



Spatio-temporal monitoring and modelling of birch pollen levels in Belgium

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Abstract In Belgium, ~ 10% of the people is estimated to suffer from allergies due to pollen emitted by the birch family trees. Timely information on forthcoming pollen exposure episodes using a forecasting system can allow patients to take preventive measures. To date, the only available information on pollen concentrations in Belgium comes from five stations that monitor daily airborne birch pollen concentrations, but real-time and detailed spatial information is lacking. Pollen transport models can both quantify and forecast the spatial and temporal distribution of airborne birch pollen concentrations if accurate and updated maps of birch pollen emission sources are available and if the large inter-seasonal

variability of birch pollen is considered. Here we show that the SILAM model driven by ECMWF ERA5 meteorological data is able to determine airborne birch pollen levels using updated maps of areal fractions of birch trees, as compared to the pollen observations of the monitoring stations in Belgium. Forest inventory data of the Flemish and Walloon regions were used to update the default MACCIII birch map. Spaceborne MODIS vegetation activity combined with an updated birch fraction map and updated start and end dates of the birch pollen season were integrated into SILAM. The correlation (R^2) between SILAM modelled and observed time series of daily birch pollen levels of 50 birch pollen seasons increased up to ~ 50%. The slopes of the linear correlation increased on average with ~ 60%. Finally, SILAM is able to capture the threshold of 80 pollen grains m^{-3} exposure from the observations.

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1 Introduction

Pollen allergy has a deteriorating effect on the human well-being and health. In Europe, more than 15% of the population suffers from pollinosis (WHO 2003). In Belgium, ~ 10% of the people is estimated to

develop allergic rhinitis symptoms due to pollen from trees of the birch family (Blomme et al. 2013). This country is a highly industrialized and densely populated region with substantial air pollution (Verstraeten et al. 2018). Typically, regions with large degree of industrialization suffer from an increase in the burden of allergic respiratory diseases. This is because air pollution can influence both the allergens and the allergic subjects by increasing the immune reaction, and/or by intensified biogenic emissions as well as the allergenic potential of the allergens (Ziello et al. 2012). Variety of pollinosis symptoms, ranging from sneezing, stuffy nose, and watery eyes, to asthmatic reactions, reduce the life quality of many people in a substantial way. Medication and allergy tablets/shots are used for relieving symptoms. Patients, however, can take preventive actions such as avoiding outdoor activities, closing car windows when travelling, wearing sunglasses, not drying clothes outside, washing your hair before going to bed, among others to prevent contact to the allergens and as such reduce the symptoms (Sciensano 2018). This implies, however, that patients are timely informed on the forthcoming severe pollen episode by an operational pollen forecast system. To date, such a forecast system does not exist specifically for the Belgian territory. So far, pollen emitted by various trees, grasses and other herbaceous plants are monitored at daily basis by Sciensano through a network of currently five offline observation stations spread over Belgium. In total, the Belgian aerobiological surveillance network has monitored airborne pollen at 13 different sites since 1982. This spatially sparse sampling and the lack of real-time observations prevent to capture the spatial and temporal impact of birch pollen on sensitized patients. Consequently, the current pollen info is not sufficient to assess individual patient's impact and moreover does not allow to take timely preventive measures.

Pollen emission and transport models based on Chemistry Transport Models (CTM's) are an interesting tool to both quantify and forecast spatial and temporal distributions of airborne pollen levels near the surface provided that sufficient data on the pollen emission sources can be ingested. Birch pollen are large biogenic aerosols (diameter of 20–25 μm) that are picked up from the tree catkins by the wind and removed from the air by gravitation and scavenged by water in the atmosphere. Pollen near the surface can also be resuspended in the air under certain

meteorological conditions. High relative humidity, high rainfall and low temperatures suppress the pollen levels in the air, while warm weather may increase the pollen emissions and keeps more pollen airborne (D'Amato et al. 2007). Wind is an important factor affecting pollen concentrations near the surface, since wind can transport pollen from emission sources, i.e. large birch forests, that are located up to 1000 km in distance (Sofiev et al. 2006) from the receptor location. Regional dispersion models can simulate and forecast airborne biogenic aerosols such as birch pollen, but only if high-quality data is available on the spatial distribution of birch trees combined with proper meteorological data (WAO 2018). Current pollen transport models, however, rely on coarse scale vegetation maps based on inventory data that may be outdated and lack inter-seasonal variations in the emissions of pollen (Siljamo et al. 2013). These inter-seasonal differences in pollen amounts can be very important, especially for trees which present typical production cycles due to mast seeding (Hoebeke et al. 2018). What is more, pollen season onsets and offsets in models are often based on general climatology (i.e. long-term averages for large areas), lacking spatio-temporal details. That is why the objectives of this paper are threefold. First is to provide pollen transport models with good-quality pollen emission sources for birch trees at the appropriate spatial and temporal scale for Belgium. Second is to improve the determination of the start (onset) and end (offset) of the pollen season. Third is to add inter-annual variations of the amount of pollen released by birch trees based on satellite data of vegetation processes. In this research, we use the pollen transport model SILAM (System for Integrated modeLLing of Atmospheric coMposition, <http://silam.fmi.fi>) (Sofiev et al. 2013, 2015b) for modelling and monitoring the birch pollen levels near the surface for the territory of Belgium at a $0.1^\circ \times 0.1^\circ$ grid.

2 Data and methods

2.1 SILAM

Pollen grains are biogenic aerosols with a diameter of typically 5–50 times larger than conventional atmospheric aerosols depending on vegetation species. Birch pollen can be treated as a large aerosol in

CTM's. The CTM SILAM is able to simulate the dispersion of pollen based on processes such as wind advection (transport with air masses), mixing due to turbulence, gravitational settling (dry deposition), and scavenging with precipitation (wet deposition) (Kouznetsov and Sofiev 2012).

