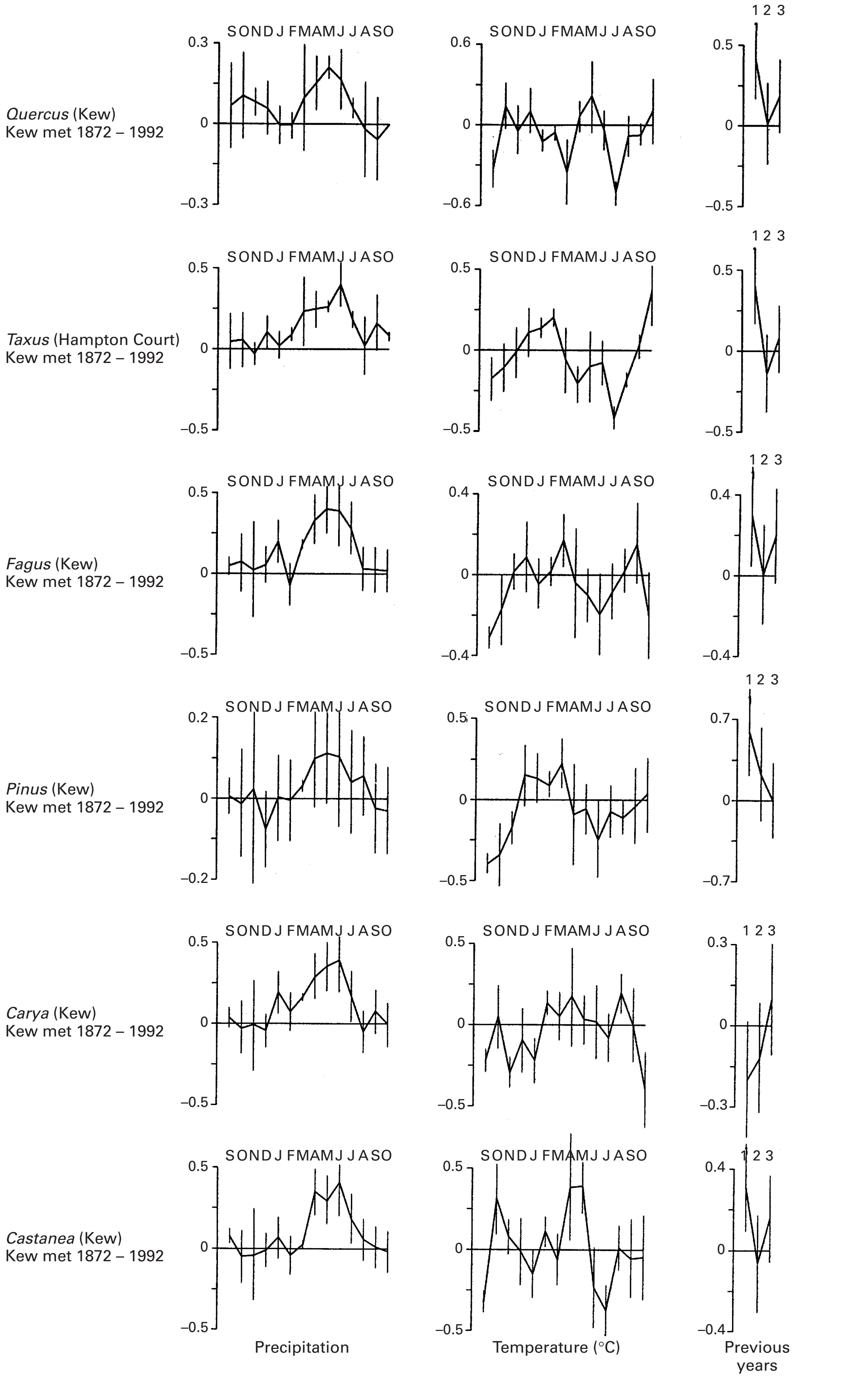

Fig. 4. Correlation coefficients for the correlations between the monthly climatic variables and six different tree chronologies from Hampton Court and Kew over the same time period.

