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Pollen season trends as markers of climate change impact: *Betula*, *Quercus* and Poaceae

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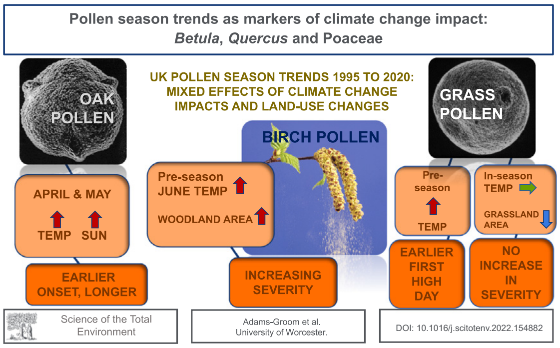
HIGHLIGHTS

- How are pollen season trends progressing – are they worsening with climate change?
- Pollen trends were analysed for 1995–2020 and correlated with climate variables.
- *Quercus* season onset is becoming earlier due to increasing Spring temperatures.
- Poaceae pollen seasons are not getting worse but *Betula* pollen seasons are.
- Climate change and land-use changes are impacting on the UK pollen seasons.

GRAPHICAL ABSTRACT



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ABSTRACT

The incidences of respiratory allergies are at an all-time high. Pollen aeroallergens can reflect changing climate, with recent studies in Europe showing some, but not all, pollen types are increasing in severity, season duration and experiencing an earlier onset. This study aimed to identify pollen trends in the UK over the last twenty-six years for a range of pollen sites, with a focus on the key pollen types of Poaceae (grass), *Betula* (birch) and *Quercus* (oak) and to examine the relationship of these trends with meteorological factors.

Betula pollen seasons show no significant trends for onset, first high day or duration but increasing pollen production in the Midlands region of the UK is being driven by warmer temperatures in the previous June and July. *Quercus* pollen seasons are starting earlier, due to increasing temperature and sunshine totals in April, but are not becoming more severe. The seasons are lasting longer, although no significant climate drivers for this were identified. The first high day of the Poaceae pollen season is occurring earlier in central UK regions due to an increasing trend for all temperature variables in the previous December, January, April, May and June. Severity and duration of the season show no significant trends and are spatially and temporally variable.

Important changes are occurring in the UK pollen seasons that will impact on the health of respiratory allergy sufferers, with more severe *Betula* pollen seasons and longer *Quercus* pollen seasons. Most of the changes identified were caused

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Abbreviations: Tmax, Maximum daily average temperature; Tmean, Mean daily average temperature; Tmin, Minimum daily average temperature; FH, First High day of the season; NH, Number of high days during the season; Kn, knots; Met, Meteorological; Pg/m^3, Pollen grains per cubic metre of air.

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by climate drivers of increasing temperature and sunshine total. However, Poaceae pollen seasons are neither becoming more severe nor longer. The reasons for this included a lack of change in some monthly meteorological variables, or land-use change, such as grassland being replaced by urban areas or woodland.

1. Introduction

Climate change is having an impact upon pollen production, dispersal, timing and season duration in various countries (Anderegg et al., 2021; Beggs, 2021; Gehrig and Clot, 2021; López-Orozco et al., 2021; Rojo et al., 2021a). Longer and more intense pollen seasons are being reported for some pollen types, which is increasing the respiratory allergy burden on sufferers, healthcare providers and society in general (D'Amato et al., 2020; Kishikawa and Koto, 2021; Lee et al., 2021). Furthermore, there are compounding effects of air pollution, which can both increase pollen potency and enhance the inflammatory effects of pollen in the respiratory system (Pacheco et al., 2021) and the potential of increasing levels of CO_2 to encourage plant reproduction (Albertine et al., 2014).

Climate change appears to be impacting on various aspects of the pollen seasons. In particular, across many areas of Europe, the *Betula* tree Seasonal Pollen Integral (SPIn) is increasing due to warmer weather in the previous summer, when the pollen is set in the flower-buds (Besancenot et al., 2019; Bruffaerts et al., 2018; Hoebeke et al., 2018; Ruiz-Valenzuela and Aguilera, 2018). Changes to the onset and duration of the pollen seasons are also occurring in Europe and beyond (Ziska et al., 2019). The onset patterns vary between countries and between regions within a single country, with not all sites recording earlier seasons. In France, Belgium and Switzerland, *Betula* pollen seasons were trending towards an earlier onset up until the late 1990s/early 2000s but then switched to a trend of later start dates (Besancenot et al., 2019; Hoebeke et al., 2018; Jockner-Oette et al., 2019). This trend reversal is related to increasingly mild autumn and early winter weather, which delays tree dormancy (Emberlin et al., 2007). In the Czech Republic, however, this switch has not been observed in *Betula*, where the onset continues to trend earlier, particularly in the north of the country, while pollen seasons are getting shorter overall (Hájková et al., 2020). In Sweden, most pollen types were observed to be starting and ending earlier, apart from grass pollen, which started earlier and lasted longer (Lind et al., 2016). However, not all of the climate change impacts reported to date will increase the symptom burden for allergy sufferers. Poaceae pollen in particular has shown decreases in both SPIn and the number of high days in some European locations (Lind et al., 2016; Hoebeke et al., 2018; Ruiz-Valenzuela and Aguilera, 2018; Besancenot et al., 2019; Jockner-Oette et al., 2019).

In the United Kingdom (UK), nearly a decade has elapsed since any pollen trends were analysed (Emberlin et al., 1999; Emberlin et al., 2002; Newnham et al., 2013) and none of these were examined in the context of climate change. There are now more pollen stations with long-term data sets, across a wider geographic area of the UK, than were previously available. Moreover, the UK has variable weather driven by Atlantic systems, which may impact on the pollen trends in a different manner to those of the continental mainland.

