



Modelling grass pollen levels in Belgium

Willem W. Verstraeten^{a,*}, Rostislav Kouznetsov^b, Lucie Hoebeke^c, Nicolas Bruffaerts^c, Mikhail Sofiev^b, Andy W. Delcloc^a

^a Royal Meteorological Institute of Belgium, Ukkel, Brussels, Belgium

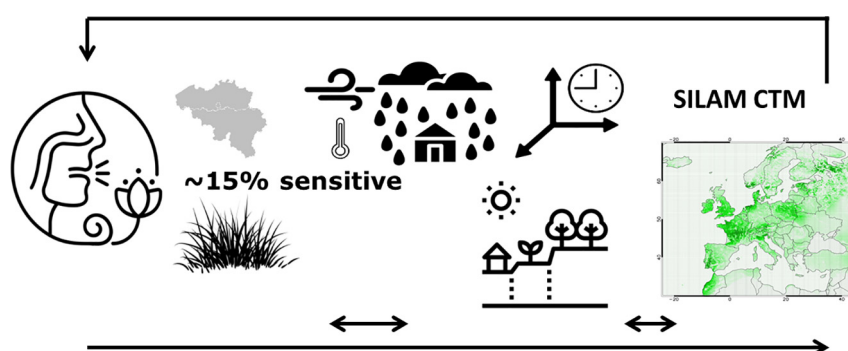
^b Finnish Meteorological Institute, Helsinki, Finland

^c Sciensano, Mycology and Aerobiology Unit, Brussels, Belgium

HIGHLIGHTS

- Grass pollen monitoring stations cannot provide timely spatiotemporal info for rhinitis patients.
- Chemistry Transport Models are capable to forecast potential pollen episodes over time and space.
- Chemistry Transport Models require seasonal updated maps of grass pollen emissions sources.
- Determination of proper start and end dates for the grass pollen seasons is essential.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:

Received 12 May 2020

Received in revised form 21 August 2020

Accepted 21 August 2020

Available online 26 August 2020

Editor: SCOTT SHERIDAN

Keywords:

Biogenic aerosols

Airborne grass pollen

Chemistry Transport Model

ABSTRACT

Biogenic aerosols such as airborne grass pollen affect the public health badly by putting additional distress on people already suffering from cardiovascular and respiratory diseases. In Belgium, daily airborne pollen concentrations are monitored offline at a few sites only, hampering the timely coverage of the country and short-term forecasts. Here we apply the Chemistry Transport Model SILAM to the Belgian territory to model the spatio-temporal airborne grass pollen levels near the surface based on bottom-up inventories of grass pollen emissions updated with the Copernicus land monitoring Service grassland map of 2015. Transport of aerosols in SILAM is driven by ECMWF ERA5 meteorological data. The emitted grass pollen amounts in SILAM are computed by the multiplication of the grass pollen source map with the release rate determined by the seasonal shape production curve during the grass flowering period. The onset and offset of this period follow a location-dependent prescribed calendar days. Here we optimize the grass pollen seasonal start and end in SILAM by comparing a 2008–2018 time series of daily airborne grass pollen concentrations from the Belgian aerobiological surveillance network with the simulations. The effect of the spatial distribution of grass pollen sources is quantified by constructing pollen source-receptor relations using model simulations with varying grass pollen emissions in five areas of the model domain as input. Up to 33% of the airborne grass pollen in one area was transport from others areas inside Belgium. Adjusting the start and end of the grass pollen season improved the model performance substantially by almost doubling the correlation with local observations. By introducing the temporal scaling of the inter-seasonal pollen amounts in the model, an additional R^2 increase up to 22% was obtained. Further improvements can be made by including more detailed grass pollen sources and more dynamic start and end dates of the pollen season.

© 2020 Elsevier B.V. All rights reserved.

* Corresponding author.

E-mail addresses: Willem.Verstraeten@meteo.be (W.W. Verstraeten), Rostislav.Kouznetsov@fmi.fi (R. Kouznetsov), Lucie.Hoebeke@sciensano.be (L. Hoebeke), Nicolas.Bruffaerts@sciensano.be (N. Bruffaerts), Mikhail.Sofiev@fmi.fi (M. Sofiev), Andy.Delcloc@meteo.be (A.W. Delcloc).

1. Introduction

Air pollution has tremendous effects on mortality and the quality of life (Landrigan et al., 2017; Liu et al., 2019). Air pollution is not restricted to anthropogenic contaminants only, since also natural sources (e.g. soils, lakes, marshes, vegetation, volcanoes) may emit substantial amounts of unhealthy pollutants (e.g. VOCs, SO_x, NO_x, aerosols) (EEA, 2017). Also emissions of biogenic aerosols such as pollen affect the public health badly, putting additional distress on people already suffering from cardiovascular and respiratory diseases (D'Amato et al., 2007). In Europe, >20% of the population suffers from pollinosis (WHO, 2003). In Belgium, at least ~10% of the people is estimated to develop allergic rhinitis symptoms due to pollen from trees of the birch family and ~18% due to pollen from grasses (Blomme et al., 2013). Belgium is a highly industrialized and densely populated country with substantial air pollution (Verstraeten et al., 2018) which may increase the burden of allergic respiratory diseases (D'Amato et al., 2007).

The Belgian aerobiological surveillance network (www.airallergy.be) has a longstanding history of observing various types of pollen and fungal spores in the outdoor air since 1982 at the Brussels station which is one of the oldest and most stable in Europe (Ziello et al., 2012). In total, this network has monitored airborne pollen at 13 different sites. Currently, daily airborne pollen concentrations are monitored offline at five locations in Belgium. This network allows reporting offline daily concentration measurements for several allergenic taxa of trees, shrubs and herbaceous plants to physicians and allergic patients. This relatively accurate information at a specific time and location, however, does not permit planning of future outdoor exposure, nor detailed spatio-temporal data on pollen levels for the whole territory of Belgium. In contrast, Chemical Transport Models (CTMs) are able to estimate airborne pollen levels both in a consistent spatial as well as temporal way by dealing with pollen as large biogenic aerosols emitted by vegetation and subjected to transport and deposition under various meteorological conditions (Sofiev et al., 2013; Sofiev et al., 2015; Sofiev, 2017). CTMs have the capability to forecast pollen exposures three to five days ahead depending on the data availability of meteorological forecasts.

The family of grasses (Poaceae) is huge and tens of species contribute substantially to the amounts of pollen levels in the lower atmosphere (Khwarahma et al., 2017; Brennan et al., 2019). This complicates the prediction of grass pollen dispersal (Emberlin, 2009). Europe-wide, grass pollen is the most-widely spread aeroallergen with the highest concentrations reported in the western Iberian Peninsula, central Europe and the UK (Skjoth et al., 2013). In Belgium, grasses in general are common species, especially in Flanders where the fraction of forested areas is low and grasslands are abundant. Grasslands, however, vary substantially both in agricultural function as well as in grass species compositions. Common grassland types are fallow, mixed, seedling grass, permanent grass, rye. Fallow, seedling grass and rye areas are considered as the main flowering grasses and as such the main sources of grass pollen (Skjoth et al., 2013). Since grass species are not differentiated while measuring the pollen amounts observed by the Belgian aerobiological surveillance network, a detailed classification of the composition of species in grasslands is not available. In Belgium the patchy landscape consists of permanent grasslands for commercial dairy production and meadows for hay production, but also of meadows for non-professional keeping of animals especially horses. These grasslands are mowed only a few times per season and thus might also be substantial grass pollen sources. Urban and build-up areas are excluded from any grass species habitats when mapped, but urban and especially suburban gardens may have substantial amounts of grass areas which can act as pollen sources (Skjoth et al., 2013) despite that most gardens are mowed frequently. Commercially managed grasslands are mowed several times a season, but verges along roads, railways, rivers and channels are not mowed before half of June as dictated by regional laws. Since Belgium is a country with the densest traffic network in the world, these verges might sum up to substantial grass pollen

sources, also in urban environments. Though, if necessary for traffic safety, these verges might be mowed earlier and more frequently. All these factors contribute to the complexity of pollen release timing and amounts complicating the modelling and forecasting of grass pollen. In short, grasses are difficult to model in terms of pollen release.

The start, end and the length of the grass pollen season varies both spatially as well as temporally. The abundance and dispersal of pollen depend on local grass species, altitude, land use and climate (Galán et al., 1995; Emberlin et al., 2000). Although the inter-seasonal differences in total pollen amounts are more important for birches than for grasses (Hoebeker et al., 2018), the grass Seasonal Pollen Integral (SPIn), defined as the cumulative daily concentrations over a whole grass pollen season (as determined by the start and its end datum) (Galán et al., 2017), also shows large variations. At the monitoring station of Brussels for the period 2008–2018, the Coefficient of Variation (mean/standard deviation * 100) is 49% for the seasonal birch pollen sum and 21% for grass pollen which is in line with other findings (Sofiev, 2017). Other important variables are the pollen season onsets and offsets in models which are often based on general climatology (i.e. long-term averages for large areas). It is known that with the altering climate, the start of the season tends to occur earlier, the length of the season becomes longer while the end of the season tends to occur somewhat earlier (Bruffaerts et al., 2018; Cristofolini et al., 2019). That is why the objectives of this paper are fourfold. Firstly, (i) we apply a grass pollen emission bottom-up inventory in the pollen transport model SILAM (System for Integrated modelling of Atmospheric composition, <http://silam.fmi.fi>) (Sofiev et al., 2013; Sofiev et al., 2015; Sofiev, 2017) in order to model the grass pollen levels near the surface over Belgium at a $0.1^\circ \times 0.1^\circ$ grid using an updated European land use map for grasslands combined with the MACCIII database for the period 2008–2018 (Sofiev, 2017). We evaluate SILAM using daily airborne grass pollen concentrations from the Belgian aerobiological surveillance network. Secondly, (ii) we investigate how the model performance can be improved by adjusting the seasonal start and end prescribed calendar days for optimal correlation with a 2008–2018 time series of airborne grass pollen concentrations from the Belgian aerobiological surveillance network for different sites in Belgium. Thirdly, (iii) a source-receptor set-up was applied to study the effect of grass pollen emission sources from source areas on the airborne grass pollen levels observed in receptor areas. Belgium was split into five geographical sectors for which in each sector varying grass pollen emissions has been used as input for SILAM simulations. Finally, (iv) we introduce temporal scaling of the grass pollen emission sources for each grass pollen season using the observed grass Seasonal Pollen Integral (SPIn) measured at different sites in Belgium in a correlation analysis with average temperature and precipitation of April and May of the preceding years.

