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Multi-decade changes in pollen season onset, duration, and intensity: A concern for public health?

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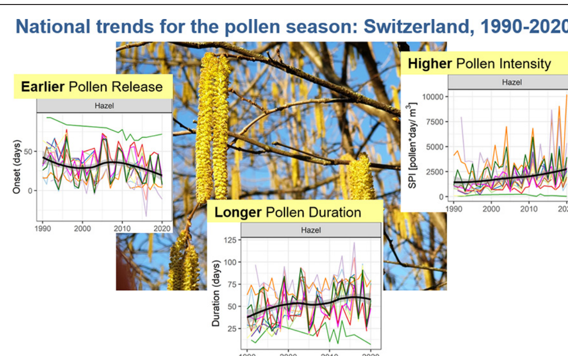
HIGHLIGHTS

- We analyzed 3 decades of Swiss data for 12 plants using 6 pollen season definitions.
- Over 1990–2020, pollen seasons began earlier for hazel, oak, grasses and nettle/hemp.
- Pollen accumulation intensified for hazel, birch, oak, beech and nettle/hemp.
- Pollen season definition impacts magnitude, direction, and significance of trends.
- Climate change is impacting public health through changes in pollen release.

GRAPHICAL ABSTRACT



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ABSTRACT

Longitudinal shifts in pollen onset, duration, and intensity are public health concerns for the growing number of individuals with pollen sensitization. National analyses of long-term pollen changes are influenced by how a plant's main pollen season (MPS) is defined. Prior Swiss studies have inconsistently applied MPS definitions, leading to heterogeneous conclusions regarding the magnitude, directionality, and significance of multi-decade pollen trends. We examined national pollen data in Switzerland between 1990 and 2020, applying six MPS definitions (2 percentage-based and 4 threshold-based) to twelve relevant allergenic plants. We analyzed changes in pollen season using both linear regression and locally estimated scatterplot smoothing (LOESS). For 4 of the 12 plant species, there is unanimity between definitions regarding earlier onset of pollen season ($p < 0.05$), with magnitude of 31-year change dependent on specific MPS definition (hazel: 9–18 days; oak: 5–13 days; grasses: 8–25 days; and nettle/hemp: 6–25 days). There is also consensus ($p < 0.05$) for modified MPS duration among hazel (21–104% longer), nettle/hemp (8–52% longer), and ash (18–38% shorter). Between-definition agreement is highest for MPS intensity analysis, with consensus for significant increases in seasonal pollen quantity ($p < 0.05$) among hazel, birch, oak, beech, and nettle/hemp. The largest relative intensification is noted for hazel (110–146%) and beech (162–237%). LOESS analysis indicates that these multi-decade pollen changes are typically nonlinear. The robustness of MPS definitions is highly dependent on annual pollen accumulation, with definition choice particularly influential for long-term analysis of low-pollen plants such as ragweed. We identify systematic differences between MPS definitions and suggest future aerobiologic studies apply multiple

Abbreviations: APIn, annual pollen integral; DOY, day of year; EAACI, European Academy of Allergy and Clinical Immunology; EAN, European Aeroallergen Network; LOESS, locally estimated scatterplot smoothing; MPS, main pollen season; SPIn, seasonal pollen integral.

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definitions to minimize bias. In summary, national pollen onset, duration, and intensity have shifted for some plants in Switzerland, with MPS definition choice affecting magnitude and significance of these variations. Future public health research can determine whether these temporal and quantitative pollen changes correlate with longitudinal differences in population pollen sensitization.

1. Introduction

Allergic rhinitis affects approximately 2,000,000 individuals living in Switzerland (Ballmer-Weber and Helbing, 2017), with the country's prevalence rate rising dramatically from 0.82% in 1926 to almost 20% in less than a century (Frei and Gassner, 2008b). The prevailing hypothesis is that a combination of environmental changes, including alterations in pollen exposure, underlie this sharp increase (Wang, 2005). Since 1959, Switzerland has experienced an average annual warming of 0.35 °C/decade (Ceppi et al., 2012). Given that climactic factors such as temperature are positively associated with plant growth, readiness for flowering, and pollen abundance (Anderegg et al., 2021; Beggs, 2016; Clot et al., 2012; Dahl et al., 2013; Rojo et al., 2021), this longitudinal change is likely to have transformed the onset, duration, and intensity of pollen release. Pollen is an emerging public health risk; understanding more precisely how seasonal temporality and intensity are evolving has far-reaching implications for health system management, environmental planning, and public awareness.

MeteoSwiss (Switzerland's Federal Office for Meteorology and Climatology) collects aerobiological, weather, and climate information at 14 monitoring stations. Swiss, European, and global studies have drawn upon this data, with inconsistent conclusions regarding the extent to which pollen season parameters have changed (Clot, 2001; Clot, 2003; Emberlin et al., 2002; Frei, 2008; Frei, 2020; Frei and Gassner, 2008a; Frei and Gassner, 2008b; Frei and Leuschner, 2000; Gehrig et al., 2015; Jochner-Oette et al., 2019; Leuschner et al., 2000; Sikoparija et al., 2017; Smith et al., 2014; Ziello et al., 2012; Ziska et al., 2019). One major obstacle when analyzing this literature is the high degree of variability between main pollen season (MPS) definitions. The protocol for delimiting onset and end of MPS logically controls the season duration as well as the seasonal pollen integral (SPIn), a sum of the average daily concentration of pollen during the defined season and a measure of the season intensity (Galán et al., 2017). Therefore, multi-decade pollen trends may differ, depending on the method chosen to define MPS.