In this study we aimed to identify pollen trends in the UK over the last twenty-six years for a range of pollen sites, with a focus on the key types of Poaceae, *Betula* and *Quercus*, and to examine the relationship of these trends with meteorological factors.

2. Methods

2.1. Experimental design

Pollen data from 1995 to 2020, from six pollen monitoring sites around the UK (Fig. 1, Table 1), were analysed for trends using linear regression and compared to monthly mean weather variables from both pre- and in-season. To determine how climate change may impact on the pollen seasons, the monthly weather variables that were found to be significant drivers of seasonal variation were themselves tested for trend significance.

2.2. Pollen monitoring sites

Six sites had sufficient data for analysis, were deemed to be representative of their region of the UK (Khwarahm et al., 2016) and lay roughly in a north to south line to give latitudinal variation. All sites are surrounded by a mixture of agricultural land, urban or suburban areas and, to a lesser extent, woodland (Rae, 2017; Ministry of Housing, 2020), while a coastal influence is exerted on Cardiff, Invergowrie and Isle of Wight (Fig. 1).

2.3. Pollen data collection

Poaceae, *Betula* and *Quercus* pollen were collected as part of the routine pollen sampling undertaken as part of the UK pollen monitoring network. We focused on three important pollen allergens for the analysis for which we had sufficient data, since not all sites counted all pollen types in the early years of this time period. The data, measured as a daily average of grains per cubic metre of air, had been collected using Burkard 7-day volumetric spore traps using the standard UK pollen monitoring method (British Aerobiology Federation, 1995). Data were used from the period 1995 to 2020 but a few sites/years had missing data (Table S1).

The term 'high day' is used when all hay fever sufferers are likely to be affected and is the terminology used in pollen forecasting in the UK. A high day is classed as a daily average per cubic metre of air of 50+ for Poaceae (Davies and Smith, 1973) and *Quercus* (Unpublished research used UK pollen forecasting) and 80+ for *Betula* (Koivikko et al., 1986).

2.4. Statistical analysis

2.4.1. Pollen trends

Pollen trends were investigated using linear regression analysis for each of the six sites and all the sites combined, using annual means for the 26 years. For each pollen type, five pollen-trend variables were investigated: onset of season (2.5% method), the Seasonal Pollen Index (SPIn), number of high days (NH), season duration (2.5%/97.5% method) and the first high day (FH). The 2.5%/97.5% season definition was chosen as being the most suitable for the UK, following previous seasonal studies by Adams-Groom et al. (2020) and Kurganskiy et al. (2021), while terminology for SPIn follows Galán et al. (2017).

2.4.2. Meteorological influences on pollen dynamics

The influence of local meteorology on the pollen dynamics for each location and all sites combined was investigated using Spearman's rank correlations (Spearman, 1904) due to the non-parametric nature of the pollen trend data (e.g. Fernández-Rodríguez et al., 2014; Ríos et al., 2016; Stach et al., 2007), as concluded by Shapiro-Wilks tests (Shapiro and Wilks, 1965). All pollen variables were compared with all mean monthly Met variables (Tmax, Tmean, Tmin, rainfall (mm), total sun hours, average windspeed and maximum wind gust (Gustmx) (knots) at each location. The specific pollen-trend and Met variables investigated varied depending on the pollen type (Tables S2,S3 & S4), since, due to pollen-specific flowering and maturation periods, Met variables from the previous season can affect the pollen production of the current season. For this purpose each season had to be temporally defined by a North-Western European standard as the following: The grass pollen season was considered to finish on the last day of August (e.g., Frisk et al., 2022), the birch pollen season on the last day of May (e.g., Skjøth et al., 2008) and the oak pollen season on the last day of June (e.g., Pashley et al., 2009). Bonferroni corrections were applied to adjust the *P*-values for the multiple correlations tested. While this correction has previously been scrutinised for lowering the statistical power and increasing the number of false negatives