Pollen modelling with SILAM is based on the temperature degree days approach or the thermal time flowering model (Sofiev et al. 2006). The parameterization of flowering follows a principle of two thresholds (start and end of the flowering season) for the temperature sum (Linkosalo et al. 2010; Sofiev et al. 2013), which assumes that the timing of birch flowering is mostly driven by accumulated ambient temperature during a certain period in time. The cumulative fraction of pollen released from the start of the pollen season until a certain period (to the end of the pollen season) is assumed piecewise linear and proportional to the temperature sum during the main flowering season. Short-term meteorological conditions such as wind speed, relative humidity and precipitation rate will affect the amount of pollen in the air. Precipitation and humidity inhibit the pollen release, and threshold values are used to compute reduction factors. Typically, the lower and upper thresholds from relative humidity are 50% and 80%, respectively. For precipitation the lower and upper thresholds are 0 and 0.5 mm h⁻¹ (the grid cell average rate), respectively. At the saturation wind speed of 5 m s⁻¹, the pollen release rate is maximal. At a wind speed around 1 m s⁻¹, no pollen emissions will occur. The transport, emission and deposition in SILAM is driven by ECMWF ERA5 reanalysis meteorological data (grid cell of 0.25° × 0.25°) (ECMWF) for the birch seasons of the period 2008–2018.

2.2 Birch pollen emission sources

The simulation of birch pollen levels in the air requires the quantification of the spatio-temporal distributions of emission sources of birch pollen in the model domain. Stated otherwise, a map with the areal fractions of birch trees is fundamental as underlying data set or input. At the European scale, such a map was first compiled by Sofiev et al. (2006) and refined by Sofiev et al. (2013). This general European map is updated for Belgium using Flemish and Walloon forest inventory data on a spatial resolution of 0.1° × 0.1°. At each sampling plot, the diameter at

breast height (DBH) for individual birch (and other) trees were measured. 11,080 plots in the Walloon region and 2,147 plots in the Flemish region were used (observed over the period of 2008–2017 and 2009–2017, respectively). For each plot, the DBH is scaled to basal area (m²) per hectare (Dujardin et al. 2017). In the next step, a 0.1° × 0.1° grid was defined over Belgium that corresponds to the native SILAM grid as illustrated in Fig. 1. The position of the forest inventory plots is shown as dots on the map. For each 0.1° × 0.1° grid cell, the basal area of all the plots in the grid was recomputed (Fig. 1) to a plot representative DBH (m ha⁻¹).

Based on the statistical relationship between DBH and birch tree canopy diameter (Hemery et al. 2005), the scaled areal fraction (percentage) at each grid cell was assessed. The equation from (Hemery et al. 2005) is (Eq. 1):

$$\text{CrD} = 16.1512 \cdot \text{DBH} + 0.97524 \quad (1)$$

with CrD the crown diameter (m), DBH the stem diameter at breast height (m), $R^2 = 0.922$.

Figure 2a shows the original birch areal fraction map (Sofiev et al. 2006). The updated areal fraction map of birch trees for Belgium based on the forest inventory data is given in Fig. 2b. Grid cells without any birch data (i.e. no forest inventory data) were filled in with data taken from the original MACCIII map. Both maps show the locations of the pollen emission sources. The birch pollen levels near the surface are then modelled and compared using both the original as well as the updated birch fraction map.

2.3 Onset and offset

As mentioned before, SILAM is based on the thermal time flowering to model pollen emissions (Sofiev et al. 2013). It is assumed that the timing of birch flowering is driven by accumulated ambient temperature using a cut-off temperature of 3.5 °C and that the birch season starts on March 1 (day 60). From a certain threshold value on, flowering starts. This is the pollen onset threshold. The end of the flowering season, or offset, is defined by a second threshold value (Linkosalo et al. 2010). These thresholds are based on climatology, and the spatial distribution of the temperature sums for the start and end of the pollen season is illustrated in Sofiev et al. (2013). Based on time series of pollen observations collected at different monitoring stations

Fig. 1 Spatial distribution of the summed basal area ($\text{m}^2 \text{ha}^{-1}$) of birch trees over Belgium based on forest inventory data from the Flemish and Walloon regions. The location of the plots is shown as dots in the background. In the grey areas, no forest inventory data are available (mainly agricultural area). The inventory dataset was extrapolated to the $0.1^\circ \times 0.1^\circ$ grid (see colour scale). The map was generated with R package

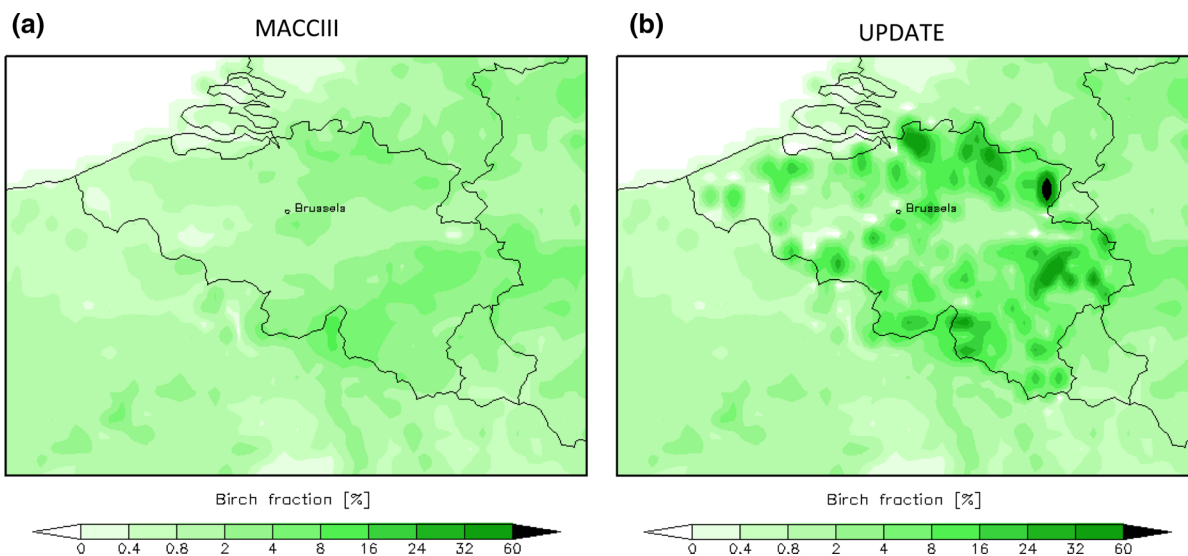
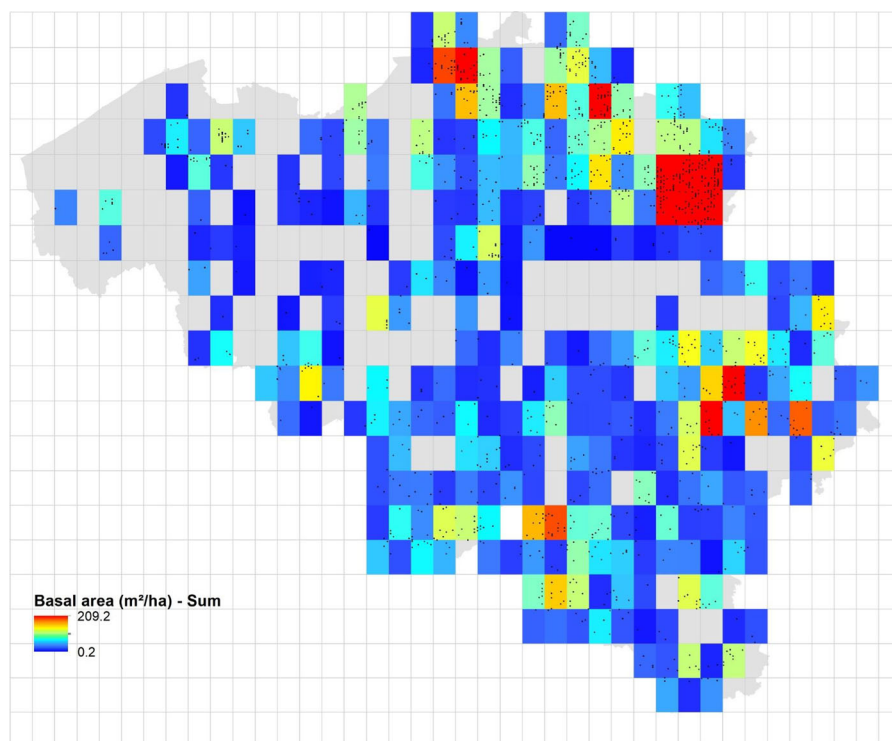


