Spatial and temporal variations in the distribution of birch trees and airborne *Betula* pollen in Ireland

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Abstract

In an Irish context, and indeed in Northern Europe, one of the most important allergenic pollen types is birch (*Betula* spp.). Thus, forecasts of such atmospheric pollen are important tools for helping patients suffering from allergenic rhinitis and/or atopic asthma to avoid high ambient concentrations and manage their symptoms. This work aims to improve knowledge about the spatial and temporal variations in the distribution of birch trees and airborne *Betula* pollen in Ireland, which is an important step towards producing such forecasts. The footprint of airborne *Betula* pollen recorded in Ireland was determined by using HYSPLIT backward Lagrangian dispersion modelling methodology and mapped using Geographic Information System (GIS) software during the Main Pollen Season (MPS) and for days with airborne concentrations > 80 pollen grains/m^3 in Dublin and Carlow (72 km apart) for 2018 and 2019. An inventory of birch trees within broadleaved forests was constructed using statistical data from different vegetation inventories for Ireland with a resolution of 100 m x 100 m. Historical datasets of airborne *Betula* pollen recorded in Dublin during 1978-1980 and 2010-2011 were also related to changes in land cover and climatic conditions over the same period. Dispersion modelling showed that air masses arriving in Ireland on days with *Betula* pollen concentrations >80 pollen grains/m^3 resided for a longer time over Great Britain. The birch tree inventory for Ireland will enhance the performance of forecast models. Airborne *Betula* pollen concentrations in Ireland have increased over the last 40 years, which is related to concomitant increases in the fraction of birch trees in forest areas as well as the ornamental use of birch trees in urban areas and their reaching maturity. Climate change did not seem to influence birch pollination.

Keywords: Allergenic Pollen, GIS, HYSPLIT, Land Cover, Pollen Footprint, Vegetation Inventory.

1. Introduction

Pollen allergens are major causes of allergy worldwide (Bousquet et al., 2008), affecting an estimated 10-30% of the global population (WAO 2011). The pollen of birch trees (*Betula* spp.) is recognised as one of the most important allergenic pollen types in Northern and Central Europe (D´Amato and Spieksma 1992; D’Amato et al. 2007) and Burbach et al., (2009) reported clinically relevant sensitization rates to *Betula* pollen allergens of 19.6% in Europe (from 4.0% in France to 49.1% in Denmark). Birch trees are frequently found in the British Isles (Thomas 2016; McIness et al., 2017) and the pollen can travel long distances (Skjøth et al., 2009; Veriankaite et al., 2010; Skjøth et al., 2015). Birch trees are also popular ornamental flora within cities, in spite of its capability to produce large amounts of allergenic pollen (Kasprzyk et al., 2019).

The Intergovernmental Panel on Climate Change (IPCC 2014) projects that the upward trend in allergic reactions attributable to pollen is expected to continue. Atmospheric carbon dioxide (CO_2) is not only an important greenhouse gas, causing a rise in global temperatures, it also has a fertilization effect on plants. These drivers could enhance plant growth and their associated pollen productivity (Albertine et al., 2014), which result in increased airborne pollen concentrations, although changes in precipitation should also be considered (Beggs et al., 2004; Ziska et al., 2011; IPCC, 2014).

In Ireland, global warming is likely to impact plant development and the subsequent release and dispersal of pollen (Jones et al., 2006). However, there is a dearth of aerobiological knowledge for the island. There have been some studies on airborne pollen in Ireland, but many publications are now forty years old (McDonald 1980; McDonald and O'Driscoll, 1980). More recent aerobiological studies have been limited to short periods of time, focused on specific pollen, such as the real-time monitoring of airborne Taxaceae pollen carried out in Killarney National Park (O´Connor et al., 2014) or looked at fungal spores concentrations at ambient sites or compost centres (O´Connor et al., 2015a; O´Connor et al., 2015b; Feeny et al., 2018). Indeed, Buters et al., (2018) mapped all available data related to worldwide pollen and spore sampling and noted the lack of stations in Ireland, particularly in comparison to mainland Europe.

Atmospheric models, such as the Hybrid Single Particle Lagrangian Integrated Trajectory model (HYSPLIT) (Draxler et al., 1998, 2014), are used to better understand the atmospheric dispersion of airborne pollen as in the case of *Betula* (Skjøth et al., 2007; Skjøth et al., 2009; Skjøth et al., 2015). This information about the airborne pollen concentrations can then be related to land cover data to identify potential sources (Rojo et al., 2015; García-Mozo et al., 2016; Maya-Manzano et al., 2017). The quality of emission data is the largest cause of uncertainty in pollen dispersion models (Skjøth et al., 2010; Pauling et al., 2011), and so the mapping of potential sources and estimating their source strength is an essential task for the development and refinement of these models (Kurganskiy et al., 2020). To this acquisition of vegetation inventories has contributed the remote sensing technologies (Skjøth et al., 2013; Devadas et al., 2018). The use of regional statistics of species distribution combined with land cover data is a ‘bottom-up’ approach for producing pollen source inventories (Skjøth et al., 2008; Verstraeten et al., 2019), whereas the ‘top-down’ approach combines land cover information with pollen data from a network of sampling stations (Skjøth et al., 2010; Thibaudon et al., 2014; Karrer et al., 2015; Rojo et al., 2016).

This work aims to improve knowledge of airborne *Betula* pollen in Ireland. This has been achieved by calculating the footprint of airborne *Betula* pollen recorded at two sites in Ireland during the Main Pollen Season (MPS) of *Betula* in 2018 and 2019, producing a high resolution (100 m x 100 m) inventory of birch trees within broadleaved forests in Ireland and examining historical relationships between atmospheric concentrations of *Betula* pollen, land cover and meteorology in the city of Dublin.

2. Material and Methods

2.1. Location

The land cover of Ireland is dominated by grasslands and pastures. Natural woodlands are primarily around 30 native and naturalized tree species, including wind pollinated gymnosperms such as Scots pine (*Pinus sylvestris*), common juniper (*Juniperus communis*) and yew (*Taxus baccata*), and the angiosperms hazel (*Corylus avellana*), alder (*Alnus* spp.), birch (*Betula* spp.), wych elm (*Ulmus glabra*), ash (*Fraxinus* spp.), willow (*Salix* spp.), poplar (*Populus tremula*), oak (*Quercus petraea* and *Q. robur*), and elder (*Sambucus nigra*) (Nelson and Walsh, 1993). Forests in Ireland are fragmented and do not cover a large area (11% of Ireland, which is the lowest forest coverage in Europe). The fraction of *Betula* in broadleaved forests is approximately 22.7% (DAFM 2017a). The country can be considered flat, with low central plains and some mountainous areas (Wicklow Mountains are situated to the south of Dublin, northeast of Carlow).