Percentage-based definitions mark the start and end of MPS based on percentile limits of the annual pollen integral (APIn), a sum of the average daily pollen concentrations over a one-year period. For previous analyses of Swiss data, percentage-based methods of MPS have included spans from 2.5% to 97.5% (Frei, 2020; Frei and Gassner, 2008a; Frei and Gassner, 2008b; Smith et al., 2014) and 5% to 95% of APIn (Clot, 2003). Alternatively, the European Aeroallergen Network (EAN) has adopted a standardized percentage-based definition with MPS starting at 1% of APIn and concluding at 95% of APIn (Bastl et al., 2018). Threshold-based definitions require the daily pollen concentration to achieve a particular level and aim to capture the time point at which individuals with moderate pollen sensitization begin manifesting clinical symptoms. One noteworthy threshold-based definition proposed in 2017 by the European Academy of Allergy and Clinical Immunology (EAACI) (Pfaar et al., 2017) has been validated using mHealth symptom information from individuals in Germany, Austria, France, and Finland (Karatzas et al., 2018a; Karatzas et al., 2018b; Pfaar et al., 2020).

Two European groups have previously performed short-term comparisons of ten MPS definitions using 3 years of pollen data from Spain and Italy (Jato et al., 2006) and 2 years of data from Austria (Bastl et al., 2015). In both instances, the authors noted significant between-definition disparities. There is uncertainty in Switzerland regarding the extent to which longitudinal pollen analyses may be significantly different, depending upon the MPS definition utilized. Attaining a reliable understanding of pollen shifts is important for national public health and future environmental planning, both in Switzerland and throughout Europe. The goal of this study is to use the most recent 3 decades of pollen data from the Swiss national pollen network and apply six MPS definitions to 12 allergenic plant species. The focus will be on understanding the directionality, magnitude, and significance of change for three measures of MPS [day of year (DOY) of onset, duration, and SPIn] as well as how outcomes differ between definitions. This study represents the first comparative longitudinal analysis of national Swiss pollen data using multiple MPS definitions as well as the first Swiss aerobiological study to utilize the consensus definitions from EAN and EAACI.

2. Methods

2.1. Pollen monitoring

The Federal Office of Meteorology and Climatology MeteoSwiss manages a network of 14 pollen monitoring stations situated at a range of altitudes, climates, and floristic regions within Switzerland (Fig. 1 & Supplement Table S.1). Pollen sampling and analysis follow the minimum requirements of the European Aerobiology Society (Galán et al., 2014) and in former years, adhered to a standardized methodology (Jäger et al., 1995). At each location, a Hirst-type volumetric pollen trap draws air at a rate of 10 l/min. The trap's internal drum rotates at a speed of 2 mm per hour, and pollen grains adhere to a silicon-coated plastic tape. Each week, this tape is removed, divided into 1-day segments, stained, and mounted with glycerine gelatin on a microscope slide. Before 1998–2005, depending on the station, Vaseline was used as adhesive and Gelvatol as mounting medium. The pollen grains of 48 plants species, genera, or families are manually counted along two longitudinal transects, yielding a raw pollen count for each pollen type. Using a conversion factor, which takes into account the volume of air and the percentage of tape segment reviewed, a daily pollen concentration (pollen/m^3) is calculated (Federal Office of Meterology and Climatology MeteoSwiss, 2020). Accurate identification of pollen grains and inter-analyst pollen count reproducibility is enhanced through MeteoSwiss's internal quality assurance protocols and participation in periodic European Aerobiology Society quality control exercises.

The Basel station commenced pollen analysis in 1969 and the remaining stations started operations between 1979 and 1997. The Geneva station began year-round pollen collection from January 1994; the remaining thirteen Swiss pollen stations function on a seasonal basis. The Basel, Bern, Lausanne, Locarno, Luzern, Münsterlingen, Neuchâtel, Visp, and Zürich stations follow similar schedules, with pollen collection beginning in early January and concluding the last day of September. Since 1995 and 2011, respectively, the Lugano and Buchs stations have commenced seasonal monitoring in December in response to earlier pollen release from alder and hazel. Davos and La Chaux-de-Fonds are located at relatively higher elevations and seasonal initiation depends on snowmelt and accessibility, typically in February or early March (Supplement Table S.1).

2.2. Selection of species for study inclusion

MeteoSwiss calculates the average daily pollen concentration for 48 types of trees, grasses, and weeds. Based upon population sensitization rates, potential to provoke allergic rhinitis symptoms, plant geographic distribution within Switzerland, magnitude of APIn, and relevance to