2. Data and methods

2.1. SILAM

Biogenic aerosols such as pollen grains are much larger than conventional atmospheric aerosols and can be treated as such in CTM's. We simulate the airborne grass pollen levels near the surface during the grass seasons (May–September) for the period 2008–2018 using the CTM SILAM (System for Integrated modelling of Atmospheric composition) over the Belgian territory (Sofiev et al., 2006; Kouznetsov and Sofiev, 2012). SILAM is a large-scale dispersion model developed for atmospheric composition and air quality. The model dynamic core – for the 3D transport of constituents over time – includes both Lagrangian and Eulerian advection-diffusion formulations. We apply the Eulerian or box mode with a basic horizontal grid cell resolution of $0.1^\circ \times 0.1^\circ$ and a vertical resolution consisting of an uneven distribution of nine layers. From surface to the free troposphere, the layer thickness is 25, 50, 100, 200, 400, 750, 1200, 2000, and 2000 m respectively. The main processes involved in pollen transport are advection with wind and

mixing due to turbulence, while pollen are removed from the air by gravitational settling (the main driver of pollen dry deposition), and by scavenging with precipitation (wet deposition). The grass pollen emission computations in SILAM do not rely on the degree-day methodology (heat sum) as it does for birch pollen emissions (Sofiev, 2017). Instead, the emitted amounts of airborne grass pollen grains in SILAM are computed by the multiplication of the grass pollen source map (containing the total amount of grass pollen that can be released during one season) for each grid cell with the release rate determined by the prescribed shape of the grass flowering intensity stretched from the season's start to the season's end (see also Fig. 3 in Sofiev, 2017). This function is the average shape of the seasonal distribution of the seasonal pollen grains production during the grass flowering period, and the onset and offset of this period follow a location-dependent prescribed calendar expressed in Julian days. Hence, for each grid cell, SILAM uses prescribed Julian days for the onset and offset of the grass pollen production season. For instance, if the grass pollen season start (end) for a certain location is prescribed as May 1st (July 15th), then the parameter of the onset (offset) for that grid cell is day 121 (day 196), respectively for non-leap years.

The produced pollen are supplied to an intermediate buffer as ready-to-fly particles. The release from the ready-to-fly buffer is controlled by meteorology and is sensitive to the same meteorological parameters as other pollen sources of SILAM. During rain and high-humidity periods the pollen release is inhibited, while wind and turbulence will increase the release (Sofiev, 2017). The transport, emission and deposition in SILAM is driven by ECMWF ERA5 reanalysis meteorological data (grid-cell of $0.25^\circ \times 0.25^\circ$) (ECMWF).

2.2. Grass pollen emission sources

Modelling the airborne grass pollen concentrations near the surface (throughout this paper we use the first model layer ranging from 0 to 25 m above the ground) in SILAM is based on a bottom-up approach using inventories of grass pollen sources. Hence, a map with the areal fractions of grasses is the fundamental underlying dataset or input. At the European scale, such a map was first compiled by Sofiev et al. (2006) and refined by Sofiev et al. (2013). We have updated this European MACCIII grassland map using the CLMS (2015) land-use maps on a 100 m spatial resolution (Copernicus, Langanke, 2017) and scaled to the $0.05^\circ \times 0.05^\circ$ grid cell. The updated map is the maximum value of the combination of the European grassland data from CLMS and the MACCIII map. The spatial distribution of grass pollen sources in Europe and Belgium is shown in the maps of Fig. 1.

2.3. Onset and offset

Unlike for birches, the onsets and offsets of the grass pollen season in SILAM are location-dependent prescribed calendar days expressed in Julian days. These calendar days are based on the grass pollen data collected by the European Aeroallergen Network and the mean days are spatially interpolated (Sofiev, 2017). In order to identify the best calendar days for the onsets and offsets we performed 17 SILAM simulations for the period 2008–2018 with different start and end days and compared the modelled time series with the observed data at five locations from the Belgian aerobiological surveillance network (see also Section 2.5). The list of the available observations is given in Table 1 which includes a map of Belgium pinpointing the monitoring stations. The key idea is to find the best determination coefficient (R^2) between the measured time series and the modelled ones with adjusted calendar days for each counting location. Based on earlier work on modelling airborne birch pollen levels in Belgium (Verstraeten et al., 2019; Delcloo et al., 2020) we only tested for an earlier onset and offset of the season.

2.4. Source-receptor relations

Tree pollen such as birch pollen might be subjected to long-range transport. For Belgium, the amount of airborne birch pollen origination from elsewhere, outside the Belgian territory, can be very substantial (Smith et al., 2005; Sofiev, 2017; Verstraeten et al., 2019). For grasses, the effect may be smaller than for birch due to limited impact of transport on these large pollens emitted near the surface (Rojo et al., 2019). In SILAM the mean pollen diameter of birch pollen is 22 μm and for grasses 32 μm . What is more, there are also morphological differences between pollen from grass and birch species that facilitates long-range transport. Grass pollen has a settling velocity which is about four times larger than that for birch pollen (Sofiev et al., 2006; Skjøth et al., 2007). For grass, the transport-induced variability is reported as ~15% of the observed total one and for birches ~30% (Sofiev, 2017). This implies that transport of grass pollen between different locations within Belgium is far more important than from outside Belgium. In order to quantify the impact of grass pollen emission sources in one area in Belgium on the modelled airborne grass pollen levels near the surface in another area of Belgium we perform source-receptor calculations. This approach is very common in atmospheric research to quantify the impact of anthropogenic emissions from one region on the air quality of another region (Sudo and Akimoto, 2007; Fiore et al., 2009; Verstraeten et al., 2015).

For the source receptor design, we have divided Belgium into five sectors covering the whole territory with five measurement stations located approximately in the centers of the corresponding sectors (Table 1). These sectors (s) are, from West to East and from North to South, De Haan (sDH), Tournai (sT), Brussels (sB), Genk (sG) and finally Marche-en-Famenne (sM-F). The sectors have a rectangular shape since this geometry is easy for preparing the SILAM model input data. This simple division, albeit not following vegetation patchwork or dynamic wind footprints, allows for distinguishing the signal from each station and delineates the area around as the most-important source of the observed grass pollen. Firstly, we quantify the effect of one sector with grass pollen emission sources on the other sectors without any single blade of grass (so, no grass pollen sources at all) on the simulated amount of airborne grass pollen near the surface. For example, panel A of Fig. 2 shows that in the sector of sDH grass pollen sources are presented, while in the rest of Belgium there are none.

We then run SILAM for the whole territory of Belgium and quantify for each sector the amount of airborne pollen near the surface. We repeat this for the other sectors in panels B, C, E and F of Fig. 2. As such we can determine the fraction of grass pollen in the air in the different receptor sectors that originate from the source sectors in Belgium. Secondly, we quantify in each sector the fraction of airborne pollen levels near the surface that are transported/originates from the other sectors. This is conducted by setting the grass emission sources to zero into one sector, while the other sectors can still emit grass pollen. This scenario is then used to run SILAM and compared with a reference run of SILAM that includes grass pollen emission sources everywhere in Belgium. The set-up of the different grass pollen emission source scenarios is shown in Fig. 3. In addition, in order to include knowledge on dominant transport by wind, wind roses were generated from wind force and direction data measured for the individual pollen seasons of 2008 and 2018, and for the complete time period 2008–2018 (Fig. 3D). The wind data are taken from the synoptic weather station of Zaventem at a reference height of 10 m, at Brussels Airport, nearby Brussels for the period May–August (Van de Vyver and Delcloo, 2011).

2.5. Inter-seasonal scaling of the seasonal grass pollen integral

The SPIn is known to change substantially from year to year depending on the combination of meteorological factors and physiology of the plant (Ranta and Satri, 2007), especially for tree species. For birch pollen, a good correlation was found between the SPIn of year t (yr_t) and

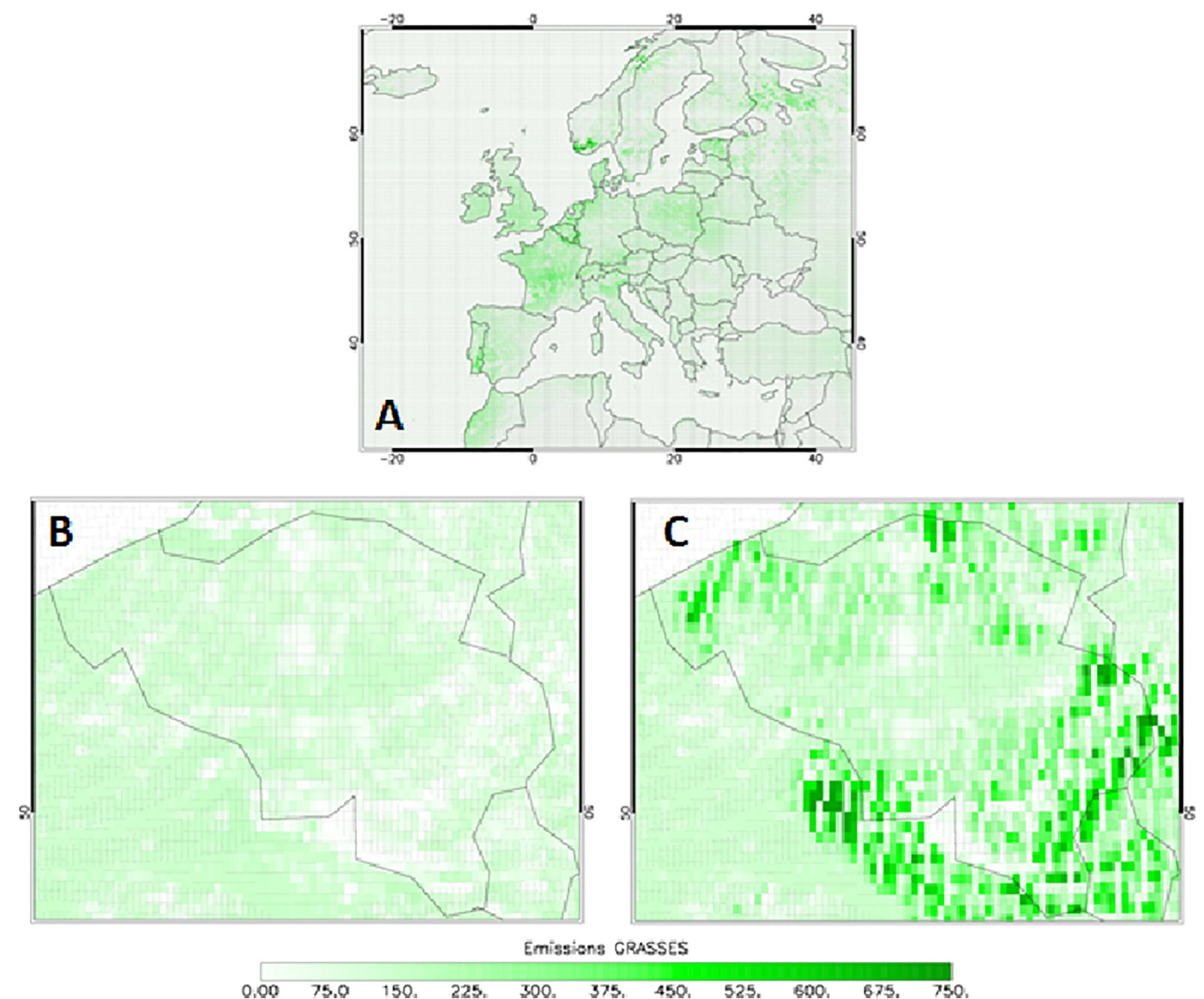


Fig. 1. Spatial distribution of grass pollen sources in Europe (top panel, A) and in Belgium (left lower panel, B) based on the reference map of (Sofiev, 2017) at a $0.05^{\circ} \times 0.05^{\circ}$ resolution. Right lower panel (C) is the updated map with grass pollen sources based on the combination of the reference and the CLMS 2015 map (C). The emissions of the grasses are expressed in $2 \times 10^{+7}$ pollen grains/m²/yr.

Table 1
The names, abbreviation and location of the pollen monitoring stations of the Belgian aerobiological surveillance network and the corresponding observation periods available for this study. In total 43 grass pollen seasons (1st May–30th September) were included. At the right, a map of Belgium shows the pollen monitoring stations and some indicative distances between locations (in red).