Its climate is characterized by mild winters and warm, rainy summers, with a temperate oceanic climate according to the Köppen climate classification (Peel et al., 2007). The influence of the Atlantic Ocean helps to maintain stable year-round temperatures whilst also providing abundant rainfall. The sampled locations were Dublin (DB) (6°15' W, 53°19' N, 20 meters above sea level, m.a.s.l.) and Carlow (Cw) (6º 55' W, 52º 49' N, 150 m.a.s.l.) (Fig. 1). Dublin (population 554,554) and Carlow (population 56,932) are representative of urban and rural areas, respectively (CSO 2016). Meteorological observations were recorded at Dublin airport, 6° 14' W and 53° 25' N (1978- 2019) and Oak Park in Carlow, 6° 54' W and 52° 51' N (2004-2019) (Met Éireann 2019). Mean maximum and minimum temperature in Dublin are 13.3 ºC and 6.1 ºC, respectively, and annual precipitation is 780 mm. For Carlow, the temperatures were similar, with an average maximum and minimum temperatures of 13.9ºC and of 6.1ºC, respectively, and slightly higher annual precipitation than Dublin of 881.7 mm (Met Éireann 2019).

2.2. Pollen sampling

The air in Dublin and Carlow was sampled during the years of 2018 and 2019 by using volumetric traps (Hirst, 1952). One sampler was located on the roof of Technological University Dublin's City Campus, which is situated in Kevin Street in Dublin City centre (height 20 meters above ground level, m.a.g.l.). The other trap was in the countryside location of Carlow (height 2 m. a.g.l.). For pollen counting, the Standardized methodology proposed by the Spanish Aerobiology Network (REA) (Galán et al., 2007) and with the modifications explained by Tormo-Molina et al., (2013) was carried out. The Minimum Requirements for pollen monitoring networks described by Galán et al. (2014) specify that at least 10% of the slide should be examined. Three longitudinal transects along the centre of the slide were counted for Dublin (10.71% of the slide surface) but due to restrictions in time and funding only two longitudinal transects were examined on slides from Carlow (7.14 % of the slide surface). Some useful unpublished data, using a similar methodology as the current study, were also available from Trinity College Dublin (from 1978-1980) and from Baldonell aerodrome (during 2010-2011). Trinity College is also located in the centre of Dublin, 1.2 km from the current pollen-monitoring site in Kevin Street, whilst Baldonell is 13 kilometres further in southwest direction, in the outskirts of the city, and both were located at 1.5 m. a.g.l.). These additional datasets were used to compare different periods of time (Section 2.5).

The main pollen season (MPS) for *Betula* pollen was determined using the method described by Nilsson and Persson (1981), whereby the season starts when 5% of the cumulative annual pollen concentration was recorded and finished when 95% of the annual record was reached. The current study examines the length of the *Betula* pollen season described as the number of days in the MPS, daily average airborne *Betula* pollen concentrations expressed as pollen grains/m^3, the date of the peak day, and the Seasonal Pollen Integral (SPIn = Pollen * day/m^3) (Galán et al, 2017).

2.3. Footprints of airborne *Betula* pollen

The footprints of airborne *Betula* pollen recorded in Dublin and Carlow during the 2018 and 2019 MPS (Table 1) were determined by using the HYSPLIT backward Lagrangian dispersion modelling methodology (Stein et al., 2015). The model was run 48 hours back in time, as described in similar studies conducted in Europe (e.g. Hernández-Ceballos et al., 2011; Fernández-Rodríguez et al., 2014; De wager et al., 2016) and in our case this generally covers the British Isles and parts of Continental Europe. Wet deposition used default values for both in-cloud and below clouds scavenging. Estimates of calculated and measured dry deposition of birch pollen vary considerably (Jackson and Lyford 1999; Zhang et al, 2014) and will in practice vary depending on the variations in size found to be the range 22 µm (Makela et al, 2006) and a density of 800 kg/m^3 (Kurganskiy et al, 2020), with the shape of 1.0. The density, however will depend on dehydration of pollen grains (Aylor et al 2003), a dynamic process that is currently not implemented in HYSPLIT, and the settling speed has therefore been fixed to 1 cm/s, similar to previous modelling studies (Zhang et al, 2014). These parameters govern gravitational settling as well as rain out and are similar to parameters commonly found in atmospheric transport models (Kurganskiy et al, 2020).

Input meteorological data were obtained from the Global Data Analysis System (GDAS) with a spatial resolution of 0.5 x 0.5 degrees. Particle dispersion coordinates were calculated for heights of 500, 1000 and 1500 m.a.g.l. and starting times of 0, 6, 12 and 18 hours (local time) for each day and location. In addition, days with high concentration (>80 pollen grains/m^3) were independently analysed following Skjøth et al., (2009). This allowed for days with low daily average concentrations of *Betula* pollen to be removed but maintained a large enough dataset for more detailed analysis. The threshold of 80 pollen grains/m^3 was used because it has been reported that 90% of allergy patients had mild symptoms at the beginning of the *Betula* pollen season when this threshold concentration was reached and it also allowed for comparisons with previous research (Skjøth et al., 2009). The output from this calculation is a set of 3D coordinates associated with the locations of the particles in the calculated footprint area.

The 3D coordinates were analysed using ArcGIS software. The calculated footprint areas were displayed using a logarithmic scale, to make easier the comparisons due to the high number of low values within the entire footprint area. This allowed for a coherent comparison between grid cells, with a size of 10 x 10 km. Also, the fraction of time that air masses spent over each territory for both groups of data were calculated using the *join spatial datasets* function in ArcGIS software (Table 2). To calculate these percentages, only terrestrial coordinates were considered.

2.4. Tree inventory

An inventory showing the percentage of birch trees within broadleaved forests with a spatial resolution of 100 m x 100 m was compiled by combining statistical data from different vegetation inventories for Ireland using the method described by Skjøth et al., (2008). These largest fractions for the territory came from the following databases:

a) European Union's CORINE Land Cover (CLC) 2012 dataset (CLC 2007).

b) Information from the National Parks and Wildlife Service’s “*National Survey of Native Woodlands 2003-2008*” (Perrin et al., 2008a, b).

c) The Department of Culture, Heritage and the Gaeltacht’s “*Ancient and long-established Woodland Inventory 2010*” (data.gov.ie, 2019).

d) The Coillte Company for Irish public forests (Coillte 2019).

Moreover, another dataset provided detailed data on the percent of vegetation by species occupying smaller fractions within a territory:

e) The Irish Department of Agriculture, Food and the Marine supplied data for the Irish private forests, (DAFM 2018).