Fig. 2 Spatial distribution of areal fractions (percentage) of birch trees in Belgium. Left panel **a** is the original (MACCIII) birch fraction map from Sofiev et al. (2006). Right panel **b** is the

updated birch tree fraction map using forest inventory data from Fig. 1. The maps were generated in GRADS

of the Belgian aerobiological surveillance network (Bruffaerts et al. 2018, Hoebeke et al. 2018) (see also Sect. 2.5), we altered the start and end thresholds in order to have more similarity with the pollen

observations. The updated onset values are smaller and set to 98 (degree days) for large parts of Belgium in order to have an earlier onset, except for the coastal area (120, later onset), and the birch season length is in

generally extended. The end of the pollen season starts earlier ($\sim 2\text{--}7\%$), as well as the start of the pollen season ($\sim 2\text{--}35\%$). That is why the length of the complete pollen season is extended ($\sim 2\text{--}25\%$).

2.4 Temporal scaling

In order to add inter-seasonal variability of the maximum amount of birch pollen potentially available for release in the SILAM model, we put forward the hypothesis that the annual vegetation activity is correlated with the seasonal pollen index (SPI) or the yearly pollen totals (Galán et al. 2017). Based on a long time series of pollen observations over Brussels (Elsene) by the Belgian aerobiological surveillance network (2002–2016), we first computed the annual pollen anomaly (Fig. 3). We used domestic pollen only. Hence, estimated transported pollen from elsewhere outside the Belgian territory were removed from the observations based on 2008 SILAM simulations of birch pollen for Belgium. By computing the difference between the SILAM simulation scenario where birch trees are presented in Belgium and the scenario without any single birch tree in Belgium, the relative amount of pollen that are transported into the Belgian territory could be assessed. The anomaly was computed by subtracting for each year the long-term mean over the 2002–2016 period. The percentage anomaly was then computed by dividing the obtained results with the long-term mean.

Time series of vegetation activity for the period 2002–2016 were obtained by extracting MODIS 8-Day Gross Primary Productivity (GPP) data (Zhao et al. 2005) for a 60×60 km grid over the region of

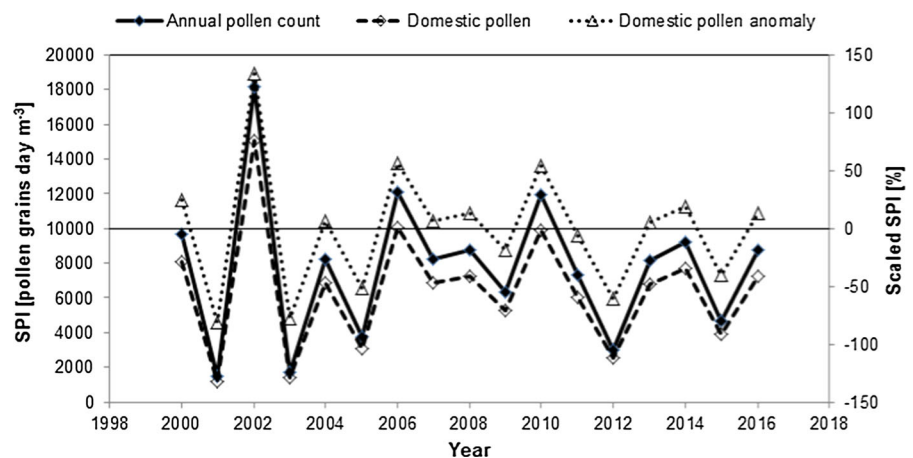
Brussels using R based software MODISstp developed by Busetto and Ranghetti (2016) (Fig. 4). GPP is the uptake of CO_2 from the atmosphere by vegetation through the process of photosynthesis. The Hirst-type sampler used for pollen observations in Brussels (see next section for more details) is considered to be representative for such a large area (circle with at least 30 km radius).

From the MODIS GPP time series, we then computed the time series anomaly as described before. We analysed the correlation (R^2) between the GPP and the domestic pollen anomaly time series for 2002–2016 using different time lags.