Pollen monitoring locations	Latitude/longitude	Period	
De Haan (DH)	51.274 N/3.022 E	2008–2018	
Tournai (T)	50.614 N/3.387 E	2013–2018	
Brussels (B)	50.825 N/4.383 E	2008–2018	
Marche-en-Famenne (M-F)	50.200 N/5.312 E	2012–2018	
Genk (G)	50.965 N/5.495 E	2011–2018	

Distances between the pollen monitoring locations: DH – G: ~180 km; DH – M-F: ~200 km; DH – T: ~80 km; DH – B: ~100 km; B – G: ~90 km; B – T: ~80 km; B – M-F: ~100 km; G – M-F: ~90 km; G – T: ~160 km; T – M-F: ~150 km.

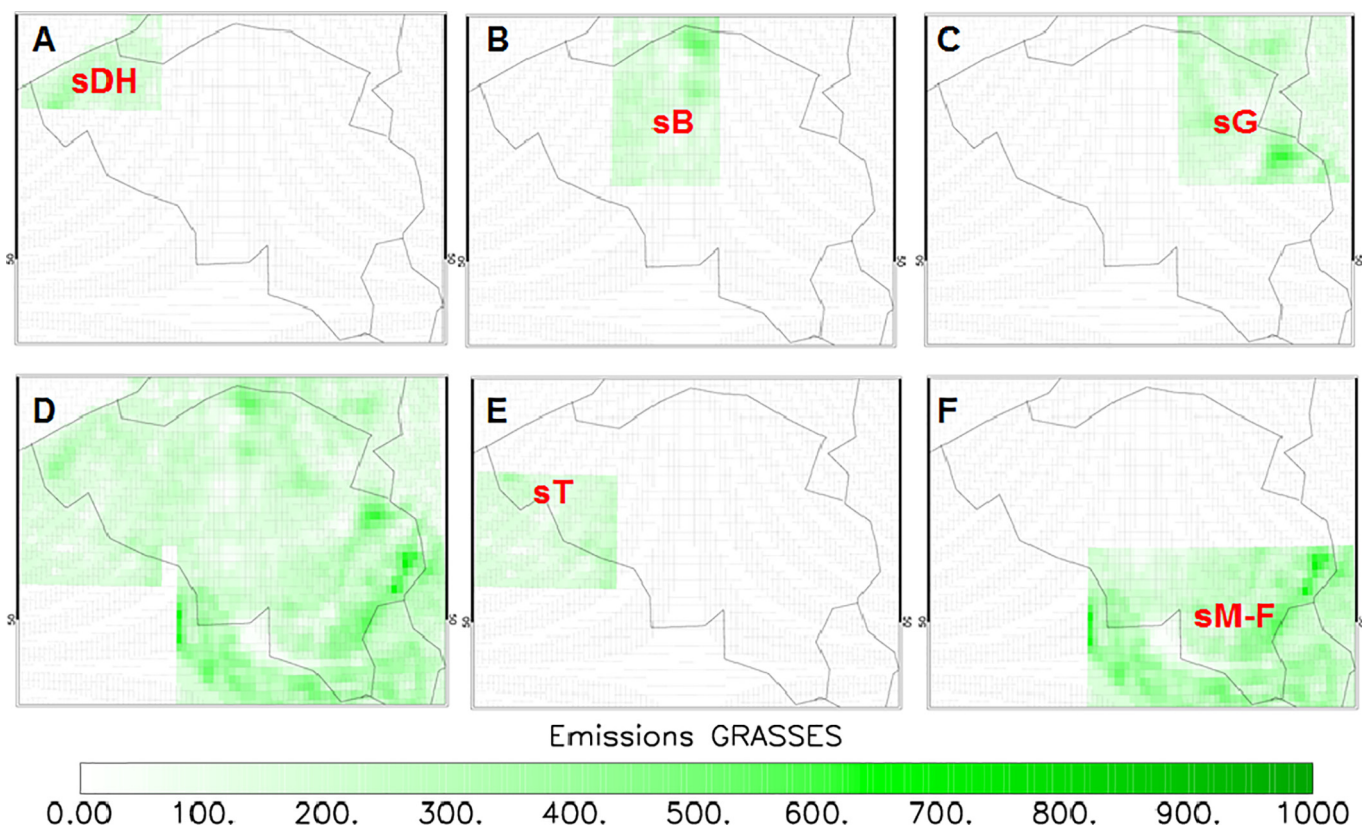


Fig. 2. Sectors in Belgium containing grass pollen emission sources for the source receptor design. In panel A, only the De Haan (DH) area shows grass pollen emission sources. The rest of Belgium has no single emission source. In panel B, only the Brussels (B) area contains grass pollen emission sources. Similarly, panel C shows only sources within the Genk (G) area, panel E only sources within the Tournai (T) area, and panel F only sources within the Marche-en-Famenne (M-F) area. Panel D shows the complete spatial distribution of grass emission sources for Belgium used in this design. The emissions of the grasses are expressed in 2×10^{-7} pollen grains/m²/yr.

the annual vegetation activity of two years before (yr_{t-2}) derived from remotely sensed vegetation photosynthesis (Verstraeten et al., 2019). For grass pollen, however, we did not find such a correlation. What is more, the inter-seasonal variability of the SPIn of grasses and birches tends to be in general not correlated as shown for the monitoring station at Brussels in Fig. 4. As mentioned before, the inter-seasonal variability is larger for birch pollen ($CV = 49\%$) than for grass pollen (21%) as illustrated in Fig. 4. Another way of incorporating inter-seasonal variability in the SPIn is to study the correlation of total seasonal pollen counts with meteorological variables such as the preceding seasonal temperatures and precipitation (Yli-Panula et al., 2009). Here we test correlations between the observed SPIn for grass pollen for 2008–2018 (for Brussels and De Haan; for Genk, Tournai and Marche-en-Famenne shorter time series apply; see also Table 1) and the average temperature and precipitation totals of the months April and May for the five Belgian monitoring stations for different annual lags using local meteorological data from Uccle/Ukkel (Brussels) from 2005 on. This statistical approach should be used only for practical operational purposes in anticipation of future methods based on better mechanistic understandings of grass phenology and blooming in relation with environmental and physiological parameters.

2.6. Pollen observations

Currently in Belgium, offline pollen observations are performed on a daily basis at five locations (see also Table 1 for the specific details) using a Hirst-type 7-day volumetric spore sampler (Burkard Manufacturing Co., Rickmansworth, UK) (Hirst, 1952). Samplers are placed at a height between 10 and 20 m above the ground level. Pollen from various taxa are morphologically identified and manually counted by light microscopy

(two longitudinal slide lines reading). The mean daily pollen concentration is then calculated and expressed as pollen grains per cubic meter of air (pollen grains/m³). Monitoring complies to the requirements of the European Aerobiology Society (EAS) (Galán et al., 2014). The Belgian aerobiological surveillance network maintains and makes available a large database from daily pollen observations collected at the current (see Table 1) and former monitoring stations. Here we used observation datasets encompassing 43 grass pollen seasons from the current five sites over the period 2008–2018, as shown in Table 1 with the locations shown at the accompanying map of Belgium. No differentiation on grass pollen from different grass species is available. In recent studies, the uncertainty of the Hirst-trap based observations (the best standard of pollen monitoring available today), was reviewed and its estimate substantially increased pointing out a systematic flow error of ~34% (Oteros et al., 2017), inadequate procedures, and sampling errors (Rojo et al., 2019). Our study has been designed so that their impact on the main conclusions is minimal (see the Discussion section).

3. Results

3.1. Grass pollen emission sources

In Belgium, grasses are distributed over the whole territory (Fig. 1B). However, in both the original MACCIII as the updated grass pollen emission sources map (Fig. 1B) the low values correspond to urban, forested and other agricultural land use. By using the CLMS map for updating, more grassland areas pop-up with higher amount of pollen emission sources (Fig. 1C). Especially locations near the coast, in the North close to the Dutch border, in the South-West near France, in the Ardennes, in the southern and eastern part of Belgium close to the German border,

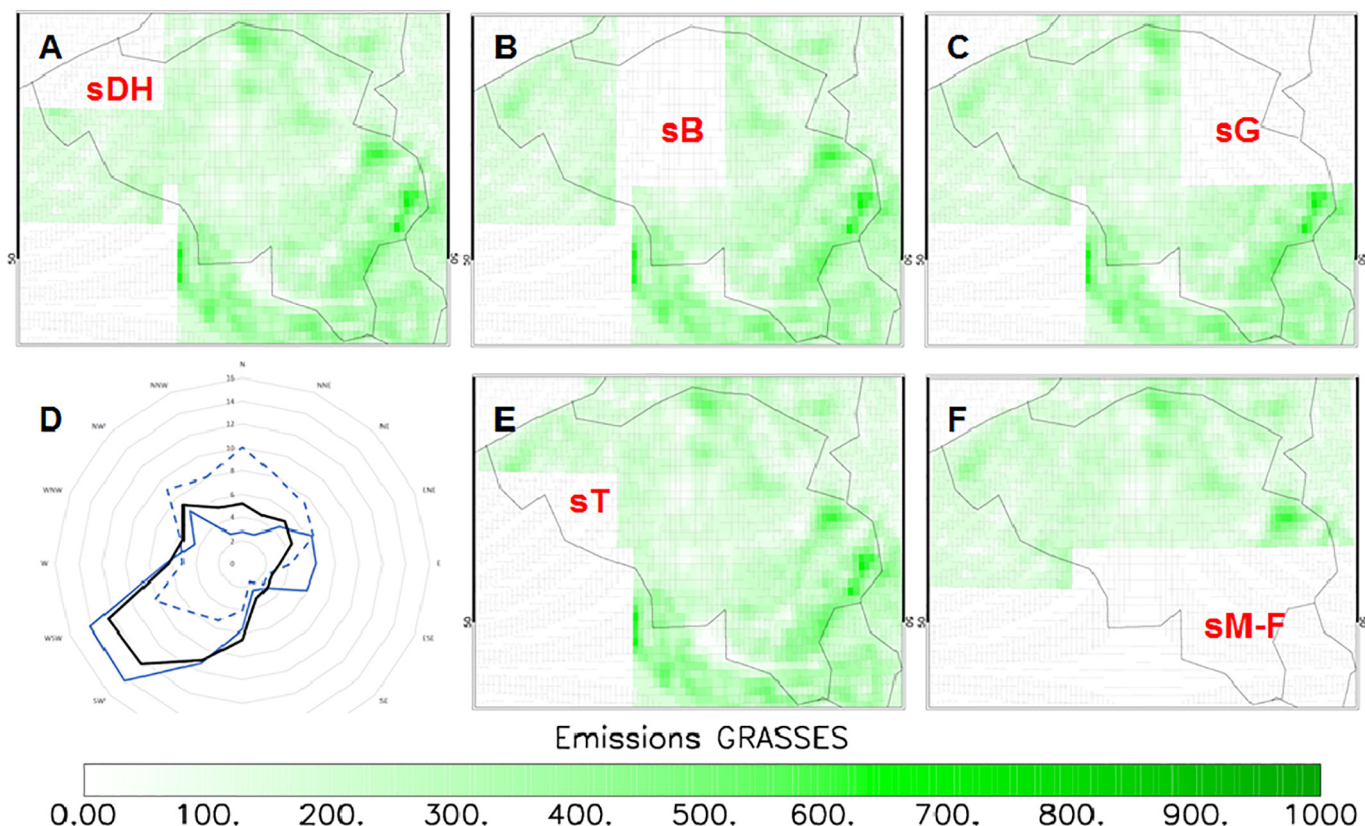


Fig. 3. Complementary maps to Fig. 2. Sectors without grass pollen emission sources in Belgium for the source receptor design. In panel A, the De Haan (DH) area contains no single grass pollen emission source. The rest of Belgium shows spatially distributed grass pollen emission sources. In panel B, the Brussels (B) area contains no single grass pollen emission source. Similarly, panel C shows no source inside the Genk (G) area, panel E no source inside the Tournai (T) area, and panel F no source inside the Marche-en-Famenne (M-F) area. Panel D shows the wind rose for the pollen seasons of 2008 in blue full line, of 2018 in dashed blue line, and for all the seasons of the time period 2008–2018 in black. The emissions of the grasses are expressed in 2×10^7 pollen grains/m²/yr.

and in the south-eastern part near the Grand Duchy of Luxembourg. The higher areal fractions of grasslands from the update do not necessarily mean that in reality more pollen can be emitted since not all grasslands are large pollen contributors (see also the Introduction and Discussion section).