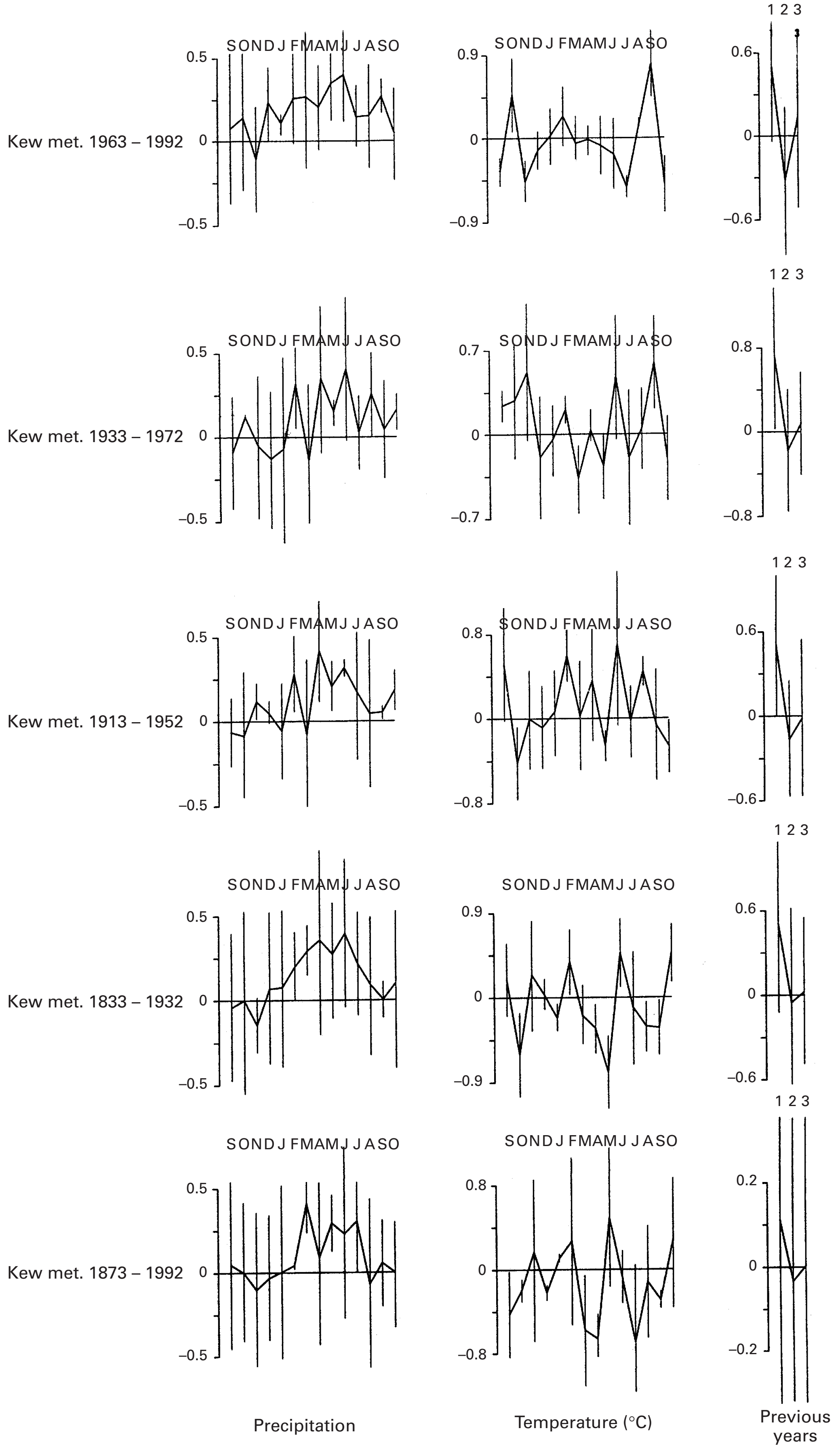

Fig. 5. Variation of correlation coefficients for the correlations between the monthly climatic variables and yew from Hampton Court (HPYEW92) over five time periods.

Table 3. *Hampton Court palace yew pointer years*

Years	Narrow rings	Wide rings
1770–1749	1702, 1724, 1737, 1740, 1749	1715, 1745
1750–1799	**1762**, 1780, **1781**, 1785, 1788, 1796	1773, 1782, **1782**, 1783, 1797
1800–1849	1827, 1833	1809, 1811, 1828, 1829, 1841
1850–1899	1870, **1896**	**1860**, 1888
1900–1949	**1901**, **1921**, 1922, **1929**, **1934**, **1938**	**1903**
1950–1992	1963, 1972, **1976**, 1989, 1990	1950, 1966, 1967, 1968, 1981

Years in bold type correspond to dry years in the case of narrow rings and wet years in the case of wide rings.