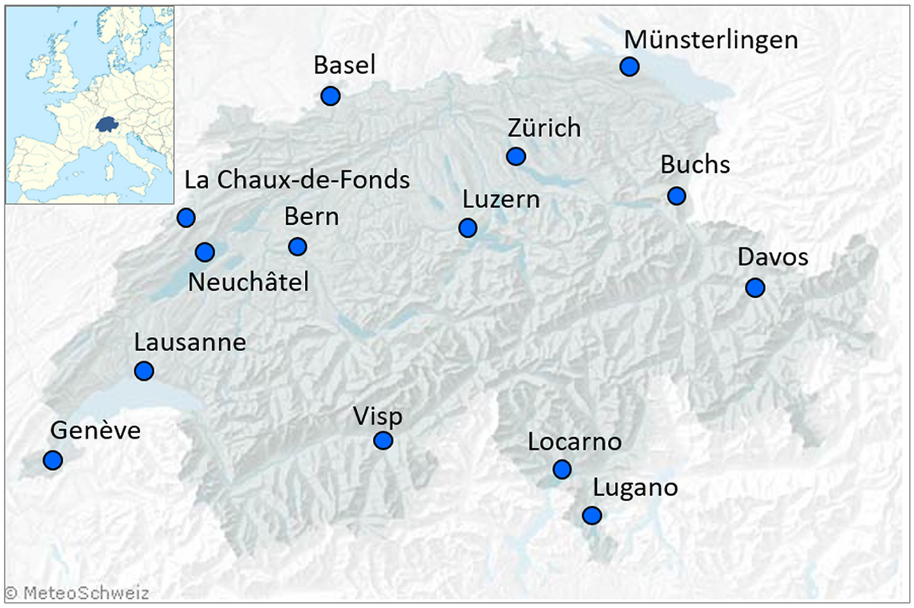

Fig. 1. Geographic distribution of 14 pollen monitoring stations maintained by Federal Office of Climatology and Meterology MeteoSwiss. These stations are situated throughout a range of climactic and vegetation regions and are located at altitudes ranging from 273 m to 1600 m. Graphic used with permission from MeteoSwiss.

historical Swiss pollen studies, we limited this investigation to the 12 most significant plants (Heinzerling et al., 2009; Wüthrich et al., 1995). This list includes: alder, ash, beech, birch, grasses, hazel, hornbeam, mugwort, nettle/hemp families, oak, plantain, and ragweed (Supplement Table S.2).

2.3. Selection of pollen season definitions for application and comparison

We performed a systematic literature review to identify publications that provided MPS definition parameters, studied MPS trends for at least one plant species, and were inclusive of Swiss data (Supplement Table S.3). The review was limited to studies published in English since 1998 and yielded eight unique pollen season definitions. Of these, three were percentage-based and five were threshold-based. To this list, we added two MPS definitions that lack a publication encompassing Swiss data but appear prominently within the wider European literature: the EAN percentage-based definition and EAACI threshold-based definition. We also considered the 2019 AeRobiology R package "moving average" MPS definition which, to our knowledge, has not yet been applied in a European pollen study (Rojo et al., 2019). In consideration of the strengths, weaknesses, clinical correlation, and generalizability of these 11 definitions, we narrowed the present analysis to six pollen season definitions felt to be most relevant to international aerobiologic and clinical research (Table 1).

The EAACI definition (Def6) provides a MPS framework for a limited number of plant species: birch, cypress, grasses, olive, and ragweed (Pfaar et al., 2017). For the nine species in this study lacking an EAACI definition framework, we adopted the birch definition for ash and nettle/hemp; the grasses definition for alder, beech, hazel, hornbeam, and oak; and the ragweed definition for mugwort and plantain (Supplement Table S.2). These assignments were based upon expert opinion in relation to pollen level-clinical symptom associations and comparable APIn and daily pollen concentrations.

2.4. Data analysis

For each of the 12 species, we applied the six MPS definitions to the 31-year period between 1990 and 2020, for which 12 of the 14 pollen monitoring stations (excepting Lausanne with 24 years and Lugano with 30 years) had reliable data available (Supplement Table S.1). The three metrics calculated for every permutation of species-station-year-MPS definition were: DOY when MPS commenced (referred to as

Table 1
List of percentage- and threshold-based main pollen season definitions applied to MeteoSwiss data. Def2 comes from EAN while Def6 originates with EAACI.

MPS Def	Definition type	Pollen season start	Pollen season end
1	Percentage	5% of APIn	95% of APIn (Clot, 2003)
2	Percentage	1% of APIn	95% of APIn (Bastl et al., 2015)
3[a]	Threshold	First day of 11-day period when moving average pollen concentration is ≥5 pollen/m^3	Last day of 11-day period when moving average pollen concentration is ≥5 pollen/m^3 (Rojo et al., 2019)
4	Threshold	First day ≥20 pollen/m^3	Last day ≥20 pollen/m^3 (Gehrig et al., 2015)
5	Threshold	Fourth day of the initial 4 consecutive days of non-zero pollen collection	Fourth day of final 4 consecutive days of non-zero pollen collection (Ziska et al., 2019)
6	Threshold	Birch: 1st day of 5 days with ≥10 pollen/m^3 (out of 7 consecutive days) and sum of 5 days ≥100 pollen/m^3 Grass: 1st day of 5 days with ≥3 pollen/m^3 (out of 7 consecutive days) and sum of 5 days ≥30 pollen/m^3 Ragweed: 1st day of 5 days with ≥3 pollen/m^3 (out of 7 consecutive days) and sum of 5 days ≥30 pollen/m^3	Birch: Last day of 5 days with ≥10 pollen/m^3 (out of 7 consecutive days) and sum of 5 days ≥100 pollen/m^3 Grass: Last day of 5 days with ≥3 pollen/m^3 (out of 7 consecutive days) and sum of 5 days ≥30 pollen/m^3 Ragweed: Last day of 5 days with ≥3 pollen/m^3 (out of 7 consecutive days) and sum of 5 days ≥30 pollen/m^3 (Pfaar et al., 2017)

[a] Def 3 "moving average" definition adapted from 2019 AeRobiology R package in which the end of MPS is marked by the *first* instance when the 11-day average pollen concentration decreases below 5 pollen/m^3. For purposes of this analysis, we defined Def 3 MPS end as the final instance when the 11-day average pollen concentration decreases below this threshold. This difference was impactful in a minority of cases, all characterized by a seasonal interval during which the 11-day moving average pollen concentration decreased below 5 pollen/m3, then returned to ≥5 pollen/m^3.

onset), duration of MPS (days), and SPIn based on the MPS [pollen * day/m^3].