The CLC considers one area as “broadleaved forest” if at least 75% of the surface is occupied by this type of tree. It means that any percentage below this threshold is not considered as belonging to this class. When considering what constitutes a broadleaved or mixed forest (CLC. 311 and 313), threshold percentages of the component trees are utilized. In this regard, forests identified as broadleaved were labelled as having 22.7 % occupation for *Betula* after the *Forest Statistics Ireland 2017* (DAFM 2017a). Following on from this, mixed broadleaved forests were estimated as having 11.37 % *Betula* occupation. The methodology used for assigning a percentage of *Betula* occupation into Corine Land Classifications was also used for datasets b and c, since these three datasets share a similar classification system (i.e. broadleaved and mixed forests). For public forests (Coillte 2019), the fractions occupied by broadleaved and mixed forests were labelled following the previous methodology, whilst the territories occupied specifically by *Betula* sp. were labelled as 75% according to the definition given by CLC. Moreover, it is acknowledged that urban areas can also be a notable source of atmospheric pollen (Skjøth et al., 2008). The percentage of trees in green urban areas (CLC. 141) in the city of Dublin was based on studies conducted by Pauleit et al., (2002) and Ningal et al., (2010). Due to the absence of data for other cities, the same percentage (14%) was used in all green urban areas. It represents around 8,400 trees according to estimations from these authors regarding the total number of trees.

2.5. The influence of environmental change on airborne *Betula* pollen concentrations

The influence of environmental change, i.e. land cover and climate, on airborne *Betula* pollen concentrations was investigated. Land cover data, CLC 1990, CLC 2012 and CLC 2018 for Dublin and CLC 2018 for Carlow, within 30 km radius surrounding the pollen traps were analysed using ArcGIS software. These three spatial datasets were chosen because their timing coincided most closely with the available datasets of airborne pollen (1978-1980, 2010-2011 and 2018-2019). The 1990 CLC land cover data is currently considered the most appropriate land cover dataset, even for older periods. Other older land cover datasets based on coarse satellite data such as ENVISAT or AVHRR do exist. However, these data have previous been shown to be to coarse to capture the small woodland structure on the British Isles, needed for aerobiological studies (Skjoth et al, 2015). The surface area (ha) was extracted for those layers likely to contain *Betula* trees (broadleaves forests, mixed forests and green urban spaces). The amount of broadleaved forests was compared to the SPIn of *Betula* and days with concentrations > 80 grains m^3 (Stach et al., 2008; Skjøth et al., 2009). After the normality test carried out by using Shapiro-Wilk test, even after the logarithmic transformation, the non-parametric Kruskal-Wallis test was used to determine whether there was a significant difference between the three datasets of airborne *Betula* pollen. After that, a Dunn´s post hoc test (1964) was applied to see where any difference exists. Results were deemed significant at $p<0.05$.

The influence of climatic conditions (daily values of rainfall, maximum and minimum temperatures) during the period 1978 to 2019 was examined using a time series approach. LOESS smoothing (LOcally wEighted Scatterplot Smoothing) was utilised to study the same period covered by the pollen studies. This technique has been successfully used in aerobiological studies in recent years to analyse changes in patterns, and to isolate the general trend from the seasonality and the remainder (unexplained variability/noise) (Maya-Manzano et al., (2020) and references therein). Moreover, to check whether trends in these meteorological parameters were significant, the confidence intervals for the slope of the trend (with a 95% confidence) were calculated by using a Mann-Kendall test with block bootstrapping, because data were serially correlated (Önöz and Bayazit 2012). Gaps in the meteorological dataset (<5%) were filled using multivariate regression models by using random training/testing of 80/20 %. Unfortunately, trends in airborne pollen could not be examined using this method as the 1978 to 2019 dataset contained a number of gaps. All statistical analyses were carried out using R software (R Development Core Team, 2014). The packages Dunn.test (Dinno 2017), ggsignif (Ahlmann 2019), ggplot2 (Wickham 2016), lubridate (Grolemund and Wickham 2011), tseries (Trapletti and Hornik 2019), zoo (Zeileis and Grothendieck 2005), boot (Davison and Hinkley 1997; Canty and Ripley 2020) and Kendall (McLeod 2011) were used.

3. Results

3.1. Airborne *Betula* pollen

The characteristics of airborne *Betula* pollen seasons recorded at Dublin and Carlow in 2018 and 2019 are shown in Table 1. In general, the MPS of *Betula* started earlier and was more intense in 2019 compared to 2018. The late start of the airborne *Betula* pollen season in 2018 can be attributed to a delay in phenology resulting from unusually cold temperatures during January, February, March and the first half of April of that year. The extreme weather conditions could have been more noticeable in rural areas such as Carlow. The MPS of *Betula* recorded in Dublin was almost twice as long in 2019 compared to 2018.

The characteristics of the historical datasets of airborne *Betula* pollen (1978-1980 and for 2010-2011) recorded at Trinity College Dublin are also presented in Table 1 and Figure 2. The earliest start to the MPS was recorded in 2011 (31 March), and the latest was in 1978 (8

May). Similarly, the earliest end date of the MPS of *Betula* was recorded in 2011 (15 May), and the latest was in 1979 (1 June). The 2011 *Betula* pollen season was similar to the 2019 season in many ways - it was a high magnitude season compared to other years in the historic dataset (although the SPIn was considerably lower in 2011 compared to 2019), it also started early and had a long duration (46 days). In general, the SPIn was higher and the number of days with daily average airborne *Betula* pollen concentrations > 80 pollen grains/m^3 was greater during 2018 and 2019 than in the historic dataset from Trinity College (Fig. 2).

The results of the Kruskal-Wallis tests show that at least one of the three datasets were different to the other ($p<0.05$). With the Dunn´s post hoc test, we observed that there was not a significant difference between airborne *Betula* pollen concentrations recorded in 1978-1980 and 2010-2011 ($p = 0.91$). However, there were significant differences between the 1978-1980 and 2018-2019 datasets, as well as between the 2010-2011 and 2018-2019 data ($p<0.05$), which reflects the general increase in the magnitude of airborne *Betula* pollen concentrations in recent years (Fig. 2).

3.2. Footprints of airborne *Betula* pollen

Calculation of source footprints 24-hr back in time were run from the receptor points in Dublin and Carlow during the MPS of *Betula.* Percentages of time that air masses spent over each territory (only terrestrial coordinates) are presented in Table 2. The air masses arriving at Dublin spent about 70.51% of the time over the islands of Ireland and Great Britain, this last in slightly higher percentage. On the other hand, air masses arriving in Carlow mostly came from within Ireland (~48%). This general pattern changed noticeably for both sites for days with airborne *Betula* pollen concentrations >80 pollen grains/m^3. Air masses arriving at both locations spent more time over the Island of Great Britain, particularly in the case of Carlow (41.91% of the time vs. 26.54 % in Ireland, whilst in Dublin we recorded the same 33.70% for both sites). Conversely, the percentage of time that air masses spent over other countries outside Ireland (other than Great Britain) was higher for the days with *Betula* pollen concentrations >80 pollen grains/m^3 rather than the days within the MPS. These other countries included, in decreasing order, France, Germany, Denmark, The Netherlands, Belgium and Sweden, amongst others. The time spent over these territories varied depending on the specific period and the Irish location considered. More information pertaining to the general patterns in air movements and the pollen footprint for both sites can be seen in Figure 3.