2.5 Pollen observations

To date, offline pollen level observations are performed on daily basis at five locations in Belgium using a Hirst-type 7-day volumetric spore sampler (Burkard Manufacturing Co., Rickmansworth, UK), namely in Brussels, Genk, De Haan, Tournai and Marche-en-Famenne (see location in Table 1). Samplers are placed at a height between 10 and 20 m above the ground level. Pollen from birch trees (*Betula* spp.) and other species are morphologically identified and counted by light microscopy (two longitudinal slide lines reading). Mean daily pollen concentration is then calculated and expressed as pollen grains per cubic metre of air (pollen grains m^{-3}). Monitoring complies to the best ability of the methodological guidelines 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

Fig. 3 Time series of the Seasonal Pollen Index (SPI) (pollen grains day m^{-3}) observed in Brussels using a Hirst-type sampler at the roof top of the Sciensano building in Elsenne (left y-axis). The estimated annual domestic pollen grains day m^{-3} (left y-axis), i.e. observations reduced with transported pollen from elsewhere (left y-axis), and the computed anomaly are shown as well (right y-axis)



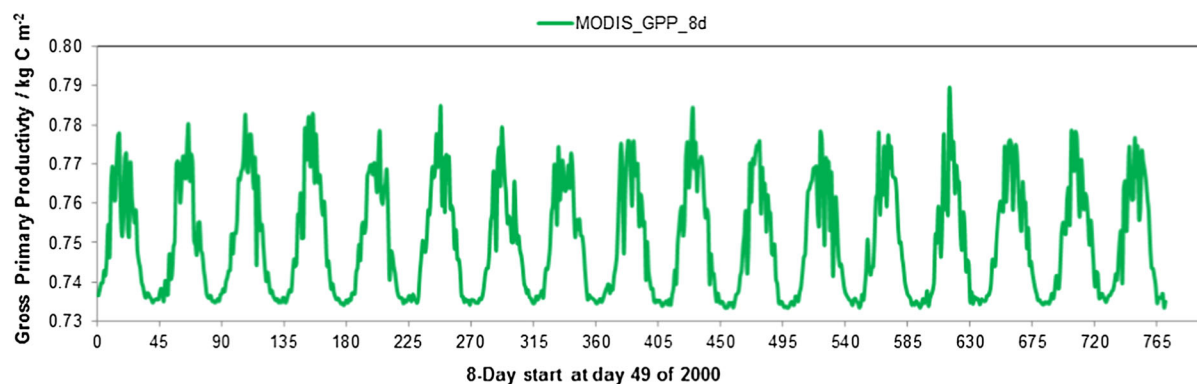


Fig. 4 Time series of MODIS 8-Day Gross Primary productivity (GPP) averaged for a 60×60 km area over Brussels for the period 2000–2016

Table 1 The location of the pollen monitoring stations of the Belgian aerobiological surveillance network and the corresponding observation periods available for this study

Pollen observation locations	Latitude/longitude	Observation period
De Haan	51.274N/3.022E	2008–2018
Tournai	50.614N/3.387E	2013–2018
Brussels	50.825N/4.383E	2008–2018
Antwerp	51.214N/4.393E	2008–2010
Charleroi	50.405N/4.400E	2008
Namur	50.468N/4.865E	2010–2012
Marche-en-Famenne	50.200N/5.312E	2012–2018
Genk	50.965N/5.495E	2011–2018

In total 50 birch pollen seasons were included

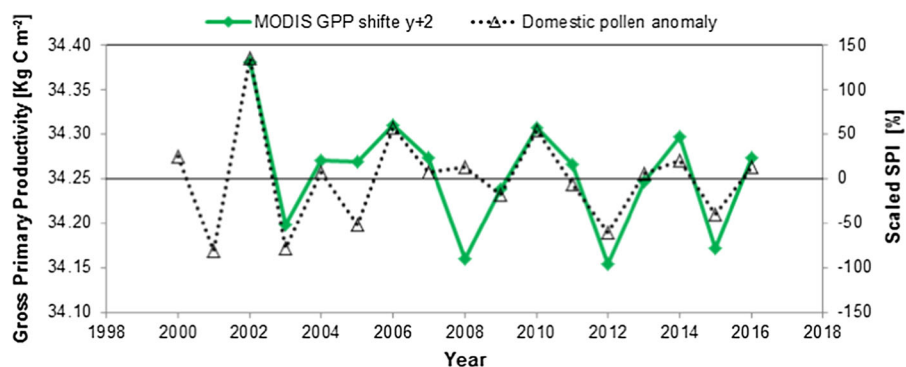
observations collected from current (Brussels, Genk, De Haan, Tournai and Marche-en-Famenne) and past monitoring stations (Antwerp, Charleroi, Namur). In this study, we used observation datasets encompassing 50 birch pollen seasons from eight sites over the period 2008–2018, as shown in Table 1 and illustrated in the map of Belgium (Fig. 5).

3 Results

3.1 Areal birch fraction map

In the original MACCIII areal fraction map of birch trees, very few birch trees are picked up in the Belgian domain (Fig. 2a), although it is a pioneers tree. Many grid cells in the west of Belgium near the coast have

Fig. 5 SPI time series anomaly of domestic pollen grains day m^{-3} in Brussels using a Hirst-type sampler at the roof top of the Sciensano building in Elsene (right y-axis, and Fig. 2) for the period 2000–2016 and the yearly Gross Primary Productivity (GPP) for the same period shifted over 2 years



less than 0.8% coverage with birch trees. The central part is dominated with grid cells of less than 2% birch, in the north and the south most grid cells have between 4 and 8% birch, and at one location near the border with France the birch fraction is more than 8%. Based on the scaled forest inventory data, the updated areal fraction map of birch trees is substantially larger (Fig. 2b), in general with 4–10% and more. Areas with less than 2% birch fractions are still frequent in the centre and the west of the country, but grid cells with 15%, 35%, 50% and even 60% occur more and more. Especially in the north-eastern and southern part of Belgium (with respect to Brussels as assumed centre of the country), higher areal fractions of birch trees occur as can also be derived from the birch DBH sum map in Fig. 1. Much more areas have an areal fraction of birch between 8 and 16%.