3.2. Onset and offset of the grass pollen season

For the timing of the grass pollen release, SILAM implements a prescribed shape of grass flowering intensity (Sofiev, 2017) stretched over time by introducing the start and end date of the pollen season. Hence, the determination of the onset and offset of the grass pollen season is of utmost importance. Fig. 5 illustrates the change in R^2 between

the measured and modelled time series when the calendar days at each of the five sectors with a monitoring location in Belgium for the start (Fig. 5a) and end of the season (Fig. 5b) are adjusted. For all locations, except for M-F, the highest R^2 values are obtained when the start of the season is set to 14 days earlier. For M-F, it is only 10 days. Next, we have performed an additional analysis with fixing the start of the season to 14 days (10 days for M-F) earlier, followed by shifting the end of season as shown in Fig. 5b. The highest R^2 values are obtained for a shift of 24 days for all sites but M-F (only 14 days). Compared to the other sites, M-F has a much more different and distinct environment. M-F is situated in a rougher terrain where altitudes vary between 200 and 600 m, with a dominant forest land use and with a more continental climate compared to the other sites.

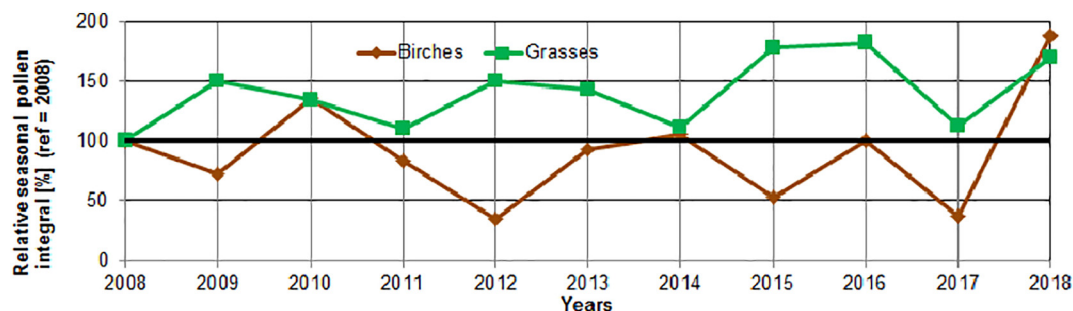


Fig. 4. The evolution of the relative seasonal pollen index from 2008 to 2018 for birch (in brown) and grasses (in green) in the monitoring station of Brussels. 2008 is set to 100%.

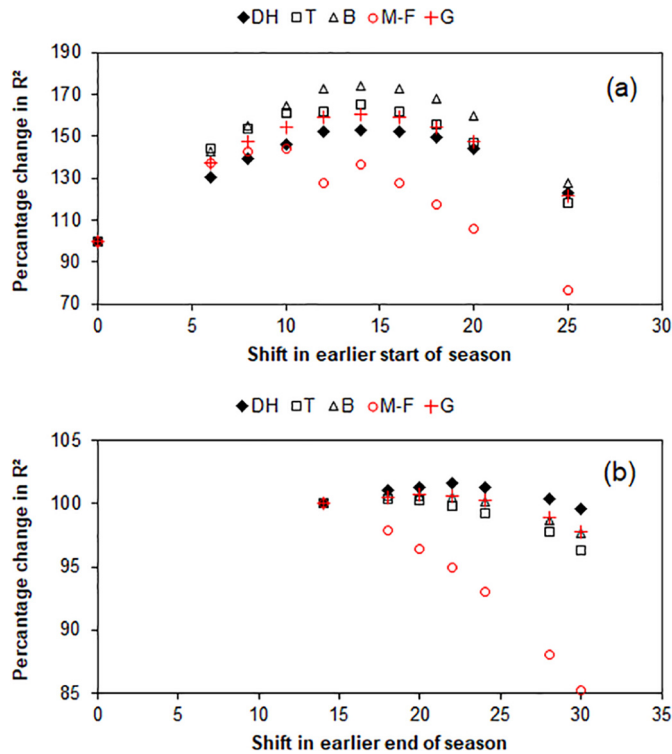


Fig. 5. Change in the R^2 values computed from the observed and modelled time series of near surface grass pollen levels with adjusted calendar days for each monitoring location in Belgium for the start date (a) and end of the grass pollen season (b).

3.3. Source-receptor relations

Near surface grass pollen levels for 2008 were simulated for the whole territory of Belgium with as model input grass pollen emission sources in one sector only (Fig. 2), while the other sectors have no grass pollen emission sources at all. Consequently, the modelled airborne pollen levels in sectors without any grass pollen (the receptor area) originate from that single sector with grass pollen emission sources (the source area). These simulations are repeated for the other source and receptor regions and the results are summarized in Table 2. Sub-table (a) shows the source and the effect on the receptor area and can be read as follows. In Fig. 2A, only the sector of DH (sDH) emits grass pollen. SILAM simulates that on average 15 pollen/ m^3 are located in the air near the surface in this sector, 3 pollen/ m^3 in the sector of B and 1 pollen/ m^3 , 5 pollen/ m^3 , 1 pollen/ m^3 in the sectors of G (sG), T (sT) and M-F (sM-F), respectively. The relative values expressed as a percentage with respect to the source sector are given in sub-table (c). For example, sDH 15 pollen/ m^3 is 60% or 15 out of the sum of 15, 3, 1, 5 or 25 pollen/ m^3 or $15 / 25 * 100 = 60\%$. In sub-table (b), the source-receptor relation is shown by setting the sector to zero grass pollen emission sources while the other sectors have emission sources as shown in Fig. 3. It is the complementary case of Fig. 2. For the empty sector of DH (sDH), only 7 pollen/ m^3 are simulated which are imported from the other sectors. In the last column of sub-table (b), the fraction of pollen in a single area that is transported from the other areas is shown (e.g. $7 / (7 + 15) * 100 = 31\%$ for sDH). Note that all the numbers are rounded.

The same procedures as shown in Table 2, Figs. 2 and 3 are repeated using meteorological data of 2018, instead of 2008. The output is very similar to 2008. The simulated transport is 30, 28, 17, 38, 9% in 2018 compared to 31, 32, 25, 33, 9% in 2008, respectively. And the contributions of the different sectors are also very similar: 62, 66, 75, 74, 95% in 2018 instead of 60, 64, 80, 67, 92% in 2008, notwithstanding the

Table 2

Sub-table (a): The area-averaged seasonal pollen index SPIn (pollen grains/ m^3) modelled by SILAM based on the scenario with grass pollen emission sources only in sDH (column 2) or sB (column 3) or sG (column 4) or sT (column 5) or sM-F (column 6), but no single grass pollen emission source in the other areas (see maps in Fig. 2). The last column shows the local pollen production as the area averaged SPIn for each sector in pollen grains/ m^3 (e.g. the sum of 15 and 7 for sDH). SILAM runs were based on 2008 ECMWF meteorological data.

Sub-table (b) is complementary to sub-table (a): The area-averaged seasonal pollen index SPIn (pollen grains/ m^3) modelled by SILAM based on the scenario without any single grass pollen emission source in sDH (column 2) or sB (column 3) or sG (column 4) or sT (column 5) or sM-F (column 6) (see maps in Fig. 3). In the last column the fraction of pollen in a single area that is imported from the other areas is shown (e.g. $7 / (7 + 15) * 100 = 31\%$ for sector sDH).

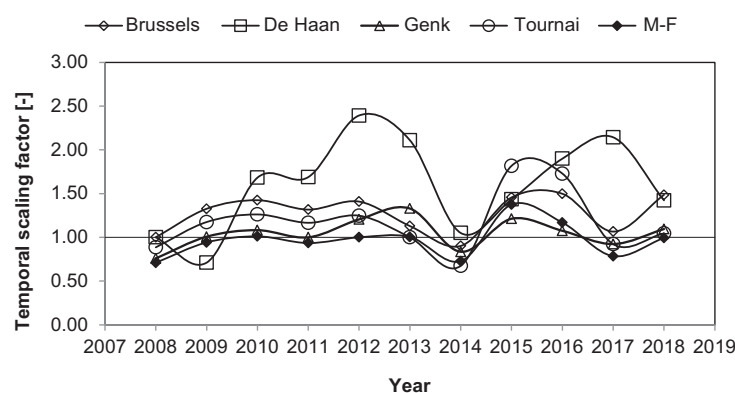
Sub-table (c): Overview of the pollen emission contribution in percentage of one single area with grass pollen emission sources on the airborne pollen levels in the other areas (see sub-table (a)). The last column shows the percentage of airborne grass pollen that originates from the local grass emission sources in one single sector.

(a) SPI 2008	sDH	sB	sG	sT	sM-F	Local pollen production
sDH	15	2	1	3	1	21
sB	3	28	4	3	3	41
sG	1	7	49	1	8	66
sT	5	3	1	20	2	30
sM-F	1	5	8	3	165	181
(b) SPI 2008	sDH	sB	sG	sT	sM-F	Pollen import (%)
sDH	7	19	20	18	20	31
sB	38	13	37	38	38	32
sG	65	59	17	65	57	25
sT	25	27	29	10	28	33
sM-F	180	176	173	178	16	9
(c) SPI in %	sDH	sB	sG	sT	sM-F	Local pollen production (%)
sDH	60	5	1	9	1	69
sB	13	64	6	11	2	68
sG	2	15	80	3	5	75
sT	20	6	1	67	1	66
sM-F	5	10	12	10	92	91

fact that 2008 and 2018 have substantial different wind patterns for Belgium (Fig. 3D). For the 2008 grass pollen season, the main wind direction is South-West. This is contrasted by the pollen season of 2018 which shows more winds blowing from the North. We have increased the grass pollen emission sources with 10% and repeated all the simulations for both 2008 and 2018. No change in the percentages were obtained (data not shown), indicating that the amount of modelled pollen in the air is linearly related to an increase or reduction in grass pollen emission sources. This numerical experiment quantifies how the amount of airborne grass pollen near the surface in one sector (receptor area) can be affected by changes in emission sources in the other sectors (source area). This is useful info when updating grass pollen emission source maps.