For all species except mugwort and ragweed, we defined the *biological year* as starting on 1 December of the previous year and running until 30 November of the current year. This allows for an undistorted MPS analysis, given that initial pollen release can occur in December for alder and hazel. For mugwort and ragweed, we specified the biological year to begin 1 February of the current year and conclude 31 January of the following year. We calculated the APIn, upon which the two percentage-based MPS definitions are dependent, as the sum of the average daily pollen concentration for each day in the stipulated biological year. If any species-station-year dataset contained a non-zero pollen measurement without other non-zero measurements in the 30 days before or after, we removed this data point prior to analysis due to the likelihood of pollen resuspension. We did not use an algorithm to fill missing data.

2.4.1. Excluded data

We excluded a species-station-year-MPS definition from the analysis if:

1) No pollen measurements were recorded at a station over a full year due to non-operation of the pollen trap (notably, Lausanne 1990–1996 and Lugano 1990);
2) The APIn for a particular species-station-year was equal to zero while the pollen trap was operational;
3) The APIn for a particular species-station-year was non-zero but did not achieve the target threshold for a threshold-based MPS definition (applicable to Def 3—Def 6).
4) Daily pollen concentrations were missing >3 days during the week preceding the demarcated MPS onset (minimizing the risk that the actual onset was missed or erroneously assigned with subsequent impact on duration and SPIn);
5) Daily pollen concentrations were missing >3 days of the week following the demarcated end of the MPS (minimizing the risk that the actual end was missed or erroneously assigned with subsequent impact on duration and SPIn); in these instances, MPS onset was retained in the analysis for Def 3-Def 6 (independent of APIn);
6) Daily pollen concentrations were missing for ≥10% of days during the defined MPS (minimizing the risk of undercalculating SPIn); in these instances, MPS onset and duration were retained in the analysis for Def 3-Def 6.

2.4.2. Statistical analysis

We fit a LOESS curve to display the time-trend for the years 1990–2020 for MPS onset, duration of MPS, and SPIn, not making any assumptions about the shape of the association. In addition, to quantify the significance of any shifts in MPS over the 31-year period, we fit a mixed model for each species, analyzing the trends in the three metrics as functions of time. We allowed for a random intercept and random slope in the linear regression model to account for systematic differences between the 14 stations and how strongly they may have been affected by climate change. Trends were only calculated if there were at least 10 years of data for a species-station-MPS method after all excluded years were accounted for. We calculated the yearly change in each metric and subsequently multiplied these numbers by 31 to report the 1990–2020 trend (and 95% confidence interval) for the six MPS definitions. We report the 14-station median for each MPS outcome per species and method as a summary for the Swiss national trend.

We conducted an analysis of the systematic differences between the methods as a measure of bias for demarcating significantly different MPS onset, duration, and/or intensity. Our decision was to use the 2017 EAACI threshold-based MPS definition as the reference for comparisons since this definition has been validated against clinical allergic rhinitis symptoms (Karatzas et al., 2018a; Pfaar et al., 2020). We performed all analyses in R version 4.0.3, using the lme4 package for the mixed models and ggplot2 to obtain the graphics (R Core Team, 2017).

3. Results

3.1. Ability of each definition to delineate MPS

The application of six MPS methods to twelve plant species at fourteen pollen monitoring stations over 31 biological years resulted in a theoretical 31,248 combinations of species-station-year-MPS definition. Considering the three MPS metrics per permutation (onset, duration, and SPIn), we examined 93,744 potential outcomes. After the exclusion parameters were applied (detailed in Methods Section 2.4.1), 66,881 MPS metrics (71%) were included in the 31-year analysis. 1728 MPS metrics were excluded due to years of non-operation of pollen traps (7 years for Lausanne, 1 year for Lugano.) Considering all 14 stations, Basel had the largest percentage of MPS metrics available for analysis (81%; 5426/6696 over 31 years) while the alpine station of Davos had the smallest percentage (43%; 2894/6696 MPS metrics over 31 years) due to more frequent non-attainment of the target pollen threshold for MPS Def 3, Def4, Def5, and Def6. On a plant species level, MPS metric analysis ranged from a maximum of 97% (7562/7812) for grasses to 23% (1776/7812) for mugwort. The median percentage of analyzable MPS metrics was 82% for all species.

The two percentage-based methods (Def1, Def2) provided a MPS onset, duration, and SPIn for ≥90% of all species-station-year datasets analyzed (Table 2). The functionality of the threshold-based MPS definitions (Def3—Def6) was closely related to the APIn magnitude for individual plant species. For seven species (hazel, alder, ash, birch, oak, grasses, and nettle/hemp families), these four definitions were able to delineate MPS onset, duration, and SPIn comparably well to the percentage-based methods (median ≥ 90%). For hornbeam and beech, the threshold-definitions functioned less well (median 70–89% MPS metric delineation) than the percentage-based Def1 and Def2. For plantain, there was a wide range of definition success (median 48–97%), with Def4 performing poorly compared with the other threshold-based definitions. For mugwort and ragweed, the threshold-based definitions were dramatically less successful at yielding MPS onset, duration, and/or SPIn, generating these metrics for downwards of 4–10% of pollen data, compared with 96–98% for the percentage-based definitions (Table 2).

3.2. Onset (DOY) of MPS

Fig. 2 provides a pictorial representation of the temporal data (onset, duration, end) generated by the six MPS definitions for a single species-station combination. Here we give the example of hazel pollen in Basel, focusing on years 2005, 2010, 2015, and 2020. During some years, there existed a high degree of agreement between the six definitions with regard to seasonal onset, as noted during 2010 in Basel when hazel MPS commenced within a six-day period (17–22 February) across all definitions. In other years, for example 2005, seasonal onset varied markedly between the definitions, with hazel MPS onset occurring >40 days earlier for Def1, Def2, Def4, and Def5 compared with Def3 and Def6 (Fig. 2).