3.2 Temporal scaling

The methodology for temporal scaling of inter-seasonal pollen amounts in SILAM is based on the inter-seasonal variation of the SPI (anomaly) observed in Brussels in combination with time series of annual MODIS GPP data. The domestic pollen anomaly illustrates the variability between the years ranging from -100 to 150% over the period 2000–2016 (Fig. 3). When shifting the annual GPP over different years with the domestic pollen anomaly, the R^2 value

is the largest (0.62) with a time lag of two years (Fig. 6). The GPP is then smoothed with the SPI of the current and the two previous years. The obtained smoothed GPP and the observed domestic pollen amounts follow an exponential relation having next general equation (Eq. 2):

$$\text{Pollen}_{p,t+2} = a \cdot \exp^{-b \cdot \text{GPP}_t} \quad (2)$$

with Pollen_p , GPP, t , a , b , respectively, predicted pollen, GPP, year, $a = 94.413$ pollen grains, $b = 0.714$ per GPP, and $R^2 = 0.6143$.

Based on this statistical exponential relationship between annual GPP and the domestic pollen anomaly, the predicted amount of domestic pollen was derived as illustrated in Fig. 7. For example, for 2016, the amount of observed domestic birch pollen is ~ 7290 pollen grains day m^{-3} (for terminology see Galán et al. 2017) and the predicted amount is ~ 7080 pollen grains day m^{-3} , based on the annual GPP of 2014. The predicted annual value for the period 2004–2016 is biased low with ~ 260 pollen grains day m^{-3} .

Using the predicted domestic pollen in Fig. 7, we derived the annual temporal scaling values as illustrated in Fig. 7 as well. These scaling values were used to add inter-seasonal variability in yearly birch pollen. Based on the 2015 and 2016 GPP values, we estimated the domestic pollen of 2017 and 2018. We scaled the 2008–2018 time series of the predicted domestic pollen between zero and one by dividing with the largest value for that period (i.e. 2018).

3.3 Time series

2008–2018 time series of birch pollen levels near the surface at daily basis were extracted from the SILAM output for each pollen monitoring station from Table 1 and compared with observations. In Fig. 8, the time series of the pollen concentration from the SILAM run with updated areal fractions of birch trees are presented as well as the observed pollen concentrations for each station. The corresponding statistics (slope, intercept, R^2 of the SILAM versus observation data) are given in Table 2.

The simulated daily pollen grains m^{-3} near the surface from the scenario with the updated emission source maps compared to the pollen observations have larger slopes closer to one, and in general better R^2

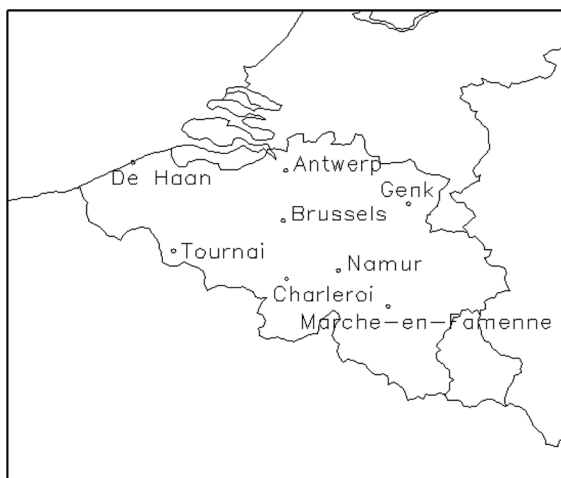


Fig. 6 The geographical location of the pollen monitoring stations of the Belgian aerobiological surveillance network as listed in Table 1

values than the MACCIII model scenario (Table 2 vs. Table 3, Fig. 8 vs. Fig. 9). This indicates that the observed pollen magnitude is generally captured well by SILAM when the birch area fraction maps are updated. Similar results can be found for the 3-day averaged, 5-day averaged pollen concentrations as well as for the 5-day moving average of pollen concentrations. With respect to the pollen monitoring stations, SILAM can reproduce the pollen time series quite well for most stations with longer amount of observations (more than five seasons), except for De Haan at the sea side where the sharp sea–land boundary does not correspond to the geometry of the ECMWF and fraction map size. If 5-day averages of birch pollen concentrations would be used, then reasonable large R^2 values from 0.60 up to 0.88 are obtained. For the location at the coast, the best correspondence between SILAM and observations is obtained using 3-day averages.

Compared to MACCIII input, the R^2 values between the time series of SILAM and the observed ones at the pollen monitoring stations increase in general with 13–47%, except for De Haan, Antwerp and Genk where a slight decrease or status quo is obtained. Similar results are found for the 3-day and 5-day averaged pollen concentrations.

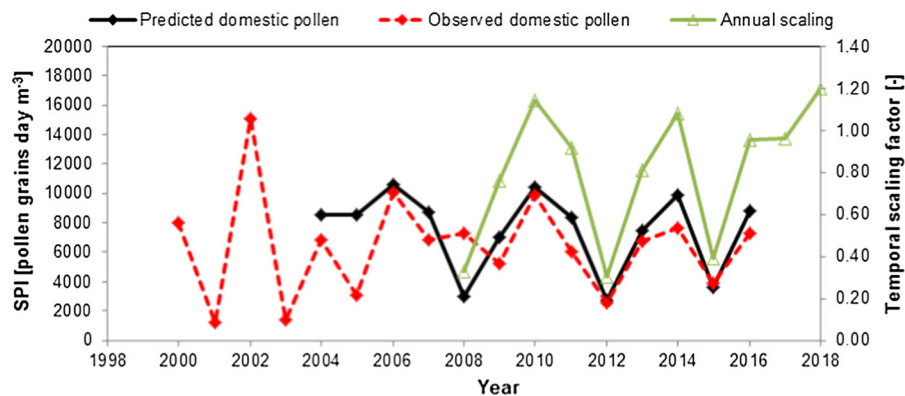
Looking to individual pollen seasons, the best two R^2 values between the time series of the updated SILAM model runs and the observations for Brussels are 0.65 (2014) and 0.81 (2018); for De Haan 0.46 (2016) and 0.45 (2017); for Genk 0.66 (2018) and 0.63 (2012); for Marche-en-Famenne 0.75 (2014) and 0.70 (2018), for Tournai 0.80 (2014) and 0.79 (2017). Generally, strong pollen seasons such as 2014 and 2018 have among the highest R^2 values indicating that

Fig. 8 Time series of observed (red) and SILAM modelled (black) daily airborne pollen concentration (pollen grains m^{-3}) at the surface for the period 2008–2018 in the current five monitoring stations of the Belgian aerobiological surveillance network. SILAM uses the updated emission source map, i.e. areal birch fraction based on the forest inventory data of Flanders and Wallonia

SILAM is able to simulate high pollen levels near the surface in a timely way. Weaker pollen seasons and locations with lower birch pollen levels seem to show lower R^2 values between modelled and observed concentrations.