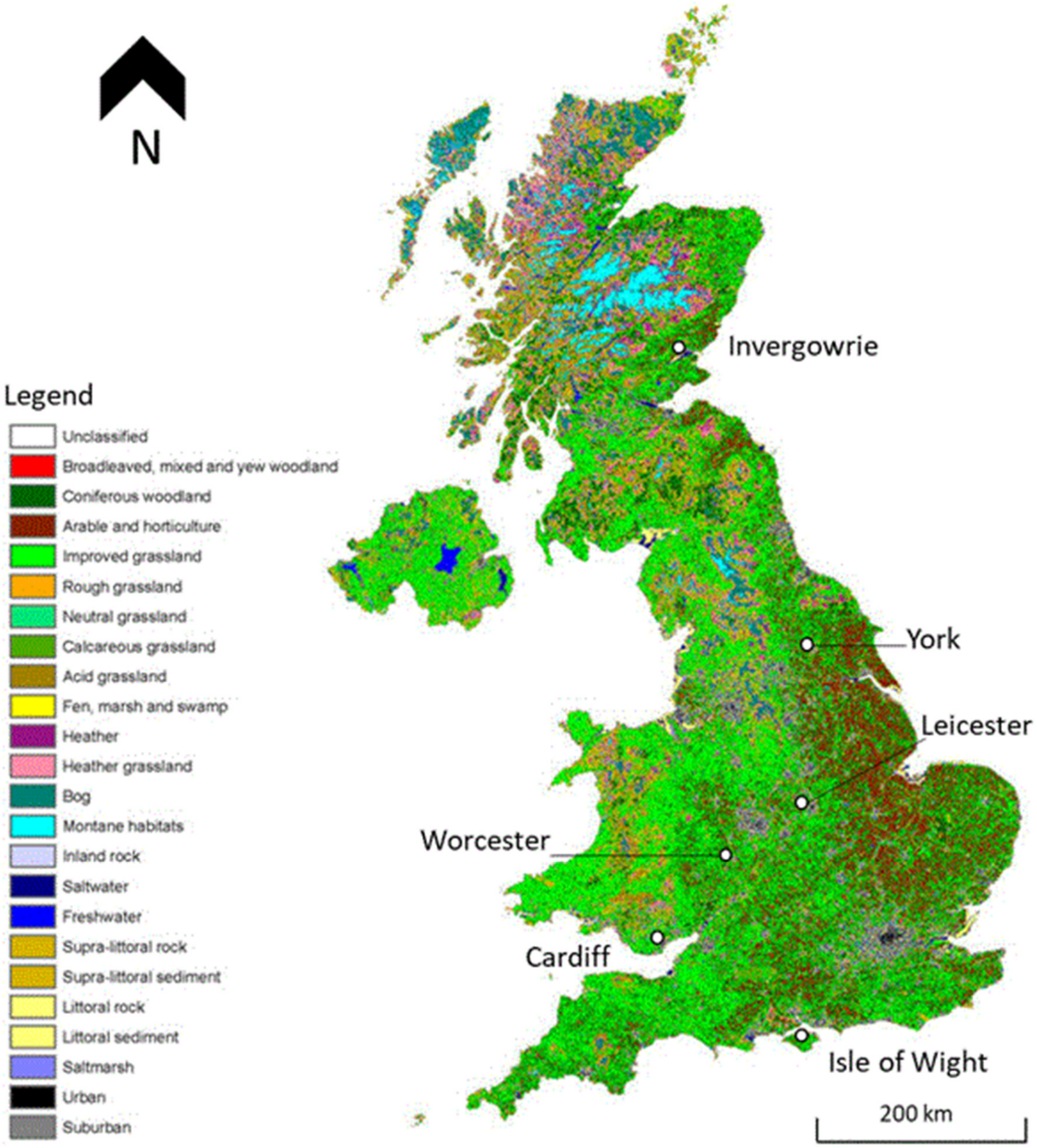

Fig. 1. Land cover map of the United Kingdom (Natural Environment Research Council, 2011) with the locations of the pollen monitoring sites.

(e.g., Perneger, 1998), it also provides conservative P-values that showcase truly reliable statistical estimates. Finally, the monthly met variables (termed 'key monthly met variables' throughout the remainder of this article) that were found to be significantly driving the pollen seasons were investigated using linear modelling for all years and for all sites combined. This was done to determine if any of the key monthly met variables could be affecting the pollen seasons, for example as a result of climate change. All statistical analyses were processed using the statistical software R, version 4.0.3 (R Core Team, 2021). All temperatures are provided in degrees Celsius.

Table 1
Location and elevation of six UK pollen monitoring sites, plus climate data from the nearest weather (Met) station.

Site	Latitude/longitude	Elevation (m)	Average rainfall (mm^{-a})	Tmean summer (°C)	Met station used	Met station distance (km)	Met station direction from site
Invergowrie	56.457558–3.068737	10	722.0	18.5	Leuchars	14.0	SE
York	53.948419–1.053544	20	626.0	20.3	Linton-on-Ouse & Cawood	17.0	NW
						14.0	SSW
Leicester	52.621919–1.12381	10	620.2	20.8	Watnall	43.5	N
Worcester	52.197405–2.243121	10	606.4	21.5	Pershore	16.0	SE
Cardiff	51.495831–3.212096	10	1151.9	21.0	Rhoose	16.0	WSW
Isle of Wight	50.711101 – 1.300887	10	699.1	20.7	Hurn	37.5	WNW

3. Results and discussion

3.1. *Betula* pollen seasons

No significant temporal trends were identified for the onset of the season, the arrival of the first high day (FH) or the season duration for *Betula* pollen (Fig. 2, Table S5). Invergowrie, the most northerly site, usually recorded a later onset than the other sites and only achieved high days in occasional years (Fig. 2). The timing of the onset and FH for all sites combined was significantly negatively correlated to Tmax, Tmin and Tmean in both February ($p < 0.001$) and March ($p < 0.001$), to April Tmax ($p < 0.01$) and Tmin ($p < 0.05$) and with the March sunshine total ($p < 0.001$) (Table S2). There were no significant climatic trends for these key months, apart from a weak increase in sunshine total for April, probably insufficient to cause a trend to earlier onset or FH (Table 2). Previous UK studies showed that the *Betula* pollen season had been starting earlier (Emberlin et al., 1997; Emberlin et al., 2002; Spieksma et al., 1995), while the later plateauing seen by Newnham et al. (2013) appears to have continued. Since both February and March are key months for the pre-season weather influence on the onset of the *Betula* season, a trend to earlier seasons would