There is unanimous agreement between the definitions for a significantly earlier pollen season onset for hazel (9–18 days), oak (5–13 days), grasses (8–25 days), and nettle/hemp (6–25 days), with the ranges reflecting the differences in Δonset generated by the individual MPS definitions (Table 3 & Fig. 3). For alder, beech, and plantain, there was a trend toward an earlier MPS onset over the past 31 years. There is general agreement for no change in onset of ash, birch, and hornbeam pollen seasons over the past three decades. The compiled national data produced inconsistent results for Δonset for mugwort, and to a lesser extent, ragweed (Table 3 & Fig. 3). Compared with the other plants, relatively fewer species-station-year-definition permutations were included in the Def3–6 MPS onset analyses (16% and 22% of the possible

Table 2
Median (25th -75th percentile) of the percentage of instances for which each definition successfully demarcated the onset (DOY), duration, and SPIn for a particular species. This table is inclusive of combined data from 14 MeteoSwiss pollen monitoring stations over the entire operational period of each individual station. (Supplement Table S.1) Species names listed in chronological order of historical MPS onset, with hazel and alder MPS beginning earliest in the calendar year and mugwort and ragweed MPS occurring latest.

	Species	MPS Def1	MPS Def2	MPS Def3	MPS Def4	MPS Def5	MPS Def6
Onset	Hazel	90 (88-97)	92 (85-96)	94 (87-100)	94 (87-97)	96 (94-99)	92 (87-99)
	Alder	96 (88-97)	96 (87-97)	97 (94-99)	96 (91-99)	96 (91-97)	96 (90-99)
	Ash	97 (94-100)	98 (94-100)	100 (100-100)	100 (100-100)	100 (100-100)	97 (94-100)
	Birch	97 (94-100)	97 (94-100)	100 (100-100)	100 (100-100)	100 (97-100)	100 (97-100)
	Hornbeam	97 (91-100)	98 (91-100)	79 (64-86)	79 (66-83)	87 (78-89)	81 (65-86)
	Oak	98 (97-100)	98 (97-100)	100 (97-100)	100 (98-100)	100 (98-100)	100 (97-100)
	Beech	100 (96-100)	100 (97-100)	73 (67-77)	70 (69-74)	80 (73-86)	74 (70-76)
	Grasses	100 (98-100)	100 (98-100)	100 (100-100)	100 (100-100)	100 (100-100)	100 (100-100)
	Plantain	100 (97-100)	100 (97-100)	79 (69-87)	50 (37-58)	97 (94-100)	90 (81-94)
	Nettle/Hemp	100 (97-100)	100 (98-100)	100 (100-100)	100 (100-100)	100 (100-100)	100 (98-100)
	Mugwort	97 (94-99)	97 (94-99)	4 (3-40)	5 (3-24)	57 (25-78)	10 (0-53)
	Ragweed	98 (96-100)	97 (96-100)	11 (1-49)	21 (4-48)	44 (16-66)	10 (0-32)
Duration	Hazel	90 (88-97)	92 (85-96)	92 (87-100)	92 (85-97)	95 (91-99)	90 (87-99)
	Alder	96 (88-97)	96 (87-97)	96 (91-99)	95 (91-99)	96 (91-97)	95 (90-99)
	Ash	97 (94-100)	97 (94-100)	100 (98-100)	100 (98-100)	100 (100-100)	97 (94-100)
	Birch	97 (94-100)	97 (94-100)	100 (100-100)	100 (98-100)	100 (97-100)	100 (97-100)
	Hornbeam	95 (91-100)	96 (91-100)	79 (64-83)	78 (66-81)	85 (78-87)	80 (65-86)
	Oak	98 (97-100)	98 (97-100)	100 (97-100)	100 (98-100)	100 (97-100)	100 (97-100)
	Beech	98 (96-100)	98 (97-100)	73 (66-77)	70 (69-74)	80 (73-84)	74 (70-76)
	Grasses	100 (98-100)	100 (98-100)	100 (100-100)	100 (100-100)	100 (100-100)	100 (100-100)
	Plantain	100 (97-100)	100 (97-100)	79 (66-87)	50 (37-57)	97 (94-100)	90 (78-94)
	Nettle/Hemp	100 (97-100)	100 (98-100)	100 (100-100)	100 (100-100)	100 (100-100)	100 (98-100)
	Mugwort	96 (93-99)	96 (93-99)	4 (3-36)	5 (3-22)	54 (25-75)	10 (0-49)
	Ragweed	98 (96-100)	97 (96-100)	11 (1-46)	21 (4-48)	44 (16-66)	10 (0-32)
SPIn	Hazel	90 (88-97)	92 (85-96)	90 (87-97)	90 (85-97)	94 (91-97)	90 (85-97)
	Alder	96 (88-97)	96 (87-97)	95 (88-97)	95 (90-97)	95 (87-97)	93 (88-97)
	Ash	97 (94-100)	97 (94-100)	100 (94-100)	100 (97-100)	97 (97-100)	97 (91-100)
	Birch	97 (94-100)	97 (94-100)	98 (97-100)	97 (97-100)	98 (97-100)	97 (94-100)
	Hornbeam	95 (91-100)	96 (91-100)	78 (64-83)	78 (66-81)	84 (78-87)	80 (65-86)
	Oak	98 (97-100)	98 (97-100)	100 (97-100)	97 (96-100)	100 (97-100)	100 (97-100)
	Beech	98 (96-100)	98 (97-100)	72 (66-74)	70 (67-74)	78 (73-84)	74 (70-76)
	Grasses	100 (98-100)	100 (98-100)	100 (97-100)	100 (98-100)	100 (100-100)	100 (100-100)
	Plantain	100 (97-100)	100 (97-100)	79 (63-84)	48 (36-57)	97 (88-100)	90 (78-91)
	Nettle/Hemp	100 (97-100)	100 (98-100)	100 (98-100)	100 (97-100)	100 (97-100)	98 (97-100)
	Mugwort	96 (93-99)	96 (93-99)	4 (3-35)	5 (3-22)	54 (25-75)	8 (0-49)
	Ragweed	98 (96-100)	97 (96-100)	11 (0-40)	21 (4-48)	44 (16-65)	10 (0-32)