The ability to detect either less or more than 80 pollen grains m^{-3} (the critical threshold above which the majority of sensitized patients is considered to develop allergy symptoms as used in Belgian aerobiological surveillance network) from the observations and the SILAM model using the updated birch fraction map is shown in Table 4, based on several statistics for dichotomous classification. The overall model accuracy (MA) represents the fraction of correct forecasts. The probability of detection (POD) is the fraction of high forecasts appeared to be correct. False alarms are quantified using the probability of false detection (POFD) which shows the fraction of low-concentration days predicted as high. The odds ratio (OR) shows how much higher are the chances to get the high than low day if the model prediction is high. The MA values of the pollen monitoring station is ~ 0.90 (0.82–0.93) for most stations, and the OR is 9.5 or higher ($9.5-\infty$) indicating that SILAM is able to detect more than 80 pollen grains m^{-3} on days where more than 80 pollen grains m^{-3} are observed. Setting

Fig. 7 SPI time series anomaly of domestic pollen grains m^{-3} observed in Brussels (red) and the predicted SPI of domestic pollen (black) based on the correlation with Gross Primary Productivity (GPP) shifted over 2 years (left y-axis). The derived temporal scaling is given in green (right y-axis)



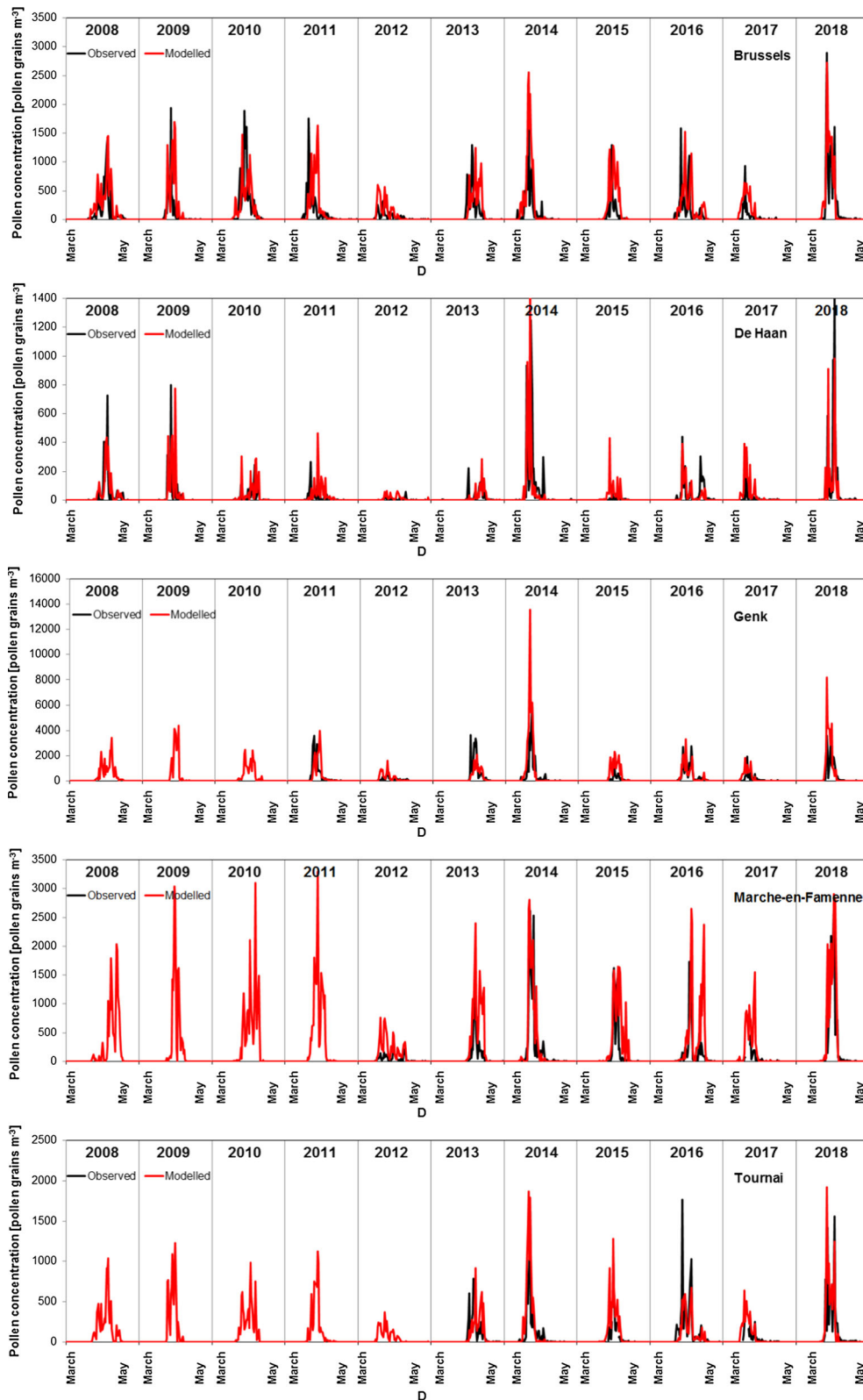


Table 2 Airborne birch pollen concentration simulated with the SILAM model using the updated areal fraction map of birch trees compared to observations collected at eight pollen monitoring stations in Belgium

	De Haan	Tournai	Brussels	Antwerp	Charleroi	Namur	Marche-en-Famenne	Genk
<i>Daily values</i>								
Slope	0.55	0.90	0.80	0.64	0.54	0.36	1.07	1.14
Intercept	14.74	22.88	61.95	114.72	85.91	64.07	77.61	59.55
R^2	0.30	0.57	0.40	0.33	0.29	0.33	0.59	0.49
<i>3-day average</i>								
Slope	0.84	1.10	1.03	0.92	0.69	0.51	1.27	1.41
Intercept	7.83	8.84	41.53	79.62	72.03	0.51	58.01	6.24
R^2	0.76	0.75	0.56	0.56	0.43	0.54	0.75	0.65
<i>5-day average</i>								
Slope	0.74	1.16	1.18	1.18	0.98	0.52	1.20	1.87
Intercept	10.45	2.26	28.99	49.76	52.94	40.85	65.98	12.68
R^2	0.49	0.83	0.63	0.75	0.65	0.58	0.77	0.84
<i>5-day moving average</i>								
Slope	0.83	1.17	1.13	1.07	0.79	0.52	1.24	1.41
Intercept	8.10	4.90	32.71	61.86	64.86	38.75	62.08	6.11
R^2	0.68	0.79	0.65	0.66	0.53	0.61	0.78	0.68