3.4. Inter-seasonal scaling of the seasonal grass pollen index

The methodology for the temporal scaling of the SPIn for grasses in SILAM is based on the inter-seasonal variation of the SPIn observed in the five Belgian pollen monitoring stations in combination with the average monthly temperature and total precipitation of April and May from previous seasons (from Uccle/Ukkel). The best correlation is opted for. The meteorological station of Uccle/Ukkel is the main reference station for Belgium and, although local differences in temperature and precipitation occur over the Belgian territory, the area is small enough to consider monthly values - provided by this station - sufficiently representative for other stations. The temporal scaling factors for 2008–2018 for the five monitoring stations in Belgium are illustrated in Fig. 6. For Brussels the average temperature of the three seasons preceding 2008 were used in combination with the one season-lag of total precipitation for April and May. For De Haan, a two season time lag for



Brussels	De Haan	Genk	Tournai	Marche-en-Famenne
Slope= -8.3	Slope= -8.9	Slope= 5.9	Slope=29.9	Slope= 16.5
Intercept= 5384.7	Intercept= 3388.7	Intercept=-352.5	Intercept=654.7	Intercept=-217.5
R ² = 0.64	R ² = 0.52	R ² =0.62	R ² =0.82	R ² =0.55

Fig. 6. The temporal scaling factors for updating the grass pollen sources in the five sectors of Fig. 2 based on the SPIn measured in the five monitoring stations in Table 1 and meteorological data on average temperature and total precipitation of the months April and May of the previous seasons for Uccle/Ukkel (Brussels). The slopes, intercepts and R² values between the combined meteorological data and the SPIn values for the five pollen stations are given. Only for the monitoring sites of Brussels and De Haan the correlation was computed for the time period 2008–2018. The three other sites have shorter time periods. Brussels was then used to extrapolate the temporal scaling back to 2008 for the other three sectors.

average temperature and total precipitation gave the best R² (see also Fig. 6 for the slopes, intercept and R² values). For the site in Genk, a four season time lag for temperature and a one season lag of total precipitation was used. For Tournai, a three season time lag for both temperature and precipitation resulted in the best R². For Marche-en-Famenne, a four year time lag for temperature and a three year time lag for total precipitation were selected. Since only two monitoring sites (Brussels, De Haan) have a 2008–2018 coverage of observed airborne grass pollen levels, the temporal scaling for the other three sectors were based on shorter times series (from 2011 on for Genk, 2012 for Marche-en-Famenne, and from 2013 on for Tournai). The site of Brussels was then used to extrapolate the temporal scaling back to 2008 for the other sites.

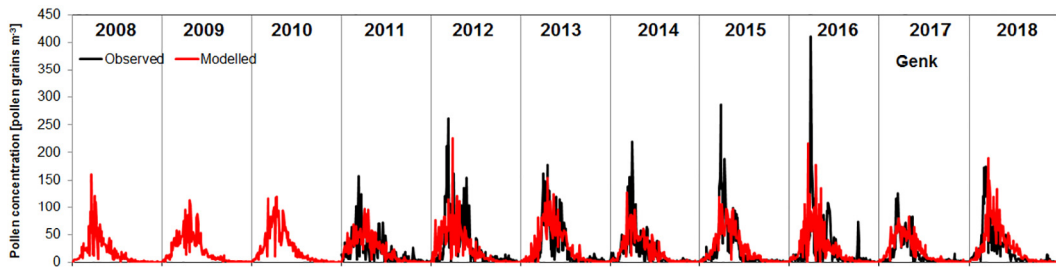
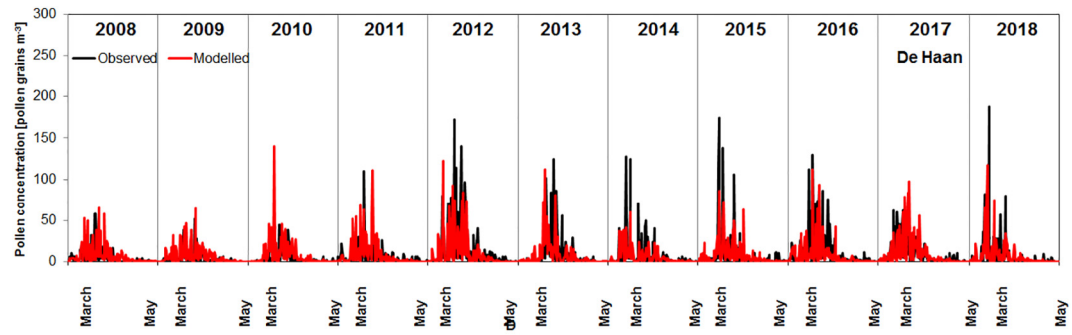
3.5. Time series of near surface grass pollen levels

Grass pollen levels near the surface at daily basis during the grass pollen season (May – September) for the period 2008–2018 were extracted from the SILAM output for the five pollen monitoring station sites in Belgium (see Table 1) and compared with observations (Fig. 7). The corresponding statistics (slope, intercept, R² of the SILAM versus observational data) are given in Table 3 for four different model scenarios, (i) including the model run with the reference MACCIII grass pollen emission sources and the prescribed start and end of the pollen season (Table 3a), (ii) the same scenario (MACCIII emission sources) but with varying start and end days (Table 3b), (iii) the updated grass pollen emission source map based on the CLMS data fixed for the simulation period including varying start and end calendar days (Table 3c), and the final run (iv) after temporal scaling of the

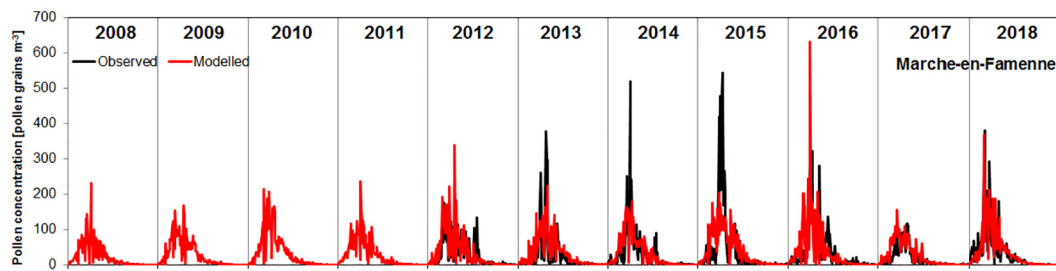
updated emission sources using meteorological variables including varying start and end calendar days (Table 3d).

In general, the R² values computed from the modelled and observed grass pollen level time series increased with a factor of ~1.4 to ~2.1 when applying the full run compared with the reference run (Fig. 7 and Table 3). Similar factors are found for the 3-day averaged pollen concentrations (Table 3) ranging between ~1.2 and ~2.1. The 3-day averaged pollen concentration smooths the daily peaks. When focusing on single pollen seasons and considering the best two R² values between the time series of the updated SILAM model runs and the observations next results can be reported: Brussels R² = 0.70 (2013) and 0.74 (2017); De Haan 0.31 (2014) and 0.32 (2015); Genk 0.67 (2013) and 0.59 (2017); Tournai 0.59 (2013) and 0.61 (2017); Marche-en-Famenne 0.62 (2017) and 0.54 (2018). Fig. S1 shows the time series of daily grass pollen levels of the best and worst modelled grass pollen seasons for the five monitoring locations in Belgium (Supplementary information). The statistics for each individual grass pollen season from 2008 to 2018 are shown in Table S1 (Supplementary information) for the SILAM run that includes temporal scaling of the pollen seasons, the updated grass pollen sources and the varying start and end of the pollen seasons. For each site the R² values between the best and worst grass pollen season may vary substantially, for instance for Brussels between 0.25 in 2011 and 0.74 in 2017. The grass pollen season of 2017 seems to be modelled reasonably well at all pollen observation sites especially for Brussels, M-H and Tournai, while 2011 (worst model performance for De Haan and Brussels) and to a lesser extend also 2012 (worst model performance for M-F) seems to be more problematic seasons for the model. Generally, the seasons 2013 (best for Genk), 2015 (best for De Haan) and 2017 (best for Brussels, M-H and Tournai) are modelled well considering the modelling statistics at the five available pollen

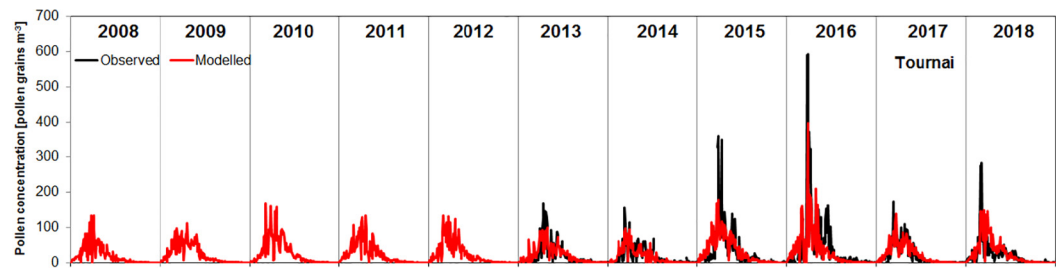
Fig. 7. Time series of observed (black) and SILAM modelled (red) daily mean airborne grass pollen concentration (pollen grains/m³) near the surface for the period 2008–2018 in five monitoring stations of the Belgian aerobiological surveillance network (see Table 1). SILAM runs with the updated emission source map from CLMS seasonal scaled using meteorological data.



D



D



D

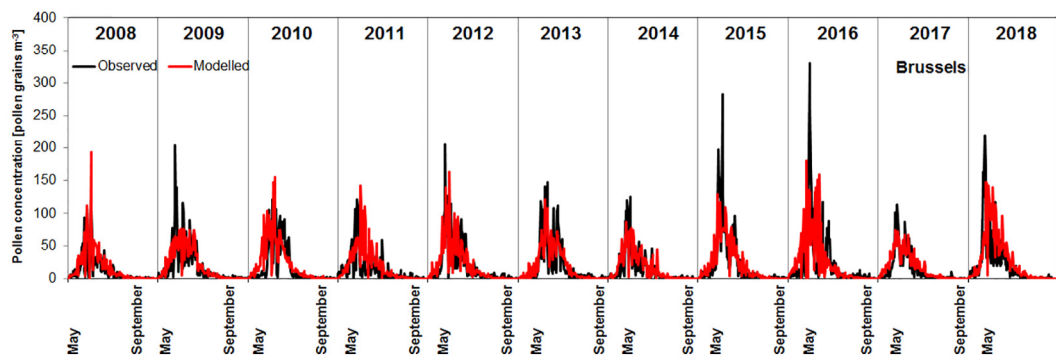


Table 3

Airborne grass pollen concentration for 2008–2018 simulated with the SILAM model using different grass pollen emission sources compared to observations collected at five pollen monitoring stations in Belgium (Table 1). Slope, intercept and the determination coefficient (R^2) between modelled and observed grass pollen concentrations are given. Comparison is made for daily pollen concentration values and for 3-day averaged values. Four scenarios are presented: (a) Reference grass pollen emission sources and prescribed start and end of the pollen season; (b) reference grass pollen emission sources and varying start and end of the pollen season; (c) updated grass pollen emission sources and varying start and end of the pollen season; (d) temporally scaled and updated grass pollen emission sources and varying start and end of the pollen season (Fig. 7).