Table 4. *An indication of the strong climatic relationship and inter-species cross-matching between data sets*

Data series	Taxus	*Quercus*	*Carya*	*Castanea*	*Fagus*	*Pinus*
Kew rainfall	7.0	3.1	4.4	5.2	5.8	4.4
Moisture	−5.3	−5.0	−3.6	−5.6	−5.2	−3.3
Taxus (Hp)		3.7	7.0	7.9	8.0	5.3
Quercus (Kew)			4.8	6.7	7.4	3.4
Carya (Kew)				6.6	7.6	4.7
Castanea (Kew)					11.6	5.8
Fagus (Kew)						5.6

CROS73 t values shown (Baillie & Pilcher, 1973).

reveals a slightly stronger positive summer correlation with rainfall. The response functions of yew are consistent with ecological evidence that mild/wet winters combined with cool summers provide ideal conditions for growth in yew, which is exemplified particularly well in 1903. Conversely, hot summers with little precipitation (drought) have a general adverse effect on yew growth. This can be seen in the high correlation between narrow-ring pointer years and drought (Table 3).

Similar responses to temperature and precipitation are evident in the overlapping response-function periods examined, although there are also some clear variations between periods (Fig. 5). Over the five periods the linear correlation changes. This is expressed by changing correlation coefficients (amount and sign) in particular months, especially October and September. The period 1873–1912 appears to be unique in that it is characterized by a very varied response to precipitation and a dramatic increase in the correlation coefficients for temperature. This period also shows a very strong negative response to April temperature which is not seen as clearly in the overall response function of the site.

The pointer years identified for the yew HPYEW92 chronology at Hampton Court are shown in Table 3. Generally, tree rings in narrow pointer years correspond to years of drought and can be explained by low precipitation of those years, although some severe drought years (e.g. 1893, 1943, 1944, 1949 and 1965) are not represented. While soil-moisture deficits may provide the best practical drought index (Rodda *et al.*, 1976), they use only a small portion of a growth year (4 months) in their equation. Wide pointer years in yew have a limited relationship to yearly precipitation. Oddly, this appears to conflict with the strong relationship between the soil-moisture deficit values for Kew against which pointer years show the following r values: -0.223 against narrow rings and -0.480 against wide rings. However, even compared individually, the effects of temperature and rainfall taken throughout the year show a better correlation with growth than soil-moisture deficits for yew from Hampton Court. Overall, the HPYEW92 chronology gave a significant correlation value of $r = -0.549$ when matched against the soil-moisture deficit values for Kew. Therefore the yew growth on this site is relatively well explained by soil-moisture deficits, with low deficits correlating with wide rings.

Table 4 shows the five different tree species from Kew, which were all found to match with high t values against the HPYEW92 chronology. *Pinus*, *Fagus*, *Castanea* and *Carya* cross-match strongly with the Hampton Court yew chronology (Fig. 4) because of the very similar positive response to summer rainfall in March–July. There are, however, some significant differences in responses to temperature between the six genera examined. *Taxus*, *Fagus*, *Castanea*, *Carya* and *Pinus* all appear to fit a 'sensitive' species category compared with the relatively 'complacent' characteristics of *Quercus* (Fritts, 1976).

There is marked agreement with the oak response function created for Kew and the generalized British Isles oak response function (Pilcher & Gray, 1982). An effect of using poorly replicated tree-ring data in response functions can be seen in the low correlation values and wide confidence limits seen in the precipitation response of *Pinus nigra* where only one tree was used.

DISCUSSION

A comparison of average growth rates for yew in the British Isles against those at Hampton Court Palace indicates that the rate of growth at this site is higher than expected (Fig. 6). A 75 cm increase in girth equates to *c.* 100 yr of growth; however there is considerable variation between the age of a tree and its mean ring width or girth measurement. Some variation in growth rates was due to the rotting centre of some yew trees: these are problems common to girth measurements taken in the field and used to estimate the age of ancient yews. These observations tend to support those of Denne (1987) that the girth width of a yew has only a very limited use as an estimate of age, at least in younger trees. No evidence was found of a relationship between growth rate and the orientation of the trunk.

While modern yew is demonstrated to be suitable for use in dendrochronology, the need to measure a number of different radii from entire yew sections in order to identify missing rings indicates that analysis by incrementally cored samples may prove inaccurate. Management (specifically the clipping of yew) does not remove the climatic signal contained within the annual increments measured. This factor is especially important in the context of the large proportion of ancient yews in churchyards, where again the yew trees may have been exposed to periodic management. Interestingly, the older trees at the Privy Garden site demonstrated a slightly higher correlation with rainfall data.