Slope, intercept and the determination coefficient (R^2) between modelled and observed birch pollen concentrations are given. Comparison is made for daily pollen concentration values, 3-day and 5-day average values, and for a 5-day moving average values

Table 3 Same as in Table 2 but the reference MACCIII areal fraction of birch trees is input in SILAM

	De Haan	Tournai	Brussels	Antwerp	Chareloi	Namur	Marche-en-Famenne	Genk
<i>Daily values</i>								
Slope	0.29	0.29	0.35	0.18	0.22	0.14	0.49	0.27
Intercept	10.84	12.07	35.54	33.96	45.00	50.27	65.79	43.46
R^2	0.32	0.50	0.35	0.39	0.18	0.17	0.40	0.49
<i>3-day average</i>								
Slope	0.43	0.37	0.45	0.25	0.30	0.21	0.56	0.34
Intercept	7.47	7.62	26.40	24.58	37.83	0.21	58.62	30.63
R^2	0.65	0.64	0.49	0.66	0.28	0.29	0.51	0.64
<i>5-day average</i>								
Slope	0.42	0.38	0.53	0.32	0.47	0.21	0.54	1.44
Intercept	7.95	6.77	20.49	16.90	26.25	39.58	63.51	0.96
R^2	0.56	0.68	0.57	0.81	0.51	0.31	0.49	0.91
<i>5-day moving average</i>								
Slope	0.44	0.39	0.50	0.29	0.36	0.21	0.57	0.34
Intercept	7.09	7.02	22.51	20.20	33.89	38.61	58.80	30.76
R^2	0.64	0.66	0.58	0.71	0.37	0.32	0.53	0.65

the exceeding threshold to 20 pollen grains m^{-3} results in OR values larger than 5.1. Null pollen levels (1–0 pollen grains m^{-3}), moderate pollen levels (10–100

pollen grains m^{-3}) and high pollen levels (100–1000) can be detected by SILAM with large probability (OR > 2.8, 1.4 and 4.6 for all stations).

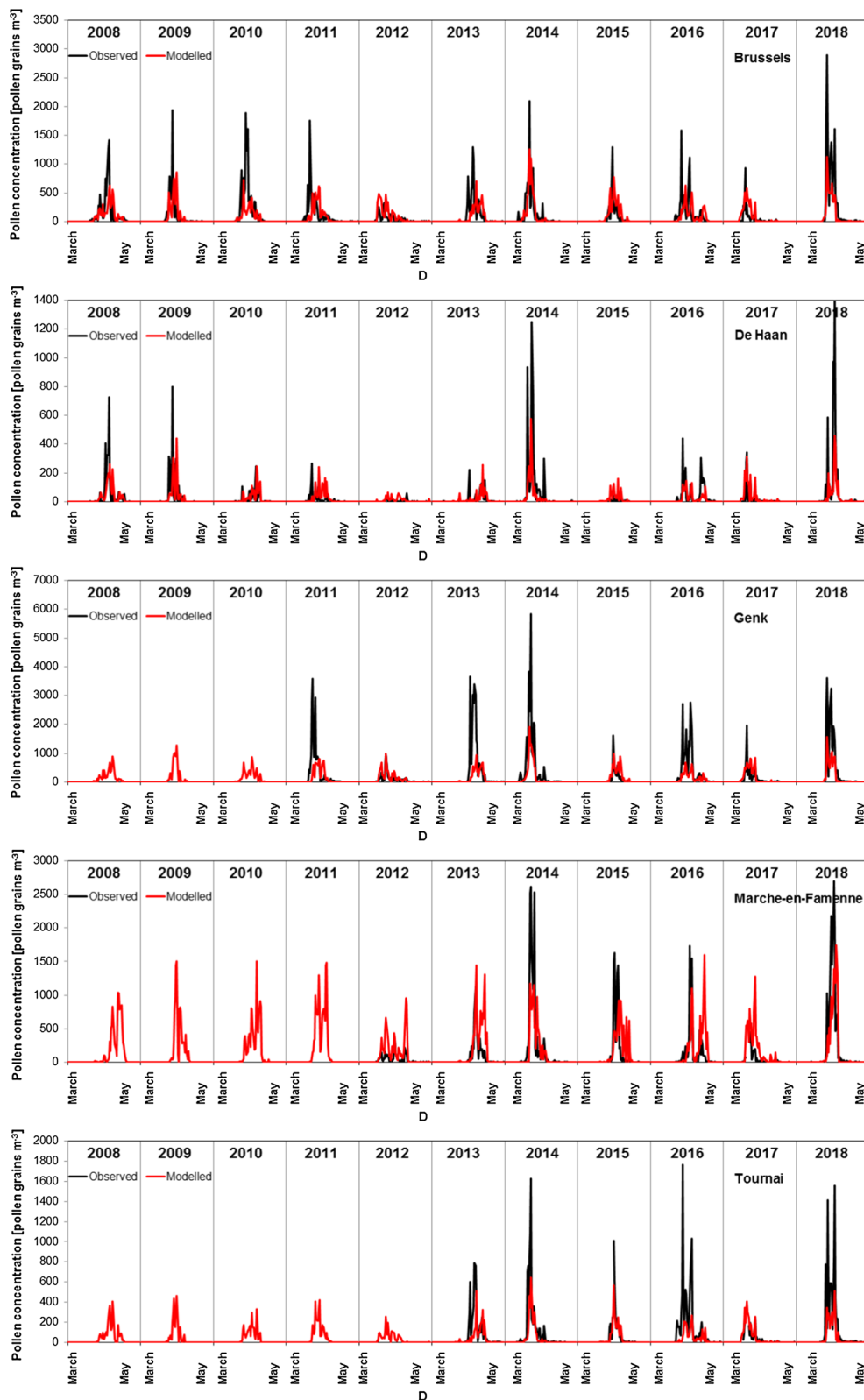


Fig. 9 Same as in Fig. 8, but SILAM simulations are based on MAC3III areal birch fractions