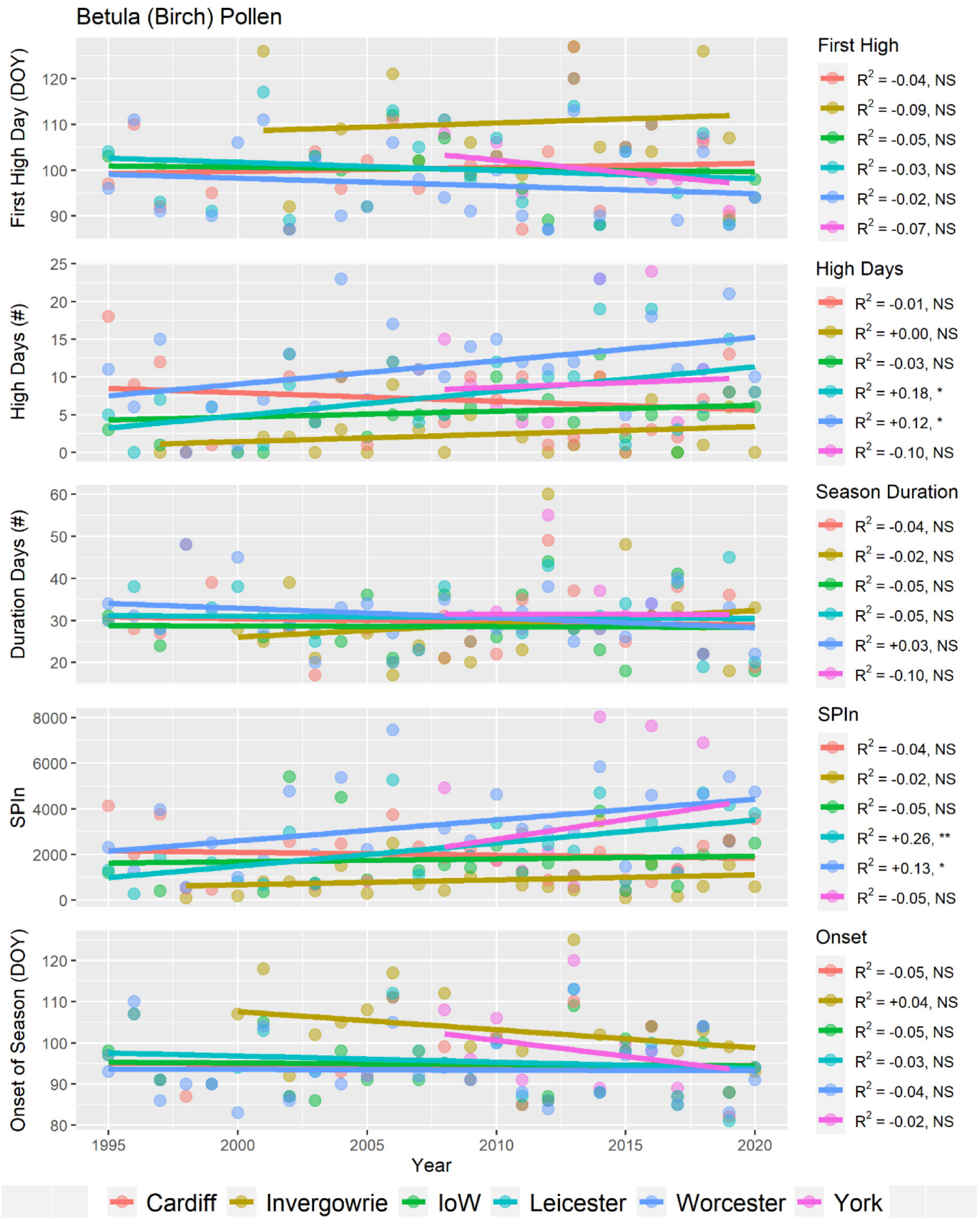

Fig. 2. Time-series and linear regression trends for onset, SPIn, duration, number of high days and first high day for *Betula* pollen seasons, 1995–2020, for six UK pollen stations. Also included are the R^2 and p values (** $p < 0.01$; * $p < 0.05$).

Table 2

Linear trends for the meteorological variables and locations (1995–2020) that impacted on the pollen season trends in this study. Bold trends indicate significant trends and are accompanied with specific p-values (*** p<0.001; ** p<0.01; * <0.05).