(a) Reference grass pollen emission sources map (MACCIII) & prescribed start and end of the pollen season					
	De Haan	Tournai	Brussels	Marche-en-Famenne	Genk
<i>Daily values</i>					
Slope	0.26	0.20	0.29	0.17	0.21
Intercept	4.54	11.13	7.09	10.25	7.86
R^2	0.11	0.26	0.27	0.25	0.24
<i>3-day average</i>					
Slope	0.46	0.21	0.37	0.18	0.25
Intercept	2.68	9.91	5.75	9.49	7.01
R^2	0.40	0.34	0.41	0.33	0.33
(b) Reference grass pollen emission sources map (MACCIII) & varying start and end of the grass season					
	De Haan	Tournai	Brussels	Marche-en-Famenne	Genk
<i>Daily values</i>					
Slope	0.27	0.27	0.33	0.23	0.26
Intercept	4.57	9.33	6.16	8.80	6.90
R^2	0.15	0.44	0.43	0.40	0.38
<i>3-day average</i>					
Slope	0.46	0.28	0.42	0.24	0.30
Intercept	2.75	8.10	4.86	7.79	5.83
R^2	0.48	0.55	0.62	0.52	0.53
(c) Updated grass pollen emission sources map (CLMS) & varying start and end of the pollen season					
	De Haan	Tournai	Brussels	Marche-en-Famenne	Genk
<i>Daily values</i>					
Slope	0.33	0.32	0.48	0.48	0.40
Intercept	5.46	10.56	7.91	16.38	10.93
R^2	0.14	0.45	0.46	0.40	0.35
<i>3-day average</i>					
Slope	0.56	0.33	0.59	0.50	0.47
Intercept	3.26	9.12	6.19	14.51	9.28
R^2	0.47	0.55	0.64	0.54	0.51
(d) Temporally scaled and updated grass pollen emission sources map & varying start and end of the pollen season					
	De Haan	Tournai	Brussels	Marche-en-Famenne	Genk
<i>Daily values</i>					
Slope	0.32	0.50	0.60	0.53	0.46
Intercept	5.05	11.81	9.39	16.91	12.56
R^2	0.15	0.55	0.47	0.43	0.36
<i>3-day average</i>					
Slope	0.54	0.54	0.72	0.57	0.55
Intercept	3.08	10.78	7.10	14.79	10.65
R^2	0.48	0.68	0.67	0.59	0.52

observation sites. A detailed look at Fig. S1 reveals that missing observed pollen peaks by the model and/or false peaks that were not observed are the main reasons for poor grass pollen modelling performances during the problematic seasons. Generally, the best seasons to model are characterized by lower pollen amounts and smaller and less pollen peaks (flatter pollen lines). Based on the dichotomous classification using the Odds Ratio (OR) (Siljamo et al., 2013; Ritenberga et al., 2018), the ability of SILAM to detect either less or >50 pollen grains/m³ (the critical threshold above which the majority of sensitized patients is

considered to develop allergy symptoms as used in the Belgian aerobiological surveillance network) shows OR values that are larger than two. Also for other thresholds (5 or 25 pollen grains/m³) the OR values exceed two. On top of using the R^2 values and the OR to evaluate the model performance of SILAM using the different improvements of the model input we have also included the Model Efficiency (ME) measure for additional comparison (Verstraeten et al., 2005, 2006). The ME is computed as:

$$ME = 1 - \frac{\sum_i^n (O_i - P_i)^2}{\sum_i^n (O_i - \bar{O})^2} \quad (1)$$

In Eq. (1), O_i is the i th observed value, P_i is i th modelled value, n is the total amount of available observations in the considered time interval, and $\bar{O}$ is the average of the observations. ME measures the correlation between observed and simulated data and should optimally be one. If $0 < ME < 1$, the modelling results are acceptable; for $ME = 0$, the average of the observed values is as good as the model; and when $ME < 0$, taking the average of the observed values gives better results and the model should be therefore rejected. The ME values for the different pollen count stations using the four model scenarios of Table 3 are given in Table S2 (Supplementary information). Except for the pollen station of De Haan, all ME values are between zero and one indicating acceptable modelling results. Generally, the ME values increase substantially when adapting the start and end of the grass pollen season and by updating the grass pollen emission sources. Adding temporal scaling to introduce inter-seasonal variability is of minor importance for Brussels and Genk but more important for Marche-en-Famenne and Tournai.

4. Discussion

Similarly to other research (Prank et al., 2013; Verstraeten et al., 2019) for ragweed and birch pollen, we have adjusted the grass pollen emission source maps so no model parameters on pollen release must be changed. Changing the model inputs such as the start and end of the grass pollen season increased the model performance substantially. It demonstrates the potential for improvement of grass pollen predictions if high-resolution information is included. The effect is governed by: (i) short transport distance of grass pollen, and (ii) grass being the only fixed-calendar species in the SILAM pollen emission model (Sofiev, 2017). As a result, the European-scale model optimization, while making the model unbiased on average, leaves very substantial room for improvement at every specific location. In the current case, the contrast between M-F and other locations considering the change in seasonal start and end (respectively 10 and 14 days) is not reproducible at the European scale where the correlation distance for the key model parameters has to be longer than 100 km. For potential operational use of SILAM for modelling grass pollen concentrations at the level of Belgium we will start with refining the maps for the onset and offset dates for the different sectors. The maps of the reference run were produced with the correlation extending up to 100 km distance between the stations. Reduction of this scale to ~20 km will lead to maps reflecting the details of the maritime microclimates in Belgium. However inter-seasonal variations in onsets and offsets must still be accounted for in an operational mode. Ambient temperatures preceding the grass growing season might be used, but this must be investigated further on. Again, it calls for a mechanistic grass flowering model applicable at regional and continental scales – still a distant solution despite several attempts made during last 10 years.

Evaluating the location of grass pollen emission sources remains a big challenge since only small fraction of the agricultural areas such as fallow, rye, grass seedling contains significant amounts of grass pollen (Skjoth et al., 2013). These portions, however, are described poorly in general land use maps such as the European one of CLMS. Large permeant grasslands, which are low pollen emitters, are much easier

to include in inventories than seasonal highly variable land use fractions mentioned above (McInnes et al., 2017; Kurganskiy et al., 2020). An additional complicating factor is that land cover type management strategies for grasses also affect pollen concentrations and thus the annual airborne pollen levels (Khwarahma et al., 2017). Alternatively, spatially high-resolution remote sensing images taken during the entire vegetation period have more potential to identify all types of grass pollen emission sources. However, high spatial resolution remote sensors in general have low revisiting times. Adding even more complexity is the fact that in urban areas also the influence of the urban heat island on phenological development of grasses (Khwarahma et al., 2017) may have effect on the timing and intensity of grass pollen release.

Vegetation distribution and activity is crucial for predicting the airborne pollen levels, but meteorological conditions during and preceding a growing season (Sánchez Mesa et al., 2003) are also very important. It has been shown that 20–40% of the inter-seasonal variation of pollen levels could be attributed to weather variations (Sofiev, 2017). One important meteorological variable is wind, the major driver for airborne pollen transport. The typical transport distance for pollen of many species is suggested to be in the range of 30–100 km (Faegri and Iversen, 1992; Avolio et al., 2008). This is corroborated by our results in Table 2a, showing that pollen sources in the sector of De Haan (coast) are hardly reaching Marche-en-Famenne which is ~200 km away, while pollen from the sector of Brussels and Genk reach Marche-en-Famenne more easily (distance is 100 and 90 km respectively) (see also Table 1 for some indicative distances between monitoring stations). Major wind directions might be very important. The dominant wind direction in Belgium during May is WSW, during June–August SW (RMI website). The two years (2008 and 2018) that were selected for the source receptor relations have substantial different wind patterns (see Fig. 3D), although the sectorial transport fractions remain quite similar. This might indicate that the grass pollen in Belgium are predominantly transported locally. Yet, grass pollen originating from distant sources beyond 200 km are also reported in literature (Smith et al., 2005).

The start and end of the grass pollen season do not necessarily correspond with the start or end of the pollinosis symptoms, since also other factors might play a role (Pfaar et al., 2017). The allergenicity of grasses is related to the relative amount of allergen and allergenic extracts in the pollen grains (Buters et al., 2012). However, the start and end are crucial parameters in pollen transport models. For birches, it has been known that the air temperature during the period directly preceding the birch pollen release is of decisive influence on the starting date (Spieksma et al., 1995). Increased temperature during spring favors the earlier flower development and pollen dispersal (Yli-Panula et al., 2009) and there is large inter-seasonal variation in start and end of the birch pollen season (Ritenberga et al., 2016). In a review, García-Mozo (2017) also points to changes in temperature and rainfall patterns during the period prior to phenophase onset of grasses as the cause of phenological trends, but also on the internal response of grass populations to the negative feedback mechanisms of population dynamics. The rationale behind that is that water availability and temperature affect plant growth and later in the season also blooming. Apart from local temperature and rainfall, plant water availability is also determined by other environmental conditions such as soil type. For example, grasses on sandy soils have less beneficial soil water conditions than grasses on more loamy soils, but this cannot be generalized too much since some grass species are adapted to dry conditions (Munson and Long, 2017). British research has shown that the onset date for the grass pollen season can be derived from remotely-sensed data, since it is correlated with the MERIS Terrestrial Chlorophyll Index (MTCI), a vegetation index on ~1 by 1 km² spatial grid (Khwarahma et al., 2017). The start of the season could be identified when 75% of the maximum MTCI was reached. Consequently, this is a promising technique. Future research should focus on the applicability of readily available remotely-sensed vegetation indices in determining the onset and offset of the grass pollen season and for identifying grass pollen emission

sources, crucial inputs in pollen transport models. The main challenge, however, is not only identifying locations with grass, but also the identification of the locations with grasses that substantially produce grass pollen. Overall, next lessons can be learned from Table 3. The correlation between modelled and observed time series of grass pollen levels near the surface increased substantially by adjusting the start and end of the grass pollen season. Using new grass pollen sources and introducing the temporal scaling between seasons resulted in slightly better R² values. Increasing the pollen emission sources over the whole area increased the slopes of the linear relation between the observed and modelled pollen level time series closer to one.

The uncertainty of the Hirst-trap based observations is an important subject receiving high attention in recent years (Oteros et al., 2017; Rojo et al., 2019). In particular, the systematic flow error of ~34% and random fluctuations of ~30% of daily concentrations have been reported. Therefore, the current study has been designed to minimize their impact. The significant systematic error can be assumed nearly constant for each trap, therefore it does not significantly affect the correlations, neither during the season nor between the seasons. The latter assumption is potentially problematic, but this hypothesis is supported by the well-pronounced grass pollen production cycle (see Fig. 4), i.e. the overall error is smaller than the variability of the herbaceous plants. Moreover, the synchronicity of this production cycle among all the five stations appears to be clear, i.e. the inter-station error is also smaller than the signal. What concerns the day-to-day repeatability, this uncertainty is significant for the specific peaks during the season but is averaged out at the annual and inter-annual levels.

5. Conclusions and future research

Airborne grass pollen levels near the surface were modelled with SILAM using an updated bottom-up inventory on grass pollen emission sources for Belgium. The model was evaluated with daily observations at five pollen monitoring stations for 2008–2018. Pollen source-receptor relations have indicated that the emission sources of grass pollen in most parts of Belgium affect each other considerably. More than 30% of the airborne grass pollen levels in one area in Belgium originate from emissions in other areas. By adapting the start and end calendar days of the grass pollen season in SILAM, the comparison with observed grass pollen data improved substantially. Temporal scaling of the inter-seasonal SPIn further increased the model performance. However, more research should be conducted on comparing and analyzing the individual modelled and observed grass pollen seasons in order to better explain the inter-seasonal variation in model performance. Further research should focus on integrating readily available remotely-sensed vegetation indices for determining the spatial distribution of the onset and offset of the grass pollen season. A more advanced way of making progress in modelling airborne grass pollen levels could be by applying the degree-day-methodology similar to the approach of modelling airborne birch pollen. In that case, there would be no need at all for setting the seasonal onset and offset days. However, attempts to formulate and parameterize such a model so far showed unsatisfactory results. High spatial resolution remote sensing data could also improve the spatial as well as temporal distribution of grass pollen emission sources, which is a critical input parameter when using emission bottom-up approaches for airborne grass pollen modelling. Daily grass pollen levels estimates can also be improved by integrating observed pollen levels in the pollen source maps in a top-down approach. The most advanced methodology is probably the 4D-var data assimilation, thereby simultaneously changing the model parameters and pollen sources accordingly to observed time series of airborne grass pollen levels. Finally, more research is required on the inter-seasonal variation of the SPIn for grasses and on how models can cope with that.