Table 4 Model scores in dichotomous classification

	De Haan	Tournai	Brussels	Antwerp	Charleroi	Namur	Marche- en-Famenne	Genk
MA	0.93	0.92	0.88	0.89	0.82	0.92	0.89	0.90
POD	0.58	0.83	0.83	0.90	1.00	0.86	0.87	0.73
POFD	0.03	0.04	0.04	0.03	0.00	0.04	0.03	0.08
OR	18.73	23.06	20.72	35.82	INF	21.07	31.66	9.48

Probability of exceeding the threshold of 80 birch pollen grains m^{-3} from the observations from the Belgian aerobiological surveillance network and from SILAM simulations using the updated areal fraction map of birch trees

MA model agreement, POD probability of detection, POFD probability of false detection, OR odds ratio

Running SILAM with the MACCIII areal fraction map of birch trees compared to observations show similar abilities to detect less or more than 80 pollen grains m^{-3} at the different stations (MA between 0.87 and 0.93; OR between 11.4 and 34.4). The ability to detect less or more than 80 pollen grains m^{-3} is not substantially different compared with SILAM simulations using the updated birch fraction maps. This could be expected since the original fraction map already provides enough birch pollen emissions sources to detect the threshold of 80 pollen grains m^{-3} .

4 Discussion

The spatial pattern of the updated areal birch fraction map follows the confirmed presence of birch trees as observed by the forest inventory data. The general distribution of birch corresponds to maps for Europe derived by Pauling et al. (2012) based on inverse modelling by using a birch pollen model combined with GLC2000 data (Global Land Cover 2000 database, 2003, European Commission, Joint Research Centre; resolution 1 km) that was weighted by the mean SPI. We used a similar approach as Prank et al. (2013) to adjust the pollen emission map (birch map) with the big advantage that it does not involve any change to model parameter values related to phenology or pollen release. From the forest inventory data, we interpolated birch fractions to a regular grid and we adjusted the map based on the ratio of the observed to the predicted SPI for all observation sites. The resulting map was used as a scaling factor for the initial source map, and the model simulations were repeated several times in an iterative process. To date, the result of the updated areal fraction data of birch

trees for Belgium is the most recent available map. The evaluation of the percentage of birch coverage on every grid cell, however, remains a challenge as updating forest inventories dataset is time-consuming and requires important human and financial resources.

It has been known for a long time 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). Increases in temperature during months preceding the onset of the birch pollen season favour the earlier flower development and pollen dispersal (Yli-Panula et al. 2009). Using the 5% (95%) criterion for the SPI, a typical start (end) of the pollen season is 70 (200) degree days for Riga (Ritenberga et al. 2016) showing large variation between pollen seasons. This is in the same order of magnitude as the values used for Belgium (starting date 98–120 degree days; ending dates 190–220 degree days). Similar start–end thresholds were found in a regional multi-model ensemble simulations of birch pollen (Sofiev et al. 2015a). Remotely sensed data can be used to determine the onset date. The onset might be correlated with the MERIS Terrestrial Chlorophyll Index, a vegetation index derived from spaceborne data, with reported R^2 values of 0.521 and higher (Khwarahma et al. 2017). Pollen season onsets and offsets do not necessarily correspond with start or end of the pollinosis symptoms, since also other factors might play a role (Pfaar et al. 2017).

Substantial correlation (R^2) of 0.62 was obtained between the SPI and the GPP shifted with 2 years as illustrated in Fig. 7. This suggests that vegetation activity of a current season may affect the potential pollen release two seasons later, which ties in with the mast (Clement et al. 2010) seeding mechanisms that

have been observed and modelled for trees (Tanentzap and Monks 2018). Predicting the inter-annual variability of birch pollen abundance was also conducted for Northern and North-eastern Europe by Ritenberga et al. (2018). The combination of meteorological and aerobiological data from the preceding years showed the best correlation (R up to 0.9) and was able to successfully reproduce both the bi-annual cycle of the SPI as well as the years when this cycle breaks down. In the same study, odds ratios were very high at most locations. For Brussels, outside the region of development of the statistical model, a temporal correlation (R) of 0.36 was reported (Ritenberga et al. 2018). Furthermore, the model accuracy for Brussels was larger than 0.65 (Ritenberga et al. 2018). The SILAM model in this study also demonstrated good performance and stability with a model accuracy of 88% or more, with odds ratios of at least 8.9, and the correlation (R^2) of SILAM time series and observations ranged between 0.29 and 0.59 at all pollen monitoring stations in Belgium (Tables 3, 4). This is in agreement with Siljamo et al. (2013) for several stations, with Sofiev et al. (2015a) for multi-model comparison, and Ritenberga et al. (2016) for Riga. Data on vegetation distribution and activity are important for predicting the pollen concentration in the air, but meteorological variability is also very important since it has been shown that 20–40% of the inter-seasonal variation of birch pollen levels could be attributed to weather variations (Sofiev 2016).

5 Conclusion

For Belgium, we have performed a unique study that evaluates birch pollen levels near the surface retrieved from SILAM simulations using updated areal fraction maps of birch trees based on scaled forest inventory data. Multi-site evaluations of the simulated birch pollen concentrations were performed using daily observations at eight pollen monitoring stations corresponding to 50 birch pollen seasons. We have adjusted the onsets and offset of the birch pollen season and introduced a temporal scaling of the potential amount of pollen that can be emitted for each pollen season based on MODIS vegetation photosynthesis data (GPP) of two preceding seasons (time lag of two seasons). Substantial correlation was obtained using the 2 years shift in GPP with the SPI of Brussels.

The odds ratio applied on the SILAM data set and the observations shows that the model is able to capture the probability of exceeding of the 80 pollen grains m^{-3} concentration near the surface. Finally, by introducing the updated map with birch pollen emission sources in Belgium, the correlation between the SILAM and observed time series of the pollen concentrations increases in general up to $\sim 50\%$ and the 5-day averaged pollen concentrations from SILAM have R^2 values between 0.49 and 0.84 at the pollen stations included in this study.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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