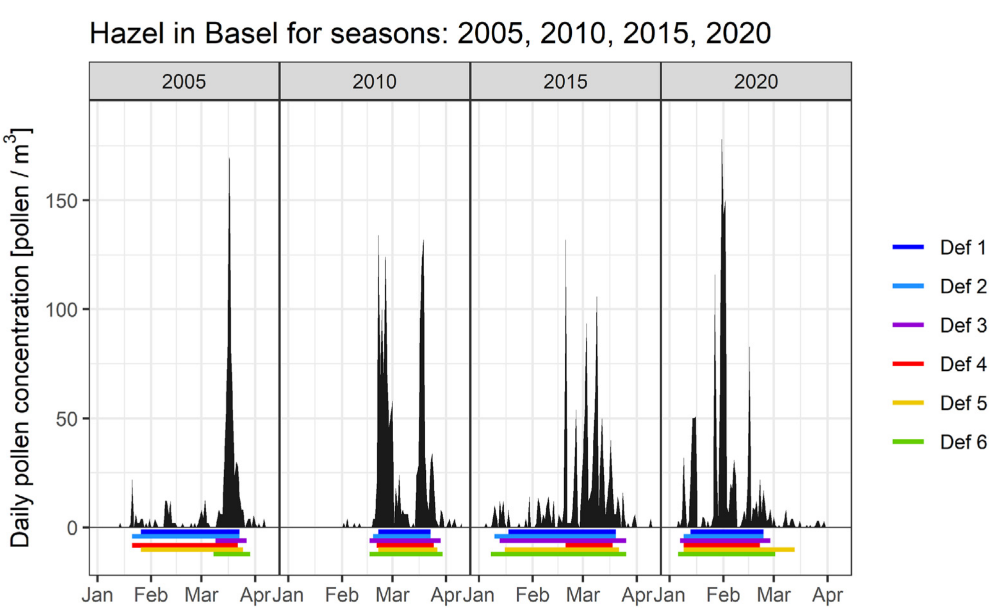

Fig. 2. Comparison between the six MPS definitions for hazel pollen at MeteoSwiss Basel monitoring station (2005, 2010, 2015, and 2020). Upper sections of the figure display daily pollen concentration for the calendar year indicated. Horizontal bars in the lower sections presents onset and duration of the MPS for Def1—Def6 (top-to-bottom).

Table 3
National median (95% confidence interval) change in MPS onset (days), duration (days), and SPIn (pollen*day/m^3) for 12 species between 1990 and 2020. Calculations derived from mixed linear regression model (see Paragraph 2.4.2). DOY indicates the onset of the MPS, with 1 January equivalent to DOY = 1. A negative number for ΔMPS onset indicates an earlier occurrence of pollen in the calendar year, whereas a positive number indicates a later onset in the calendar year. A negative number for Δduration indicates a shortening of the MPS while a positive number indicates a lengthening of the MPS. SPIn indicates the cumulative sum of the average daily pollen concentration during the defined MPS (pollen*day/m^3). A negative number for ΔSPIn indicates a decrease in seasonal pollen integral while a positive number indicates an increase. Species names listed in historical chronological order of MPS onset.