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2020.141903>.

CRedit authorship contribution statement

Conceptualization, WWV; methodology, WWV; model software, AWD, RK and MS; validation, WWV and NB; formal analysis, WWV; investigation, WWV; resources, WWV, NB, RK, MS and AWD; data curation, WWV, NB, AWD; writing—original draft preparation, WWV; writing—review and editing, RK, NB, MS, AWD; visualization, WWV; project administration, WWV, NB and AWD; funding acquisition, WWV, NB and AWD. All authors have read and agreed to the published version of the manuscript.

Funding

This research was partly funded by the Belgian Science Policy Office (BELSPO) in the frame of the Belgian Research Action through Interdisciplinary Networks Brain (BRAIN.be) programme – project RETROPOLLEN (B2/191/P2/RETROPOLLEN) and partly funded by the Royal Meteorological Institute of Belgium. The SILAM pollen-related developments were supported by the Academy of Finland project PS4A (grant 318194) and Copernicus Atmosphere Monitoring Service CAMS-50.

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.

Acknowledgements

The graphical abstract was developed using several building blocks such as icons made available by thenounproject.com.

References

- Avolio, E., Pasqualoni, L., Federico, S., Fornaciari, M., Bonfiglio, T., Orlandi, F., Bellecci, C., Romano, B., 2008. Correlation between large-scale atmospheric fields and the olive pollen season in Central Italy. *Int. J. Biometeorol.* 52, 787–796.
- Blomme, K., Tomassen, P., Lapeere, H., et al., 2013. Prevalence of allergic sensitization versus allergic rhinitis symptoms in an unselected population. *Int. Arch. Allergy Immunol.* 160 (2), 200–207.
- Brennan, G.L., Potter, C., de Vere, N. et al., 2019. Temperate airborne grass pollen defined by spatio-temporal shifts in community composition. *Nat. Ecol. Evol.* 3, 750–754.
- Bruffaerts, N., De Smedt, T., Delcloo, A., Simons, K., Hoebeke, L., et al., 2018. Comparative long-term trend analysis of daily weather conditions with daily pollen concentrations in Brussels, Belgium. *Int. J. Biometeorol.* 62 (3), 483–491. <https://doi.org/10.1007/s00484-017-1457-3>.
- Buters, J.T.M., Thibaudon, M., Smith, M., Kennedy, R., Rantio-Lehtimäki, A., Albertini, R., et al., 2012. Release of bet v1 from birch pollen from 5 European countries. Results from the HIALINE study. *Atmos. Environ.* 55, 496–505.
- Cristofolini, F., Anelli, P., Billi, B.M., et al., 2019. Temporal trends in airborne pollen seasonality: evidence from the Italian POLLnet network data. *Aerobiologia* 36, 63–70. <https://doi.org/10.1007/s10453-019-09609-8>.
- D'Amato, G., Cecchi, L., Bonini, S., et al., 2007. Allergic pollen and pollen allergy in Europe. *Allergy* 62, 976–990. <https://doi.org/10.1111/j.1398-9995.2007.01393.x>.
- Delcloo, A., Verstraeten, W.W., Dujardin, S., et al., 2020. Spatio-temporal monitoring and modelling of birch pollen in Belgium. *Air Pollution Modeling and Its Application XXVI* https://doi.org/10.1007/978-3-030-22055-6_12.
- ECMWF, d. <https://www.ecmwf.int/en/newsletter/147/news/era5-reanalysis-production>.
- Emberlin, J., 2009. Grass, Tree, and Weed Pollen. *Allergy and Allergic Diseases*. Wiley-Blackwell, pp. 942–962.
- Emberlin, J., Jaeger, S., Dominguez-Vilches, E., Soldevilla, C., Hodal, L., Mandrioli, P., Lehtimäki, A., Savage, M., Spijksma, F., Bartlett, C., 2000. Temporal and geographical variations in grass pollen seasons in areas of western Europe: an analysis of season dates at sites of the European pollen information system. *Aerobiologia* 16, 373–379.
- European Environment Agency, 2017. Air Pollution Sources. European Environment Agency, Denmark <https://www.eea.europa.eu/themes/air/air-pollution-sources-1>. (Accessed 6 April 2020).
- Faegri, K., Iversen, J., 1992. *Textbook of Pollen Analysis*. John Wiley and Sons.
- Fiore, A.M., et al., 2009. Multimodel estimates of intercontinental source-receptor relationships for ozone pollution. *J. Geophys. Res.* 114, D04301.
- Galán, C., Emberlin, J., Domínguez, E., Bryant, R.H., Villamandos, F., 1995. A comparative analysis of daily variations in the Gramineae pollen counts at Córdoba, Spain and London, UK. *Grana* 34, 189–198.
- Galán, C., Smith, M., Thibaudon, M., et al., 2014. Pollen monitoring: minimum requirements and reproducibility of analysis. *Aerobiologia* 30, 385. <https://doi.org/10.1007/s10453-014-9335-5>.
- Galán, C., Ariatti, A., Bonini, M., et al., 2017. Recommended terminology for aerobiological studies. *Aerobiologia* 33, 293–295. <https://doi.org/10.1007/s10453-017-9496-0> (2017).
- García-Mozo, H., 2017. Poaceae pollen as the leading aeroallergen worldwide: a review. *Allergy* 72, 1849–1858. <https://doi.org/10.1111/all.13210>.
- Hirst, J.M., 1952. An automatic volumetric spore trap. *Ann. Appl. Biol.* 39, 257–265. <https://doi.org/10.1111/j.1744-7348.1952.tb00904.x>.
- Hoebeke, L., Bruffaerts, N., Verstraeten, C., Delcloo, A., Desmedt, T., et al., 2018. Thirty-four years of pollen monitoring: an evaluation of the temporal variation of pollen seasons in Belgium. *Aerobiologia* 34, 139. <https://doi.org/10.1007/s10453-017-9503-5>.
- Khwarahma, N.R., Dash, J., Skjøth, C.A., Newnham, R.M., Adams-Groom, B., Heade, K., Caulton, E., Atkinson, P.M., 2017. Mapping the birch and grass pollen seasons in the UK using satellite sensor time-series. *Sci. Total Environ.* 578, 586–600.
- KMI, Royal Meteorological Institute of Belgium, d. <https://www.meteo.be/nl/klimaat/klimatologisch-overzicht/2011-2015/2012/augustus-2012>. (Accessed 8 April 2020).
- Kouznetsov, R., Sofiev, M., 2012. A methodology for evaluation of vertical dispersion and dry deposition of atmospheric aerosols. *J. Geophys. Res.* 117. <https://doi.org/10.1029/2011JD016366>.
- Kurganskiy, A., Skjøth, C.A., Baklanov, A., et al., 2020. Incorporation of pollen data in source maps is vital for pollendispersion models. *Atmos. Chem. Phys.* 20, 2099–2121 2020. <https://doi.org/10.5194/acp-20-2099-2020>.
- Landrigan, P.J., et al., 2017. The Lancet Commission on Pollution and Health. Published online October 19, 2017. [https://doi.org/10.1016/S0140-6736\(17\)32345-0](https://doi.org/10.1016/S0140-6736(17)32345-0).
- Langanke, T., 2017. Copernicus Land Monitoring Service – high resolution layer grassland: product specifications document. Copernicus team at EEA. <https://land.copernicus.eu/user-corner/technical-library/hrl-grassland-technical-document-prod-2015>. (Accessed 6 April 2020).
- Liu, C., Chen, R., Sera, F., et al., 2019. Ambient particulate air pollution and daily mortality in 652 cities. *N. Engl. J. Med.* 381, 705–715. <https://doi.org/10.1056/NEJMoa1817364>.
- McInnes, R.N., Hemming, D., Burgess, P., et al., 2017. Mapping allergenic pollen vegetation in UK to study environmental exposure and human health. *Sci. Total Environ.* 599–600, 483–499. <https://doi.org/10.1016/j.scitotenv.2017.04.136>.
- Munson, S.M., Long, A.L., 2017. Climate drives shifts in grass reproductive phenology across the western USA. *New Phytol.* 213, 1945–1955. <https://doi.org/10.1111/nph.14327>.
- Noun Project, d. Free icons for everything. www.thenounproject.com. (Accessed 29 July 2020).
- Oteros, J., Buters, J., Laven, G., et al., 2017. Errors in determining the flow rate of Hirst-type pollen traps. *Aerobiologia* 33, 201–210. <https://doi.org/10.1007/s10453-016-9467-x>.
- Pfaar, O., Bastl, K., Berger, U., Buters, J., Calderon, M.A., Clot, B., et al., 2017. Defining pollen exposure times for clinical trials of allergen immunotherapy for pollen induced rhinoconjunctivitis – an EAACI Position Paper. *Allergy* 72, 713–722. <https://doi.org/10.1111/all.13092>.
- Prank, M., Chapman, D.S., Bullock, J.M., Belmonte, J., et al., 2013. An operational model for forecasting ragweed pollen release and dispersion in Europe. *Agric. For. Meteorol.* 182–183, 43–53. <https://doi.org/10.1016/j.agrformet.2013.08.003>.
- Ranta, H., Satri, P., 2007. Synchronized inter-annual fluctuation of flowering intensity affects the exposure to allergenic tree pollen in North Europe. *Grana* 46, 274–284. <https://doi.org/10.1080/00173130701653079>.
- Ritenberga, O., Sofiev, M., Kirillova, V., Kalina, L., Genikhovich, E., 2016. Statistical modelling of non-stationary processes of atmospheric pollution from natural sources: example of birch pollen. *Agric. Forest Meteorol.* 226–227, 96–107.
- Ritenberga, O., Sofiev, M., Siljamo, P., Saarto, A., Dahl, A., Ekebome, A., Sauliene, E., Shalaboda, V., Severova, E., Hoebeke, L., Ramfjord, H., 2018. A statistical model for predicting the inter-annual variability of birch pollen abundance in Northern and North-Eastern Europe. *Sci. Total Environ.* 615, 228–239.
- Rojo, J., Oteros, J., Pérez-Badia, R., et al., 2019. Near-ground effect of height on pollen exposure. *Environ. Res.* 174 (2019), 160–169. <https://doi.org/10.1016/j.envres.2019.04.027>.
- Sánchez Mesa, J.A., Smith, M., Emberlin, J., Allitt, U., Caulton, E., Galan, C., 2003. Characteristics of grass pollen seasons in areas of southern Spain and the United Kingdom. *Aerobiologia* 19, 243–250.
- Siljamo, P., Sofiev, M., Filatova, E., et al., 2013. A numerical model of birch pollen emission and dispersion in the atmosphere. Model evaluation and sensitivity analysis. *Int. J. Biometeorol.* 57, 125–136. <https://doi.org/10.1007/s00484-012-0539-5>.
- Skjøth, C.A., Sommer, J., Stach, A., Smith, M., Brandt, J., 2007. The long range transport of birch (*Betula*) pollen from Poland and Germany causes significant pre-season concentrations in Denmark. *Clin. Exp. Allergy* 37, 1204–1212, 2007.
- Skjøth, C.A., Ørby, P.V., Becker, T., et al., 2013. Identifying urban sources as cause of elevated grass pollen concentrations using GIS and remote sensing. *Biogeosciences* 10, 541–554. <https://doi.org/10.5194/bg-10-541-2013>.
- Smith, M., Emberlin, J., Kress, A., 2005. Examining high magnitude grass pollen episodes at Worcester, United Kingdom, using back-trajectory analysis. *Aerobiologia* 21, 85–94.
- Sofiev, M., 2017. On impact of transport conditions on variability of the seasonal pollen index. *Aerobiologia* 33, 167–179. <https://doi.org/10.1007/s10453-016-9459-x>.
- Sofiev, M., Siljamo, P., Ranta, H., Rantio-Lehtimäki, A., 2006. Towards numerical forecasting of long-range air transport of birch pollen: theoretical considerations and a feasibility study. *Int. J. Biometeorol.* 50, 392–402. <https://doi.org/10.1007/s00484-006-0027-x>.
- Sofiev, M., Siljamo, P., Ranta, H., Linkosalo, T., Jaeger, S., Rasmussen, A., Rantio-Lehtimäki, A., Severova, E., Kukkonen, J., 2013. A numerical model of birch pollen emission and dispersion in the atmosphere. Description of the emission module. *Int. J. Biometeorol.* 57, 45–58. <https://doi.org/10.1007/s00484-012-0532-z>.