Key monthly Met variable	All	Inver	York	Leics	Worc	Card	IOW
Jan Tmax	**0.0348***	0.01552	0.04424	0.03935	0.03173	0.03781	0.04014
Feb Tmax	−0.00599	−0.00092	−0.01624	−0.00417	−0.00362	−0.00332	−0.00769
Mar Tmax	0.018	0.00841	0.03067	0.02427	0.02034	0.00373	0.01761
Apr Tmax	**0.056****	0.0212	0.05969	0.05443	0.06677	0.06862	0.06769
May Tmax	**0.05****	**0.06089***	0.05347	0.04147	**0.06742***	0.03303	0.04506
Jun Tmax	**0.0383***	0.00492	0.05641	0.03357	0.04448	0.03238	0.05802
Jul Tmax	0.026	0.02014	0.02667	0.00393	0.06238	−0.00075	0.03371
Aug Tmax	−**0.052****	−0.04161	−0.04561	−0.03942	−0.05921	−0.06756	−0.05768
Sep Tmax	0.007	−0.00287	0.01087	0.00858	−0.00015	0.00862	0.01009
Oct Tmax	−0.003	−0.00877	−0.00308	0.00023	−0.004	0.00185	−0.00531
Dec Tmax	**0.1017*****	0.07008	**0.10585***	**0.11315***	0.09631	**0.11062***	**0.11446***
Jan Tmean cumu >5.5 °C	0.269	0.18063	0.35581	0.25913	0.23362	0.31872	0.26415
Feb Tmean cumu >5.5 °C	−0.24619	−0.20414	−0.34333	−0.1207	−0.27492	−0.17169	−0.36236
Mar Tmean cumu >5.5 °C	−0.057	−0.20315	−0.02538	−0.12472	−0.08333	−0.17554	0.26733
Apr Tmean cumu >5.5 °C	0.711	−0.03359	0.52313	0.76075	0.78489	1.36026	0.8715
May Tmean cumu >5.5 °C	0.685	1.09453	0.08116	0.81607	0.96489	0.70014	0.45121
Jan Tmean	0.26868	0.0094	0.03897	0.03925	0.02636	0.03641	0.02961
Feb Tmean	−0.01	−0.01159	−0.01959	−0.00762	0.00092	−0.00092	−0.01398
Mar Tmean	0.008	0.00674	0.01552	0.01227	0.00383	−0.00041	0.01586
Apr Tmean	**0.035****	0.00875	0.03012	0.03641	0.03344	0.05538	0.04335
May Tmean	**0.034****	**0.04427***	0.03549	0.03272	0.04133	0.02913	0.024
Jun Tmean	**0.05*****	0.0215	**0.04817***	0.04	0.03689	0.05159	**0.05559****
Jul Tmean	0.025	0.02103	0.01973	0.01665	0.02638	0.01891	0.0292
Aug Tmean	−0.024	−0.03094	−0.01651	−0.00766	−0.03169	−0.03002	−0.02677
Sep Tmean	0	−0.0106	0.00547	0.00041	−0.02169	0.01723	0.00082
Feb Tmin	−0.01403	−0.01962	−0.02072	−0.00968	−0.01039	−0.0013	−0.02246
Mar Tmin	0.0	0.00684	0.00195	−0.00082	−0.01723	−0.00284	0.0121
Apr Tmin	0.01471	−0.00414	0.00311	0.02205	0.00383	0.04116	0.02222
May Tmin	0.01838	0.0267	0.01788	0.02523	0.03617	0.02612	0.00092
Jun Tmin	**0.0453*****	0.03747	0.03528	**0.04571***	0.03689	0.06407	**0.05306***
Jul Tmin	**0.02497***	0.0227	0.01494	0.02492	0.02638	0.03839	0.02311
Feb Sun Total	−0.00019	−0.02041	0.0094	0.01522	−0.00905	0.02098	−0.00222
Mar Sun Total	0.01388	0.00468	0.0306	0.03316	0.01134	0.02544	−0.00595
Apr Sun Total	**0.03198***	0.04605	0.04441	0.08459	0.01379	0.01764	0.02766
Jan Wind Speed mean	−0.02742	0.05586	0.0161	−0.04626	−0.04441	−0.11026	−0.03559
Feb Wind Speed mean	−0.03067	−0.07436	−0.01573	−0.04636	−0.03087	−0.01887	0.00219
Mar Wind speed mean	0.02282	0.044	0.03357	0.00981	−0.0121	0.0035	0.04732
Apr Wind speed mean	−0.00377	0.01706	0.01771	0.00256	−0.02568	−0.03273	−0.01207
May Wind speed mean	0.00452	0.05227	0.05039	0.00598	−0.0334	−0.03385	−0.01426
Jun Wind speed mean	0.01295	0.01436	0.02865	0.01166	0.00455	−0.00369	0.02215
Jul Wind speed mean	0.02129	**0.05005***	**0.04267***	0.00786	0.00846	−0.01217	0.03952
Aug Wind speed mean	**0.0670*****	**0.0800*****	**0.1063*****	**0.0539*****	**0.04434***	0.05368	**0.0639****
Sep Wind speed mean	0.01242	0.06639	**0.06345***	0.00619	−0.02615	−0.04243	0.01344
Oct Wind speed mean	−0.03812	0	0.01138	−0.02692	−0.06331	−**0.1166****	−0.03315
Nov Wind speed mean	0.01294	0.01338	0.04431	0.00677	−0.01654	0.00146	0.02823
Dec Wind speed mean	0.03088	0.08992	0.07746	0.00177	0.042	−0.05492	0.02908

only be expected if these months had showed significant increase in temperature variables, which they did not. This finding, particularly in the context of earlier UK *Betula* onset studies, is similar to that of the nearby countries of France, Belgium and Switzerland (Besancenot et al., 2019; Glick et al., 2021; Hoebeke et al., 2018; Jockner-Oette et al., 2019). However, a 50-year study from Basel in Switzerland, the longest dataset available, shows the seasons trending significantly earlier in that particular location and over that longer time-frame (Gehrig and Clot, 2021). Importantly, most of the pollen trend studies mentioned in our article span only 20 to 30 years, which may not be sufficient to demonstrate true long-term changes.

The severity of the *Betula* pollen season has clearly increased for SPIn for all sites combined ($p < 0.01$). However, for individual sites only the central regions were significant (Leicester $p < 0.01$; Worcester $p < 0.05$), where the number of high days (NH) has also increased ($p < 0.05$) (Fig. 2, Table S5). Worcester, York and Leicester had the highest SPIn and Invergowrie had the lowest. June, and to a lesser extent July and August, of the previous year, were the key months affecting pollen production, correlating positively with SPIn and NH for either or both Tmax and Tmean ($p < 0.05$ to $p < 0.001$) (Table S2). Of these key months, June had a significant trend of increasing temperatures (Tmean) at some sites, indicating that warmer summers had allowed more pollen to be produced over time. However, July had only a weak warming trend and August temperatures were actually cooling in the UK (Table 2). For in-season correlations, a warm May was associated with higher SPIn (Table S2). Invergowrie and Worcester sites showed a trend to warmer May weather (Table 2) but this was not affecting the pollen trend at the former (Fig. 2). Higher wind speed reduced SPIn and NH in April and May ($p < 0.05$–0.01) (Table S2). However, there were no significant climatic trends in wind speed for those months (Table 2).