3.3. Tree inventory

Areas with greater forest cover are mainly located in the SE, SW and W of the Island (Fig. 1). This corresponds well with the Wicklow Mountains National Park (SE of the Island, South of Dublin), Killarney National Park (SW), and several Natural Heritage Areas (NHA) such as the Lough Atorick District Bogs (County Clare) and Derryoober Bog (County Galway) in the West. In addition, there are other smaller areas scattered throughout Ireland. Dublin has a partially forested area in the West of the city that corresponds to Phoenix Park, and another one in the South West that corresponds to the Wicklow Mountains National Park. As for Carlow, there is a large number of areas with broadleaved forests in the W and NW of the city, including 2.3 ha pure birch 20-year-old plantation located at 0.8 km N from the pollen trap. Moreover, there are other three important local sources of birch pollen close to the pollen trap. Two mature trees less than 100m to the E, 2.5 ha mature natural birch wood 1 km S, and 20 ha of mature coppiced oak with 10% birch 2-2.5 km SE. Regarding the surface occupied by these trees, in Figure 1b can be seen that the most of forests occupied by birch trees (50% data) in Ireland are between 0 and 12.5% of the surface. This reflects the high ratio of fragmentated territory.

3.4. The influence of environmental change on airborne *Betula* pollen concentrations

Changes in the amount of land cover types containing suitable habitats for *Betula* (based on different CLC databases) were examined (Table 3 and Fig. 4). In the city of Dublin, the total surface occupied by broadleaved forest, mixed forest and urban green spaces has risen during the three periods studied. The surface occupied by these land cover types in Dublin was twice that of Carlow in 2018, but in Carlow birch trees were closer to the trap as it has been explained in section 3.3.

LOESS smoothing of daily values of minimum and maximum temperatures and rainfall recorded in Dublin was carried out for the period 1978-2019 (Fig. 5). A decreasing trend can be observed for minimum temperatures, and an increasing trend can be seen for maximum temperatures. Non substantial changes in rainfall were detected. Overall, this means that variations in daily temperature are increasing over the 41-year period, with summers becoming slightly warmer and winters cooler, with larger differences in average daily temperature now compared to 1978. However, when we look at the grey bars in Fig. 5, representing the variance provoked by the different components, we can observe that the seasonality or the remainder (background noise or residual component in the time series) have a greater influence than the general trend, which indicates that the effects of these slight trends were not significant for the analysed period. The Mann-Kendall test with the correction of block bootstrapping (Önöz and Bayazit 2012) found that the trends for the slopes of the meteorological parameters (95% confidence) were not significant, with confidence intervals of (-0.0240, 0.0258), (-0.0247, 0.0238) and (-0.0247, 0.0248) for maximum temperature, minimum temperature and rainfall, respectively.

4. Discussion

This study aims to improve knowledge of airborne *Betula* pollen recorded in Ireland. When evaluating the risk of exposure to airborne pollen in an area, it is important to consider different sources. Local contributions are important, and some authors reported that small sources in a 20 km radius surrounding the trap can explain at least the 70% of the airborne content for one city (Rojo et al., 2015). This agrees also with Bogawski et al. (2019a) who stated that variations in daily pollen concentrations can be attributed to the distribution of local birch trees around the pollen trap (within 1 km). It is therefore likely that birch trees near the traps (especially in Carlow, as reported in Section 3.3) influence recorded airborne pollen concentrations.

In addition to pollen arriving from the immediate area around a trap, a large fraction of pollen recorded can potentially originate from more distant sources as documented in the case of *Betula* (Hjelmroos 1991 and 1992; Skjøth et al. 2007, Skjøth et al. 2009, Skjøth et al., 2015). For example, this study has shown that the risk of high concentrations of airborne *Betula* pollen in Ireland increased when air masses originated from the island of Great Britain, especially in Dublin during the MPS and in Carlow for days with higher concentrations. Sources of *Betula* pollen in Great Britain therefore appear to be more important for exposure of the Irish population to high magnitude episodes of *Betula* pollen than sources in Ireland.

The pollen footprints (Fig. 3a and 3b) calculated in this study show that the air masses containing higher pollen concentrations are likely to spend more time over central parts of England. Two studies (Skjoth et al. 2008; McInnes et al. 2017) have calculated the abundance of birches in woodlands and found that most of the broadleaved woodlands with high birch tree densities are found in central and southern England, while smaller amounts are found in Wales and Scotland. This is supported by Adams-Groom et al, (2020) who reported low airborne *Betula* pollen concentrations in Northern Ireland and Scotland and much higher concentrations in the W Midlands and SE England.

Analyses also showed that air masses spent time over more distant areas like France, Germany, Denmark, the north of the Iberian Peninsula and even Scandinavia but these were less important for the airborne concentrations. Pollen data in Ireland also correspond well with phenological data from Great Britain. According to the online tool 'Natures Calendar' (https://naturescalendar.woodlandtrust.org.uk), previously used for aerobiological studies by Brennan et al. (2019), the majority of observations of the first open flower on birch trees happens more or less at the same time throughout England while there is a delay of one or several weeks in Scotland. In 2018 the majority of the observations in Great Britain show first flowering from mid-April to mid-May, which fitted the pollen recorded in Carlow (same dates). In Dublin, the MPS was earlier (from early to late April), with the maximum concentration peaks reached on April 11th. In 2019, the majority of the phenological observations in Great Britain show first flowering in April, hence a slightly earlier season compared to 2018. Both seasons show a number of outlier observations in coastal regions or in early spring such as March. This corresponded well with another coastal area like Dublin in 2019, whereas for Carlow during the same year the MPS was concentrated within April, matching with the phenological data in the island of Great Britain too.

In addition to calculating the footprint of airborne *Betula* pollen recorded at Dublin and Carlow, we created a high resolution (100 m x 100 m) inventory of potential sources of *Betula* pollen in Ireland using a bottom-up approach that incorporates national statistics for species occupation (Perrin et al., 2008a, b; Coillte 2019; DAFM 2017b). The inventory of birch trees within broadleaved forests is useful for regular forecasting because, as previously discussed, much of the recorded pollen generally originates from nearby sources. Such inventories can also be used as tool to provide information to environmental protection agencies and other stakeholders, as in the forestry sector.

Corine Land Cover (CLC 2007) is often used for this kind of study in the European context (e.g. Skjøth et al. (2008)). The CLC database only includes areas where land uses greater than 75% are reached, and so surfaces occupied by a lower percentage are not considered. It can therefore underestimate the distribution of potential sources of *Betula* pollen. Another disadvantage associated with this bottom-up approach is that species distribution are usually based on statistics for larger regions. This results in higher resolution polygons within these larger areas having the same percentages of land cover classes as adjacent areas.