This paper demonstrates that a modern yew chronology can be dated by reference to oak chronologies, and also that it cross-matches higher than oak against the four other tree species examined: hickory, chestnut, beech and pine (Table 4). The ability to date yew in an architectural setting has already been demonstrated (Bebber & Corona, 1986), and large sources of prehistoric (sub-fossil) yew have been widely recorded in England (Godwin, 1975; Anon., 1995). While the potential for dating sub-fossil yew has yet to be proved, this source further highlights the potential of yew to become the third major species in British dendrochronological studies.

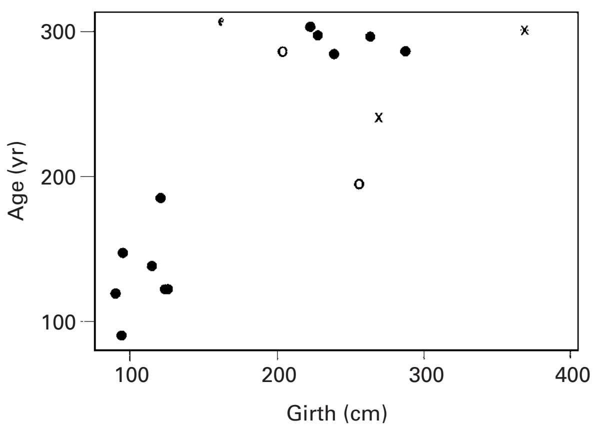

Fig. 6. Relationship between age and girth measurements for the Hampton Court yew in comparison with tentative yew tree growth rates for the British Isles (Milner, 1992). Closed circles, dated yew; open circles, hollow yews from site; crosses, tentative British Isles yew tree growth rates (Milner, 1992).

A strong relationship is demonstrated between yew growth and climate, which indicates a good potential future for this species in climatic reconstruction. Yew growth at the Privy Garden site is relatively well explained by monthly temperature and precipitation. Evidence of a strong positive correlation between rainfall and yew growth is presented, while late summer temperature shows a strong inverse relationship to ring width (Figs 4 and 5). In general, the pointer years for the site match well with records of seasonal extremes in temperature and precipitation in corresponding years (Table 3).

The occurrence of pointer years changes over the five different time periods examined. The apparent change in response pattern over time could be attributed to a number of changes in biotic or anthropogenic influences on radial growth. The period 1896–1939, when the British Isles experienced an unusual run of mild winters (Ford, 1982), may be worthy of further study. Although these factors may be small, the change in response over time may reflect climatic change. The response of yew in this study should be related to the fact that London is one of the warmer sites in England; the analysis of a large sample from outside London would be helpful in assessing whether the growth behaviour of yew at Hampton Court is typical and may be applied regionally.

The most responsive trees for dendrochronological study tend to be found near their climatically determined limits of distribution. At present yew is considered native over most of its range in England (McEvoy, 1943; Godwin, 1975; Webb, 1977; Graham, 1988), reaching its northern limit in Scotland (Dickson, 1994). However, rainfall and humidity appear to influence the distribution of yew, even over the relatively small area of the South Downs in southern England (Tittensor, 1980). Site factors such as water table and aspect may also play a significant role in the use of yew in dendroclimatology. Variation between sites has been found to influence the growth response (Fritts, 1974), and it is likely that on appropriate sites the moisture signal detected in yew would be amplified.

The changes in the five response-function periods observed at Hampton Court may also indicate the increased urbanization of London, through an increased effect of the London heat island. Pilcher and co-workers identified a possible urban heat-island effect in Paris through response function variations (Gray *et al.*, 1981). It is expected that yew outside London will have a different response function due to the different temperature regime.

The effect of different temperature or precipitation extremes (indicated by the pointer years) within each discrete time period of a response function may reveal a species-specific response to those extremes through threshold response analysis. The effect of a species threshold in response to temperature and precipitation should be further investigated in relation to response functions, especially where only short periods of climatic data are available. Using maximum and minimum climatic data instead of the average data used in this study could help refine a tree species response to climate.

Maximum late-wood density and ring-width measurements from pines in the Scottish highlands have been used to reconstruct July–August temperatures for Edinburgh (Hughes *et al.*, 1984). Measurement of maximum late-wood density may strengthen the yew/climate correlations, and the promise of this technique for a conifer such as yew is clearly high. Successful dating of a tree species such as yew, with different thresholds of response to climate and possibly stronger relationships to different months, may help refine climate reconstructions for the UK.

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