The trend to increased *Betula* pollen production and increasing number of high days is similar to trends recorded in recent studies from several countries across Europe and beyond (Besancenot et al., 2019; Bruffaerts et al., 2018; Glick et al., 2021; Hoebeke et al., 2018; Lind et al., 2016; Rojo et al., 2021a; Rojo et al., 2021b; Ruiz-Valenzuela and Aguilera, 2018; Ziska et al., 2019). However, this trend was only found to be significant at two of the six sites in the UK, similar to that recorded in Switzerland (Jockner-Oette et al., 2019). Research to investigate how *Betula* SPIn might change as climate change impacts take effect has been undertaken by Rojo et al. (2021b). Their modelling study for Bavaria, Southern Germany, predicts that *Betula* pollen will continue to increase as climate change progresses. Trees at lower altitudes, however, will become stressed, emitting less pollen over time, while trees at higher altitudes are expected to benefit from the warming and produce more pollen.

3.2. *Quercus* pollen seasons

The onset of the *Quercus* pollen season became significantly earlier ($p < 0.001$) for the UK as a whole, but particularly for Invergowrie ($p < 0.001$), and there was a positive significant trend for the FH at three sites (Fig. 3, Table S5). Warm weather in February, March and April and high sunshine totals in March and April are all associated with early onset and FH (Table S3). The increasing pollen trend at Invergowrie is not being matched by rising temperatures in that region, however temperature trends (Tmax and Tmean) and increasing sunshine totals show that April and May were becoming significantly warmer ($p < 0.01$) (Table 2), leading to earlier seasons generally in the UK.

Leicester had distinct significant trends to more severe *Quercus* seasons (SPIn and NH) ($p < 0.001$) occurring from the mid-2000s onwards (Fig. 3) but this was not true for any other sites. The trend at Leicester was most likely related to the maturing of a set of *Quercus robur* trees planted in the 1980s in parkland near the site. The lack of a general trend to increased *Quercus* pollen production found in this study (Table S5) is in contrast to the few studies that include analysis on this genus: Lind et al. (2016) in Stockholm, Sweden, Ruiz-Valenzuela and

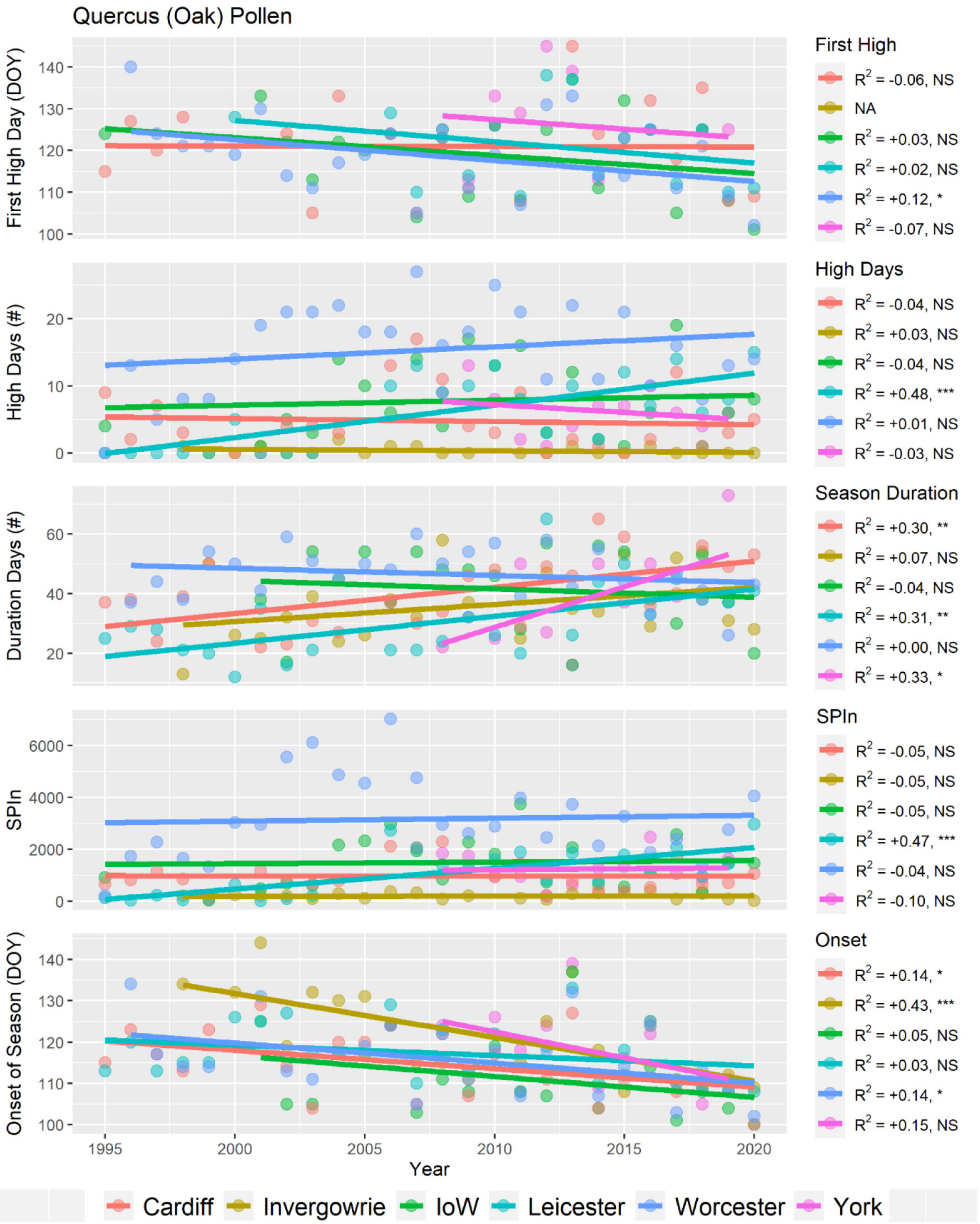

Fig. 3. Time-series and linear regression trends for onset, SPIn, duration, number of high days and first high day for *Quercus* pollen seasons, 1995–2020, for six UK pollen stations. Also included are the R^2 and p values (*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$).