Such issues can be mitigated by adopting a top-down approach and adding pollen datasets to enhance the performance of forecasts (Zink et al., 2017). For instance, Pauling et al., (2011) produced vegetation distribution maps for *Betula* pollen by combining the Swiss Forest Inventory with land cover data. Categories of *Betula* density were assigned by the authors to each land use and this relationship was extrapolated to a larger area by utilising the Global Land Cover 2000 dataset, weighted using the *Betula* SPIn from European pollen-monitoring stations distributed over the whole COSMO-7 domain (Pauling et al., 2011). In order to mimic this approach in an Irish context, it would be necessary to have sufficient pollen sampling points for the country. Unfortunately, in the current study, only pollen data from Dublin and Carlow were available and these were for limited time periods. As a result, we were restricted to the bottom-up methodology.

Airborne *Betula* pollen concentrations in Ireland, e.g. SPIn and days with high concentrations (>80 pollen grains/m^3), have increased noticeably over the three periods examined in the current study (i.e. 1978-1980, 2010-2011 and 2018-2019) (Fig. 4). Although the lack of available data over the last four decades, together with the changes for trap locations, (being the three periods within a 13 km-distance area) means that this study is somewhat limited and could be skewed by suitable conditions for the production, release and dispersal of *Betula* pollen occurring in the last two years of the study. Indeed, Verstraeten et al.,

(2019) described a high magnitude *Betula* pollen season in Belgium in 2018. In this study, the increase in airborne *Betula* pollen concentrations can be related to a concomitant rise in land area containing suitable habitat for *Betula* trees (Fig. 4). In fact, reforestation policies in Ireland have resulted in an increase in the area occupied by native trees, such as *Betula pendula* and *Betula pubescens*, from 4.8% of forest surfaces in 2006 (National Forest Inventory, DAFM 2006) to 7% in 2017 (National Forest Inventory, DAFM 2017b). Land cover surrounding pollen monitoring sites (Rojo et al., 2015; Maya-Manzano et al., 2017) and changes in land cover over time (García-Mozo et al., 2016) have frequently been reported as a key factor for understanding changes in the airborne pollen content in one area. Furthermore, the study carried out by Pauleit et al., (2002) showed that birch constituted around 14% of ornamental trees used in Dublin, the largest city in Ireland.

Increases in airborne pollen concentrations can also be related to the maturity of individuals planted in the past. These trees are now capable of producing more pollen, once they reach a minimum trunk development and crown diameter. According to Bogawski et al. (2019b), higher pollen production is reached in mature individuals. Although, as the authors report, it can be expected that competition for space in forests limits the crown diameter even in mature individuals.

Meteorology is a crucial factor influencing birch phenology and pollen production (Dahl and Strandhele 1996, Stach et al., 2008). Observed pollen concentrations in one year are the combined result of the catkin formation process, usually in the year before flowering, plus the occasion of favourable conditions in the year pollen is released. For example, low *Betula* pollen concentrations were recorded in Dublin and Carlow in 2018 despite the high magnitude *Betula* pollen season witnessed at some sites in Continental Europe in that year (Verstraeten et al. 2019). We observed that favourable conditions in 2017 resulted in well-developed catkins but the first four months of 2018 were unusually cold and conditions were therefore unfavourable for pollen release.

In the following year, 2019, airborne *Betula* pollen concentrations were higher in both Dublin and Carlow, which could have been caused by the cold start to 2018 and extremely warm summer later that year (Government of Ireland, 2020). Lower temperatures from January to April in one year have been reported to increase atmospheric concentrations of *Betula* pollen in the following year (Stach et al., 2008), and weather conditions during the summer prior to flowering are also important for birch pollen production; daily average minimum temperatures during the months of May and June the year before flowering have been significantly correlated with the initiation of catkins (Grewling et al., 2012).

Ritenberga et al. (2018) also found that meteorology alone explained variability in the SPIn of *Betula* but additional environmental and aerobiological parameters, such as the SPIn in the preceding year and atmospheric CO_2 concentrations, increased the accuracy in predictive models and showed that there are other drivers involved in phenological processes. It is interesting to note, therefore, that Kim et al. (2018) argued that increasing temperatures combined with carbon fertilisation caused by elevated levels of atmospheric CO_2 may result in significantly higher amount of pollen and allergenic protein than under present conditions.

With respect to climate change over the last 40 years, LOESS decomposition of daily meteorological variables showed that a decrease in minimum temperatures and increase in maximum temperatures did not have a clear influence in our data (shown in the range bars and the confidence intervals for Mann-Kendall tests with bootstrapping corrections). Moreover, rainfall did not vary a great deal over the studied period (Fig. 5). As a result, the trend was not so important when compared to seasonality or the remainder component.

In Ireland, Jones et al. (2006) reported that such changes in temperature can influence plant phenology, and Donnelly et al. (2004) also found that some trees advanced their leafing by ten days per decade over a thirty-year study. There are numerous examples of changes in temperature influencing the timing and magnitude of airborne *Betula* pollen seasons. For instance, there have been reports of advances in the start dates of the main *Betula* pollen seasons in Denmark (Rasmussen, 2002) and Switzerland (Frei and Gassner, 2008). In the Danish study, Rasmussen (2002) also reported a distinct rise in the total amount of atmospheric *Betula* pollen recorded annually in the country. In Bavaria, Germany, Bergmann et al. (2020) reported a significant increase in the number of days with atmospheric *Betula* pollen concentrations higher than 100 pollen grains/m^3 for the period 1998-2018, which was comparable to our study (Table 1). Similar results were reported in Belgium, where Hoebeke et al. (2017) observed trends towards more days with high airborne *Betula* pollen concentrations, higher peaks and earlier starts to the *Betula* pollen seasons.

On the other hand, Ziello et al. (2012) reported a decrease in airborne *Betula* pollen concentrations, which they related to adverse impacts of warming due to the plant being adapted to mid to high latitude environments at lower temperatures. Similar results were reported by Marchesi (2020) in the Northern Italy for the period 1991-2017. Thus, any climatic change, especially at the limits of its distribution range, could negatively impact birch tree populations and their flowering phenology. However, closer to Ireland, Newnham et al. (2013) did not find any significant trends in the onset for *Betula* pollen seasons at three sites in England.

This lack of a consensus in the scientific literature suggests that any changes in the flowering phenology of birch trees related to increases in temperature are specific to different regions. This article has been the first attempt to explain spatial and temporal trends in *Betula* pollen seasons in Ireland. Maintaining aerobiological monitoring in the country will help to fill gaps in current knowledge about trends in airborne pollen, and provide valuable insights into how Irish vegetation will respond to projected climatic changes.

5. Conclusions

This study aimed at improving our knowledge of the behaviour and sources of airborne *Betula* pollen in Ireland. The calculation of footprints of airborne *Betula* pollen has shown that the chance of recording high atmospheric concentrations of *Betula* pollen >80 pollen grains/m^3 in Dublin and Carlow increases when air masses spend more time over Great Britain. The construction of a 100 m x 100 m resolution inventory of potential sources of *Betula* will enhance the performance of forecast models and can provide of important information for forestry industries and environmental protection agencies. It can be seen that the territory occupied by birch trees is severely fragmented. Furthermore, we have shown how airborne concentrations of *Betula* pollen have increased over the last 40 last years, which is likely due to the increase in forest surface occupied by broadleaved forest, but also because of the ornamental use of birch in urban areas and individuals planted in the past reaching maturity. Climate change did not seem to influence birch pollination.