- Sofiev, M., Vira, J., Kouznetsov, R., Prank, M., Soares, J., Genikhovich, E., 2015. Construction of the SILAM Eulerian atmospheric dispersion model based on the advection algorithm of Michael Galperin. *Geosci. Model Dev.* 8, 3497–3522. <https://doi.org/10.5194/gmd-8-3497-2015>.
- Spiekma, F.Th.M., Emberlin, J.C., Hjelmroos, M., Jäger, S., Leuschner, R.M., 1995. Atmospheric birch (*Betula*) pollen in Europe: trends and fluctuations in annual quantities and the starting dates of the seasons. *Grana* 34 (1), 51–57. <https://doi.org/10.1080/00173139509429033>.
- Sudo, K., Akimoto, H., 2007. Global source attribution of tropospheric ozone: long-range transport from various source regions. *J. Geophys. Res.* 112, D12302.
- Van de Vyver, H., Delcloc, A.W., 2011. Stable estimations for extreme wind speeds. An application to Belgium. *Theor. Appl. Climatol.* 105, 417–429. <https://doi.org/10.1007/s00704-010-0365-9>.
- Verstraeten, W.W., Muys, B., Feyen, J., Veroustraete, F., Minnaert, M., Meiresonne, L., De Schrijver, A., 2005. Comparative analysis of the actual evapotranspiration of Flemish forest and cropland, using the soil water balance model WAVE. *HESS* 9 (3), 225–241.
- Verstraeten, W.W., Veroustraete, F., Feyen, J., 2006. On temperature and water limitation of net ecosystem productivity: implementation in the C-Fix model. *Ecolog. Mod.* 199 (1), 4–22.
- Verstraeten, W.W., Neu, J.L., Williams, J.E., Bowman, K.W., Worden, J.R., Boersma, K.F., 2015. Rapid increases in tropospheric ozone production and export from China. *Nat. Geosci.* 8, 690–695. <https://doi.org/10.1038/ngeo2493>.
- Verstraeten, W.W., Boersma, K.F., Douros, J., Williams, J.E., Eskes, H., Liu, F., Beirle, S., Delcloc, A., 2018. Top-down NOX emissions of European cities based on the down-wind plume of modelled and space-borne tropospheric NO2 columns. *Sensors* 18, 2893. <https://doi.org/10.3390/s18092893>.
- Verstraeten, W.W., Dujardin, S., Hoebeke, L., Bruffaerts, N., Kouznetsov, R., Dendoncker, N., Hamdi, R., Linard, C., Hendrickx, M., Sofiev, M., Delcloc, A.W., 2019. Spatio-temporal monitoring and modelling of birch pollen levels in Belgium. *Aerobiologia* 35 (4), 703–717. <https://doi.org/10.1007/s10453-019-09607-w>.
- WHO, 2003. *Phenology and Human Health: Allergic Disorders*. WHO, Copenhagen.
- Yli-Panula, E., Fekedulegn, D.B., Green, B.J., Ranta, H., 2009. Analysis of airborne *Betula* pollen in Finland; a 31-year perspective. *Int. J. Environ. Res. Publ. Health* 6, 1706–1723. <https://doi.org/10.3390/ijerph6061706>.
- Ziello, C., Sparks, T.H., Estrella, N., Belmonte, J., Bergmann, K.C., et al., 2012. Changes to air-borne pollen counts across Europe. *PLoS One* 7 (4), e34076.

Table S1. Airborne grass pollen concentration for each individual grass pollen season from 2008 to 2018 simulated with the SILAM model using the temporally scaled and updated grass pollen emission sources and varying start and end of the pollen season (see also Figure 7) compared to observations collected at five pollen monitoring stations in Belgium (see also Table 1). Slope, intercept and the determination coefficient (R^2) between modelled and observed grass pollen concentrations are given for each grass pollen season.

	Brussel	De Haan	Genk	M-F	Tournai
2008 slope	0.97	0.32			
Intc	3.80	5.35			
R^2	0.69	0.07			
2009 slope	0.54	0.34			
Intc	9.12	5.71			
R^2	0.54	0.06			
2010 slope	0.73	0.63			
Intc	9.34	4.60			
R^2	0.51	0.10			
2011 slope	0.57	0.31	0.46		
Intc	10.66	5.68	11.90		
R^2	0.25	0.05	0.29		
2012 slope	0.59	0.30	0.35	0.88	
Intc	9.83	6.48	14.42	10.15	
R^2	0.40	0.17	0.25	0.43	
2013 slope	0.68	0.30	0.66	0.51	0.56
Intc	7.30	4.29	10.41	18.88	9.96
R^2	0.70	0.15	0.67	0.47	0.59
2014 slope	0.66	0.29	0.53	0.51	0.68
Intc	6.70	3.06	9.41	14.85	5.67
R^2	0.56	0.31	0.49	0.54	0.57
2015 slope	0.52	0.34	0.41	0.32	0.46
Intc	10.26	4.80	13.05	24.87	15.11
R^2	0.57	0.32	0.44	0.44	0.55
2016 slope	0.46	0.30	0.32	0.72	0.45
Intc	13.02	3.97	15.68	9.62	11.72
R^2	0.34	0.19	0.18	0.44	0.57
2017 slope	0.73	0.55	0.66	0.96	0.70
Intc	6.53	4.57	8.13	8.90	7.91
R^2	0.74	0.25	0.59	0.62	0.61
2018 slope	0.63	0.20	0.57	0.67	0.60
Intc	12.43	5.33	14.08	13.90	13.36
R^2	0.40	0.07	0.32	0.54	0.47

Table S2. Model performance of SILAM for the four (A-D) scenarios of Table 3A-D evaluated using the Model Efficiency (ME)

	De Haan	Tournai	Brussels	Marche-en-Famenne	Genk
ME [-]					
Daily values					
A	-0.08	0.22	0.24	0.17	0.17
B	0.05	0.35	0.38	0.27	0.28
C	-0.10	0.40	0.45	0.38	0.34
D	-0.02	0.54	0.43	0.40	0.32

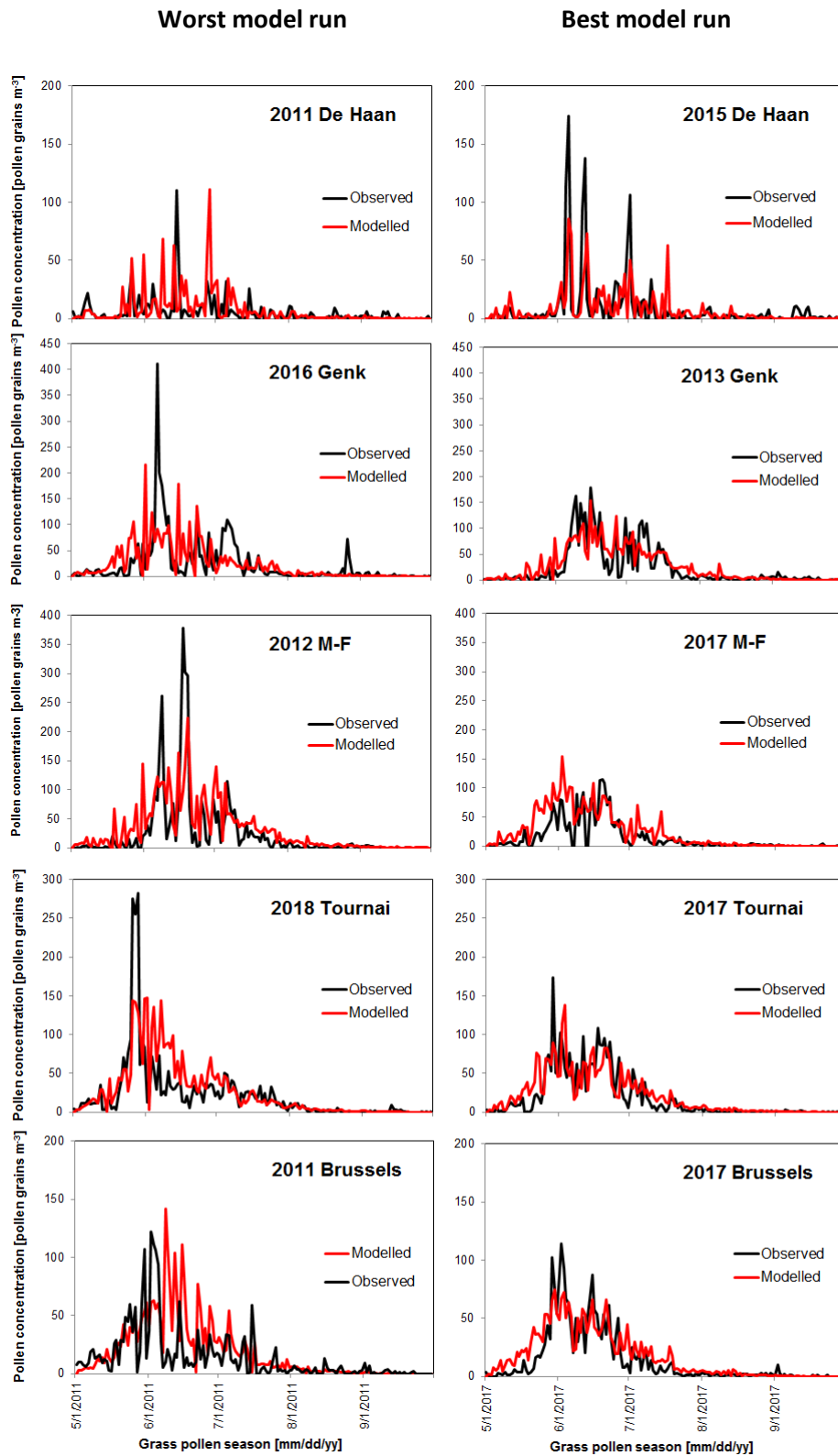


Figure S1