	Species	MPS Def1	MPS Def2	MPS Def3	MPS Def4	MPS Def5	MPS Def6		Current National Median[a]
ΔMPS Onset (days)	Hazel	-9 (-15, -4)	-12 (-18, -7)	-16 (-22, -9)	-13 (-20, -7)	-18 (-25, -11)	-15 (-22, -8)	Median MPS Onset (DOY)	28
	Alder	-10 (-22, 2)	-13 (-23, -4)	-6 (-18, 7)	-4 (-16, 7)	-15 (-27, -3)	-8 (-18, 3)		35
	Ash	1 (-3, 4)	-2 (-6, 1)	6 (2, 9)	6 (-0.1, 12)	0.002 (-6, 6)	3 (-1, 7)		84
	Birch	1 (-2, 4)	1 (-2, 4)	-1 (-4, 3)	0.03 (-4, 4)	-2 (-6, 2)	-1 (-5, 3)		91
	Hornbeam	-1 (-4, 2)	-0.5 (-4, 3)	-3 (-7, 1)	-2 (-6, 2)	-6 (-10, -1)	-5 (-10, 1)		89
	Oak	-6 (-9, -2)	-5 (-9, -2)	-6 (-10, -3)	-7 (-11, -3)	-13 (-16, -9)	-9 (-12, -5)		103
	Beech	-6 (-10, -2)	-2 (-6, 1)	-15 (-20, -9)	-15 (-21, -9)	-14 (-20, -8)	-13 (-19, -8)		105
	Grasses	-8 (-11, -5)	-17 (-20, -14)	-13 (-18, -8)	-9 (-13, -5)	-25 (-29, -20)	-15 (-19, -11)		113
	Plantain	-13 (-18, -7)	-21 (-25, -17)	-13 (-30, 4)	-2 (-23, 18)	-45 (-58, -31)	-20 (-33, -6)		131
	Nettle/Hemp	-6 (-9, -3)	-13 (-18, -9)	-14 (-18, -10)	-13 (-18, -8)	-25 (-31, -20)	-14 (-19, -9)		141
	Mugwort	-7 (-13, -1)	-10 (-18, -2)	25 (7, 43)	37 (2, 72)	4 (-9, 16)	22 (-3, 47)		225
	Ragweed	-3 (-9, 2)	-8 (-14, -3)	-0.1 (-7, 6)	-1 (-10, 8)	-9 (-15, -3)	-6 (-20, 7)		234
ΔMPS Duration (days)	Hazel	10 (4, 15)	13 (7, 19)	22 (15, 30)	20 (13, 28)	29 (22, 36)	24 (16, 31)	Median MPS Duration (days)	57
	Alder	-5 (-23, 13)	-2 (-17, 13)	1 (-23, 25)	-0.4 (-23, 22)	41 (25, 58)	20 (1, 39)		100
	Ash	-10 (-15, -5)	-7 (-12, -2)	-18 (-23, -14)	-19 (-24, -15)	-8 (-13, -3)	-11 (-15, -6)		31
	Birch	-8 (-11, -5)	-9 (-12, -6)	-6 (-12, -1)	-10 (-15, -4)	10 (4, 15)	-6 (-11, -2)		34
	Hornbeam	-5 (-9, -1)	-7 (-11, -3)	2 (-2, 6)	-1 (-7, 5)	9 (4, 15)	4 (0.05, 8)		25
	Oak	1 (-3, 5)	-0.03 (-4, 4)	6 (2, 10)	5 (1, 10)	18 (14, 22)	9 (5, 14)		42
	Beech	-2 (-6, 2)	-6 (-12, -1)	4 (-2, 11)	3 (-2, 9)	13 (7, 20)	5 (-2, 12)		31
	Grasses	5 (-4, 14)	14 (5, 22)	16 (3, 28)	1 (-11, 12)	41 (33, 50)	20 (8, 32)		116
	Plantain	18 (11, 26)	28 (19, 36)	22 (-1, 45)	-1 (-27, 24)	72 (50, 94)	31 (10, 53)		112
	Nettle/Hemp	8 (4, 12)	15 (10, 19)	21 (16, 26)	18 (12, 24)	37 (31, 44)	22 (16, 28)		108
	Mugwort	9 (-1, 19)	9 (-15, 32)	-37 (-66, -8)	-18 (-35, -2)	-5 (-27, 17)	-40 (-74, -6)		27
	Ragweed	4 (-2, 10)	4 (-3, 12)	-3 (-15, 9)	-9 (-21, 2)	21 (12, 29)	4 (-10, 18)		25
ΔSPIn (pollen*day/m^3)	Hazel	1309 (791, 1828)	1351 (806, 1897)	1452 (880, 2024)	1441 (874, 2009)	1484 (911, 2057)	1452 (874, 2030)	Median SPIn (pollen*day/m^3)	2498
	Alder	249 (-588, 1087)	251 (-618, 1120)	248 (-688, 1184)	231 (-716, 1177)	346 (-585, 1276)	291 (-648, 1229)		2368
	Ash	813 (-194, 1821)	848 (-193, 1889)	923 (-195, 2042)	905 (-213, 2023)	998 (-117, 2112)	984 (-138, 2106)		4830
	Birch	3055 (1040, 5070)	3113 (1051, 5175)	3311 (1111, 5511)	3293 (1089, 5496)	3387 (1187, 5587)	3296 (1086, 5506)		8377
	Hornbeam	290 (-11, 590)	297 (-15, 608)	315 (-20, 650)	284 (-51, 619)	378 (46, 711)	329 (-6, 664)		827
	Oak	1332 (768, 1897)	1363 (781, 1946)	1449 (828, 2070)	1429 (807, 2051)	1514 (883, 2146)	1455 (836, 2075)		3361
	Beech	1510 (857, 2162)	1546 (874, 2217)	1654 (934, 2374)	1648 (927, 2369)	1718 (1012, 2423)	1656 (937, 2375)		2444
	Grasses	775 (-521, 2072)	807 (-539, 2154)	829 (-613, 2271)	731 (-710, 2171)	922 (-528, 2372)	835 (-609, 2279)		5128
	Plantain	183 (13, 353)	193 (16, 370)	160 (-58, 379)	-36 (-261, 190)	314 (119, 509)	208 (-6, 421)		596
	Nettle/Hemp	1626 (1031, 2220)	1693 (1074, 2312)	1805 (1146, 2464)	1777 (1117, 2436)	1858 (1201, 2516)	1812 (1144, 2480)		4855
	Mugwort	-436 (-842, -30)	-470 (-900, -40)	-513 (-989, -37)	-386 (-791, 20)	-392 (-822, 39)	-534 (-1011, -56)		75
	Ragweed	-142 (-410, 125)	-149 (-429, 131)	-172 (-487, 144)	-219 (-525, 87)	62 (-148, 272)	-140 (-482, 203)		196

[a] Current national situation numbers represent the derived median of the 2020 MPS metrics generated from the 6 MPS definitions, making use of the mixed linear regression model. Each of these derived values takes into account data from 14 Swiss monitoring stations.

1736 combinations for mugwort and ragweed, respectively.) This was primarily due to years with low APIn when the definition-specified pollen concentration threshold was not attained. For the percentage-based definitions, 91% (mugwort) and 86% (ragweed) of the possible 868 species-station-year-definition permutations were included in the MPS onset analysis. Considering only the percentage-based Def1 and Def2, the mugwort pollen onset has moved forward in the calendar year by 7–10 days ($p < 0.05$ for Def1 and Def2) and the ragweed pollen onset has shifted 3–8 days earlier ($p < 0.05$ only for Def2) (Table 3).