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Tables and Figures.

Tables.

Table 1. Main pollen season characteristics for *Betula* in Dublin (DB) during the periods 1978-1980 and 2010-2011 and in Dublin and Carlow (CW) during 2018-2019.

Year and place Dublin = DB Carlow = CW	Start Date	Peak Date	End date	Length (days)	Mean daily average pollen concentration (pollen grains m^{-3})	Peak daily average pollen concentration (pollen grains m^{-3})	SPIn (Pollen * day/m^3)	Days with concentrations > 80 pollen grains m^{-3}
1978 (DB)	30 April	10 May	24 May	24	35	240	880	4
1979 (DB)	8 May	9 May	1 June	24	28	139	711	4
1980 (DB)	29 April	10 May	30 May	32	20	91	650	2
2010 (DB)	25 April	30 April	25 May	31	32	135	1,000	5
2011 (DB)	31 March	8 April	15 May	46	35	242	1,606	6
2018 (DB)	5-April	11-April	25-April	19	131	346	2,494	12
2019 (DB)	28-March	18-April	7-May	41	111	554	4,550	16
2018 (CW)	18-April	4-May	13-May	26	27	125	696	2
2019 (CW)	8-April	22-April	22-April	24	276	1,385	6,626	18

Table 2. Percentages of time that air masses spent over each territory (particles obtained from HYSPLIT) travelling to Dublin and Carlow during the period 2018-2019. Only terrestrial coordinates were considered in these calculations.

Territory	*Betula* (MPS) 2018-2019		*Betula* (days> 80 pollen grains m^{-3}) 2018-2019	
	Dublin	**Carlow**	**Dublin**	**Carlow**
	%	**%**	**%**	**%**
Isle of Ireland	33.61	47.88	33.70	26.54
Isle of Great Britain	36.90	28.89	33.70	41.91
France	13.55	12.82	9.58	14.76
Other countries	15.94	10.41	23.023	16.79

Table 3: Distribution of land cover (based on CLC) suitable for birch trees during the period 1990, 2012 and 2018 for Dublin, and for 2018 for Carlow within a buffer zone of 30 km radius around the sampler. Land cover in hectares (ha).

Land cover (ha)	**1990 DB**	**2012 DB**	**2018 DB**	**2018 CW**
Broad-leaved forest	698.2	996.1	1333.5	1856.5
Mixed forest	721.6	880.94	1244.7	880.9
Green Urban Spaces	2927.6	2849.8	2707.7	9.63
Total	4347.4	4726.8	5285.9	2747.0

Figures

Figure 1a. Percentage cover for *Betula* trees within broadleaved forests across Ireland.

Cell size = 100m x 100m.

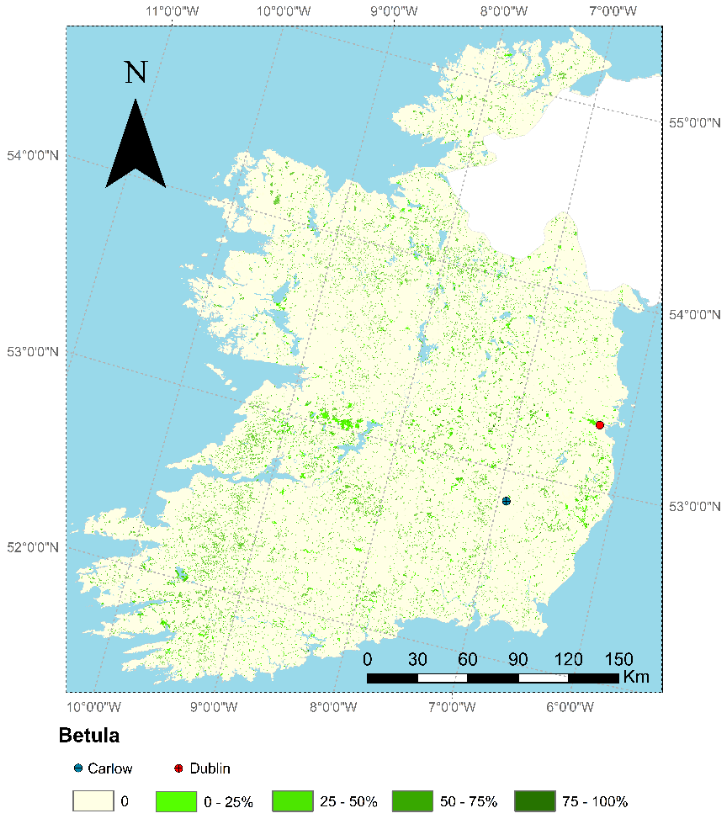


Figure 1b. Boxplot showing the percentage cover for birch trees forests within all datasets suitable to contain them.

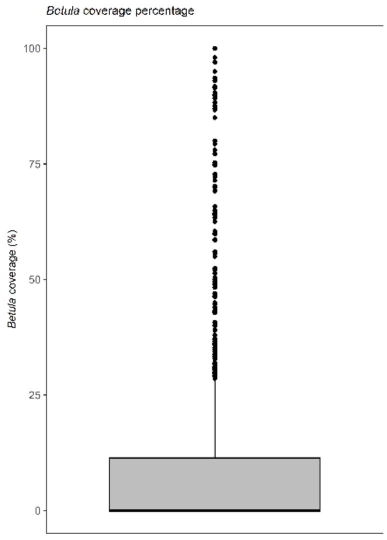


Figure 2. Box-plots of daily average airborne *Betula* pollen concentrations recorded in Dublin, during the MPS and specifically for days with concentrations > 80 pollen grains/m^3, for the different periods analysed.

(NS. = $p > 0.05$, * = $p \leq 0.05$, **= $p \leq 0.01$, *** = $p \leq 0.001$)