Aguilera (2018) and Recio et al. (2018) in Spain and Gehrig and Clot (2021) in Basel, Switzerland.

There is much spatial variation in SPIn in the UK, with Worcester having by far the highest and Invergowrie the lowest (Fig. 3). Pre-season analysis shows that high temperatures in July, August and September allowed for increased pollen production, while windy weather in Autumn and Winter impacted negatively on SPIn and NH (Table S3). These key monthly met variables were largely non-significant, however, apart from a cooling trend for August. In-season analysis showed that warm temperatures in April, May or June led to increased SPIn and NH, while higher wind speeds reduced them (Table S3). These key monthly weather variables showed increasing trends at a few sites and for all sites combined, apart from wind speed (Table 2), but were not sufficient to produce significant general trends in SPIn or NH (Fig. 3, Table S5). York, Leicester and Cardiff all showed an increase in the duration of the *Quercus* pollen season, although it was variable between years and sites (Fig. 3). However, season duration had no significant climate drivers (Table S3).

3.3. Poaceae pollen seasons

The onset of the Poaceae pollen season was variable both temporally and spatially with no significant trends (Fig. 4, Table S5). The FH, however,

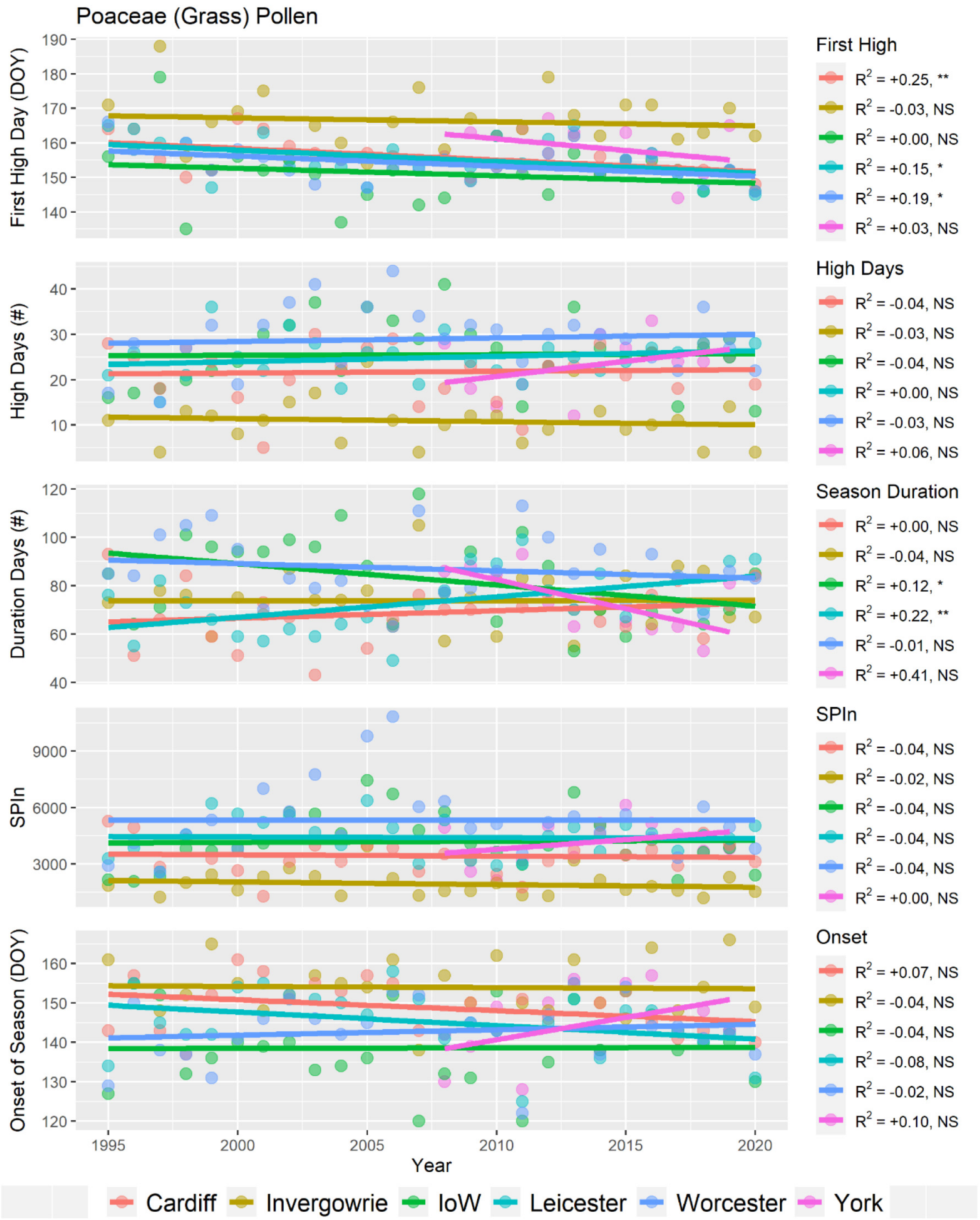

Fig. 4. Time-series and linear regression trends for onset, SPIn, duration, number of high days and first high day for Poaceae pollen seasons, 1995–2020, for six UK pollen stations. Also included are the R^2 and p values (** $p < 0.01$; * $p < 0.05$).

arrived significantly earlier ($p < 0.05$–$p < 0.01$) at the central sites of Leicester, Worcester and Cardiff (Fig. 4). Early onset of the Poaceae pollen season was associated with mild weather in the months of February to May (Table S4). These months had no climatic trends of significance, hence the lack of any trend in onset. However, the trend to an earlier FH was associated with mild weather in the previous December, January, April, May and June (Table S4) and all of these months showed an increasing trend for all temperature variables (Table 2).