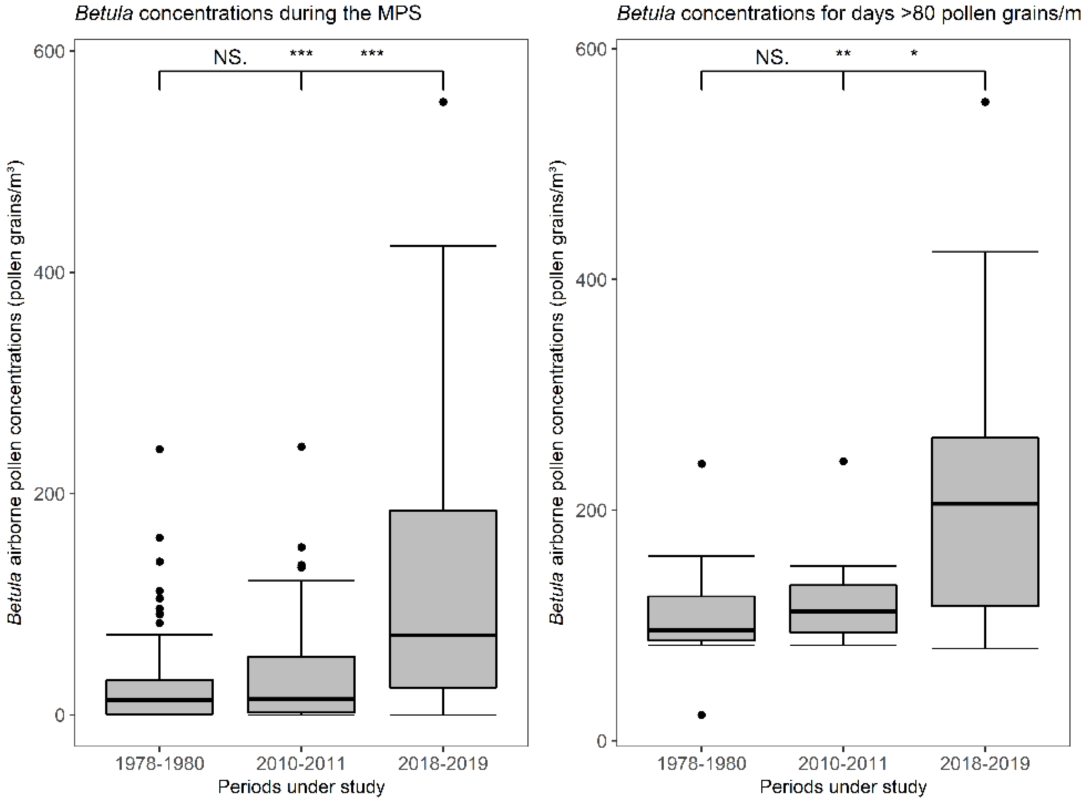


Figure 3. *Betula* pollen footprint according to the air masses arriving to Carlow and Dublin during the MPS days and for those days with concentration >80 pollen grains/m^3 (Period 2018-2019). The legend shows the number of particles contained in each 10 km grid resolution for both periods in logarithmic scale.

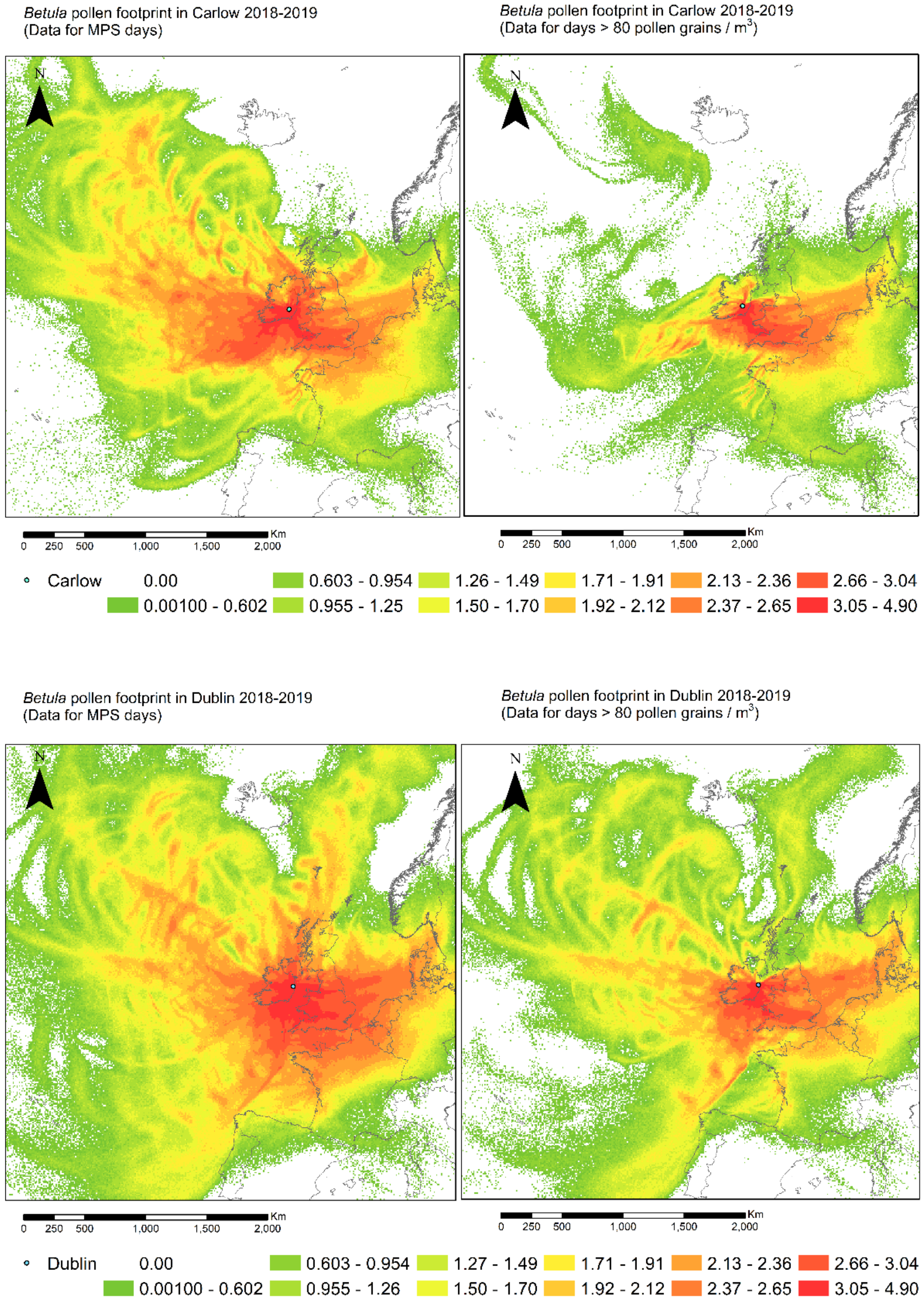


Figure 4. Comparison of surface occupied by land cover classes containing suitable habitats for birch trees within a buffer of 50 km in diameter surrounding the city of Dublin (based on different CLC databases deemed to closely reflect the studied period from 1978-2019).

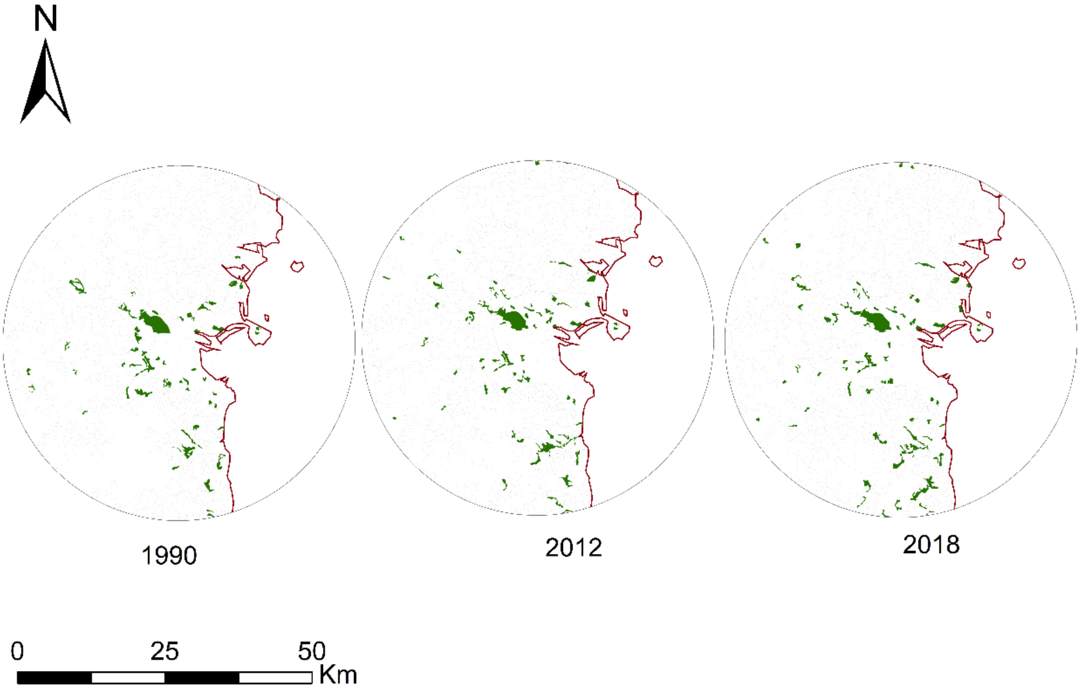
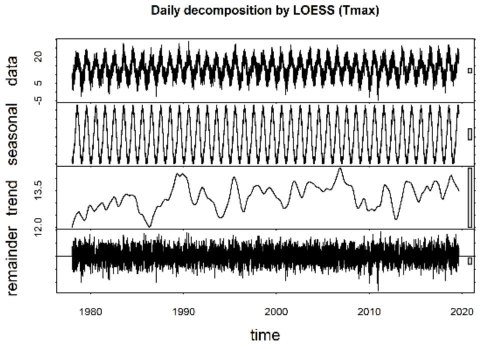
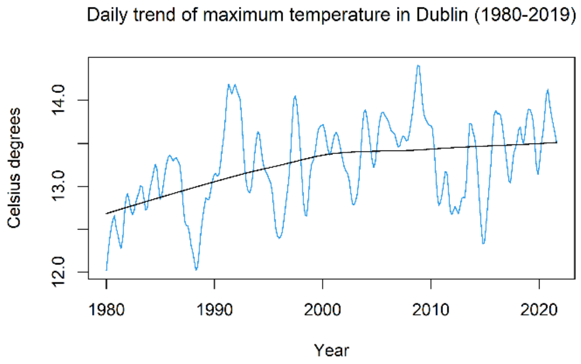
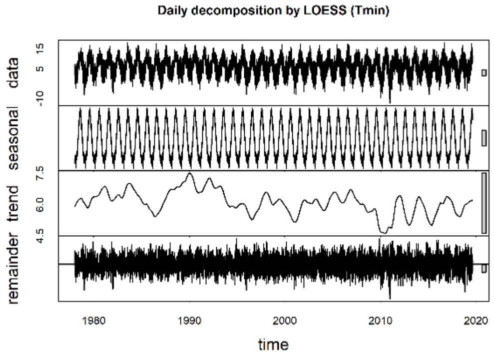
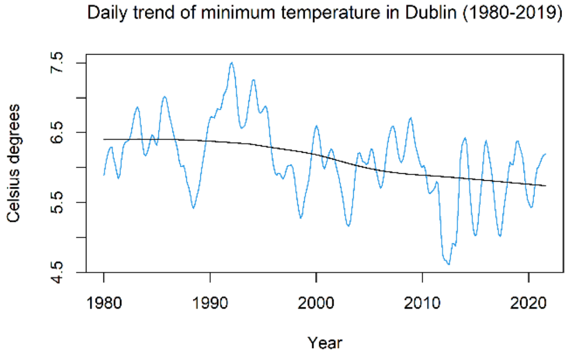


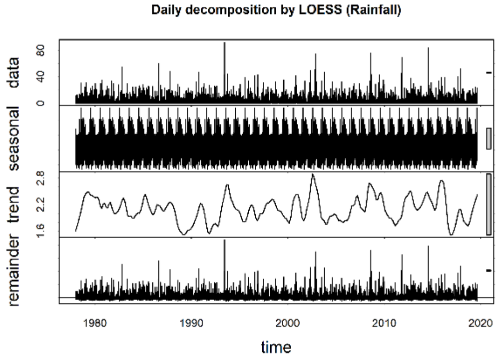
Figure 5. LOESS smoothing of daily values for selected meteorological parameters (minimum temperature, maximum temperature and rainfall) recorded in Dublin during the period 1978-2019. In the left side graphs, the different components for the LOESS decomposition are shown for daily data (total data, seasonal, trend and remainder or residual component). The grey blocks show the associated variation to each component, reflected in the numerical range displayed in the y axis labels in left and right. The right side graphs show the trend along the studied period, together with the smoothed line of tendency for these daily data.

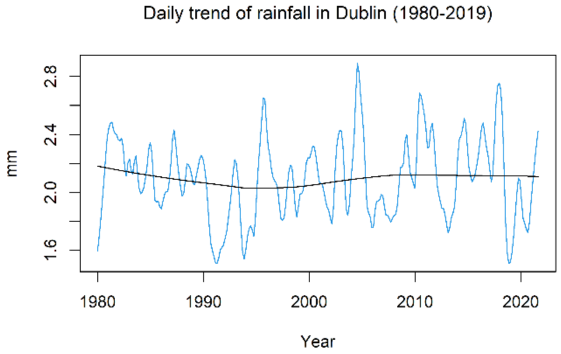

Daily decomposition by LOESS (Tmax)
data
seasonal
trend
remainder
-5
5
20
4
0
-6
12.0
13.5
10
0
-10
1980
1990
2000
2010
2020
time


Daily trend of maximum temperature in Dublin (1980-2019)
Celsius degrees
12.0
13.0
14.0
1980
1990
2000
2010
2020
Year


Daily decomposition by LOESS (Tmin)
data
seasonal
trend
remainder
-10
5
15
4
0
-4
4.5
6.0
7.5
10
0
-10
1980
1990
2000
2010
2020
time


Daily trend of minimum temperature in Dublin (1980-2019)
Celsius degrees
4.5
5.5
6.5
7.5
1980
1990
2000
2010
2020
Year


Daily decomposition by LOESS (Rainfall)
data
seasonal
trend
remainder
0
40
80
1
-1
1.6
2.2
2.8
80
40
0
1980
1990
2000
2010
2020
time


Daily trend of rainfall in Dublin (1980-2019)
mm
1.6
2.0
2.4
2.8
1980
1990
2000
2010
2020
Year