In terms of severity, there were no significant trends for either SPIn or NH (Fig. 4, Table S5). Worcester had the highest SPIn and NH, due to its mild weather and abundance of meadowland in the area, and Invergowrie the lowest, with large spatial and temporal variation in both of these (Fig. 4). Pre-season, SPIn was positively correlated ($p < 0.01$) with cumulative Tmean >5.5 °C in January (Table S4). This key weather variable showed no significant climatic trend (Table 2) and may partly explain why the Poaceae SPIn trend remained flat. Grass growth and pollen production mostly occur in April, May and early June in the UK. These monthly met variables correlated positively with SPIn, both in this study and in one undertaken by Kurganskiy et al. (2021), but, despite the increased temperature trends, they were not leading to more severe grass pollen seasons. Higher wind speeds in Autumn and again in February and March were related to reduced SPIn and NH (Table S4) in the ensuing pollen season but there were almost no climatic trends in these monthly met variables (Table 2). In-season, higher temperatures between May and August caused greater season severity, while windy weather during May to August led to a reduction (Table S4). Although the temperature trends acted positively in some of these months, the wind speeds acted negatively, with an overall flat trend in the pollen levels (Table 2).

The lack of an increase in Poaceae SPIn is in contrast to a new mechanistic model by Kurganskiy et al. (2021) that suggests grass SPIn will rise under increased CO_2 levels, as pre-season weather is expected to become more favourable for pollen production. However, the research presented here is in agreement with recent pollen trend studies: Hoebeke et al. (2018) found that the number of high days in Belgium was in decline and severity decreasing; Jockner-Oette et al. (2019) found that of six sites studied in Switzerland, half of them had decreased SPIn, one was flat and only two showed any increase, while Lind et al. (2016) and Gehrig and Clot (2021) showed a flat trend in Sweden and Switzerland respectively, similar to this study. Furthermore, Ruiz-Valenzuela and Aguilera (2018) and Piotrowska-Weryszko et al. (2021) found that warming trends may be adversely affecting pollen production in a range of herbaceous pollen types, not just Poaceae. A decrease in SPIn and NH had previously been observed in the UK (Emberlin et al., 1993; Emberlin et al., 1999).

Season duration for Poaceae was also variable temporally and spatially with Leicester showing a trend to a longer season, while in contrast, Isle of Wight was trending to shorter seasons (Fig. 4). The season duration was significantly, positively correlated with February Tmean >5.5 °C and February and March Tmax ($p < 0.001$) (Table S4). However, there were no significant climatic trends in these key Met variables (Table 2).

3.4. General climatic changes and impacts on pollen seasons in the UK

The UK is located in the temperate climatic zone and has a generally mild climate with cool, wet winters and warm, often wet, summers, although there is large variation on a daily, seasonal and yearly basis (Met Office, 2021). The weather conditions are also changeable, often with windy weather. Wind speed, often associated with changeable weather, was found to be significantly decreasing SPIn and NH, as Grundstrom et al. (2017) also found in Sweden. It is likely that the variability of the UK weather partly explains why there were several flat trends revealed in this research. Some of the key monthly Met variables do not, as yet, show significant trends according to our study, although this may well change in the future as climate change progresses.

It is likely that this research, which used monthly weather variables, did not expose the tendency under climate change for more extreme but relatively short-term temperature and rainfall events (Dunn et al., 2020; Kendon et al., 2020; Vautard et al., 2020). Such events at key points in the development of plants can lead to reduced growth or pollen production, or both, although the tolerance ranges vary between plant species (Hatfield and Prueger, 2015). It seems that some woody plants are responding to warmer summers but grasses are not. However, changes in grassland area are likely to be impacting on both grass and tree SPIns. A recent study reported that almost 2 million hectares of UK grassland were lost to both urbanisation and woodland between 1990 and 2015 (UK Centre for Ecology and Hydrology, 2021) and our results likely reflect Emberlin et al. (1993) who had determined that loss of grassland leads to reduced grass SPIn.

In a dynamic climate such as the one in the UK, high temporal and spatial variation in pollen seasons is likely to continue. Moreover, climate projections suggest that more extreme weather events of heat and rainfall and a general increase in temperatures and rainfall (Met Office Hadley Centre, 2021), will impact on the seasons in the decades to come. Regular research will be required to keep abreast of the changing trends and to update the people and organisations who are affected by seasonal respiratory allergy.

4. Conclusion

This study has found important changes are occurring in the UK pollen seasons that have the potential to impact on the health of hay fever and pollen asthma sufferers. Pollen production in *Betula* trees is being aided by warmer summers in the previous year, which is reflected in a significant increase in the annual *Betula* pollen totals and the number of high days in the following Spring in the Midlands. *Quercus* pollen seasons are starting earlier and lasting longer and Poaceae has a trend to an earlier date for the first high count. In contrast, Poaceae seasons are not becoming more severe and the onset and first high day of the *Betula* pollen seasons are not occurring earlier. For most of the changes in trends, climate drivers of increasing temperature and sunshine total were identified. However, reasons for flat trends included a lack of change in some monthly meteorological variables, or land-use change, such as grassland replacement by urban areas or woodland.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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