The LOESS curves provide Δonset trend lines for the individual stations at a species level (Fig. 4 & Supplement Figs. S.4.A—L). The LOESS curves for grasses and alder are mainly linear for all six MPS definitions over the 31 years of analysis. The remaining species generated other patterns, with the slope and/or directionality of the LOESS curves inconsistent across the time range or between definitions. There were not substantial differences between the general results of the linear regression and LOESS.

3.3. Duration of MPS

There is less agreement between the six definitions as to the directionality and magnitude of 31-year change in MPS duration compared with the other outcomes (Table 3 & Fig. 3). For hazel and nettle/hemp families, the between-definition consensus is that MPS duration has significantly increased, by 10–29 days (21–104% longer) and 8–37 days (8–52% longer), respectively. For oak, grasses, and plantain, there exists a trend toward a longer MPS duration, with statistical significance achieved for 4 of the 6 MPS definitions for each plant. There is unanimity for a significant reduction in national ash MPS duration (18–38% shorter) over the past three decades. For birch, five of the six MPS definitions noted a significantly shorter national MPS duration (↓15–22%, excepting Def5). There were some between-definition inconsistencies in 31-year Δduration, particularly evident for beech and hornbeam. For both plants, the individual definitions supplied results encompassing significantly shorter duration, no statistical difference, and significantly

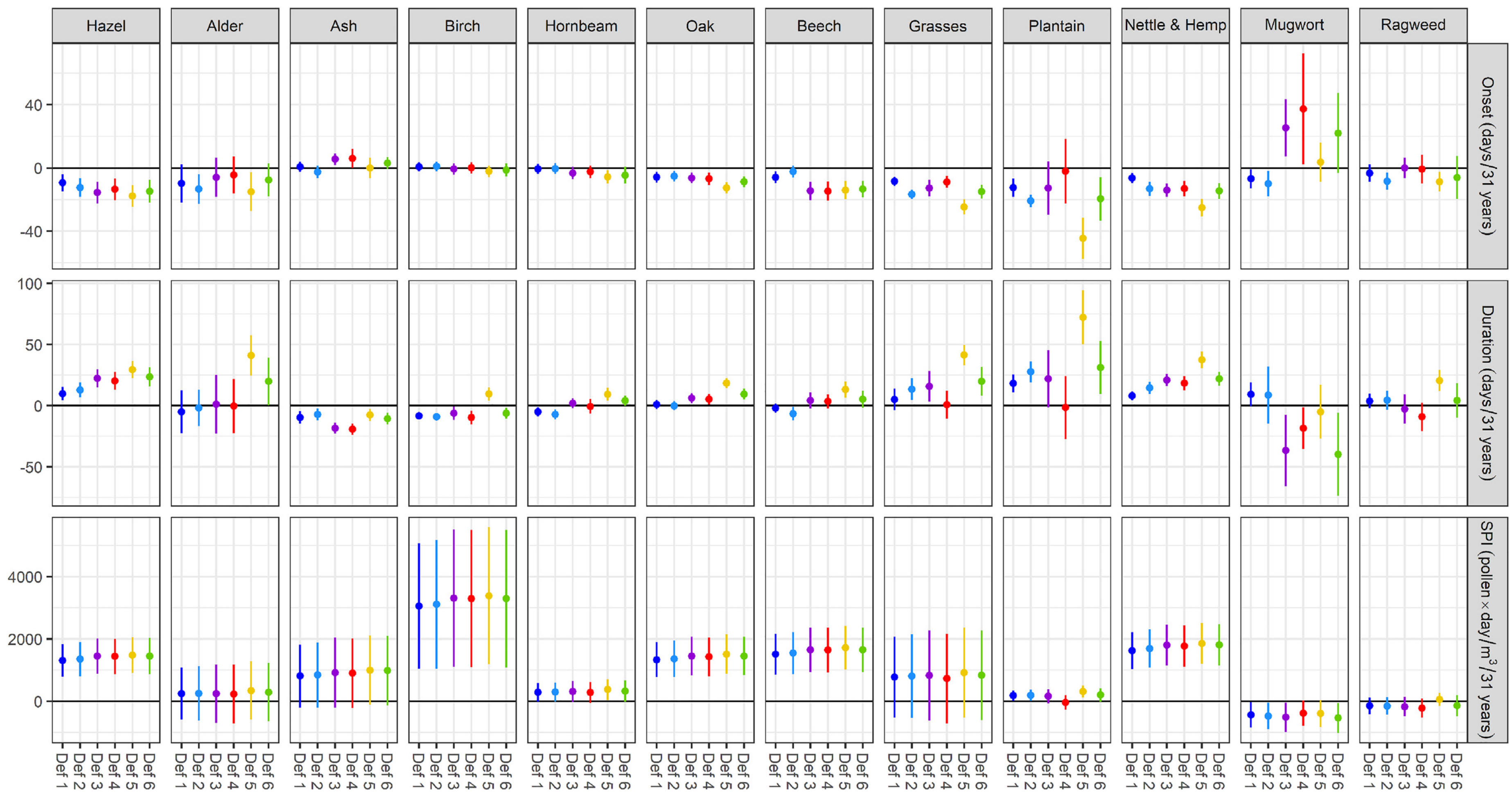

Fig. 3. Per-year change for MPS onset (number of days), MPS duration (number of days), and SPIn (pollen*day/m^3) for each of the 12 species. Calculations represent national averages, considering data from all 14 Swiss pollen monitoring sites between 1990 and 2020. Vertical lines demarcate the upper and lower confidence intervals (95% range). Species have been listed from left to right based on historical commencement of MPS (earliest for hazel and alder and latest for mugwort and ragweed).

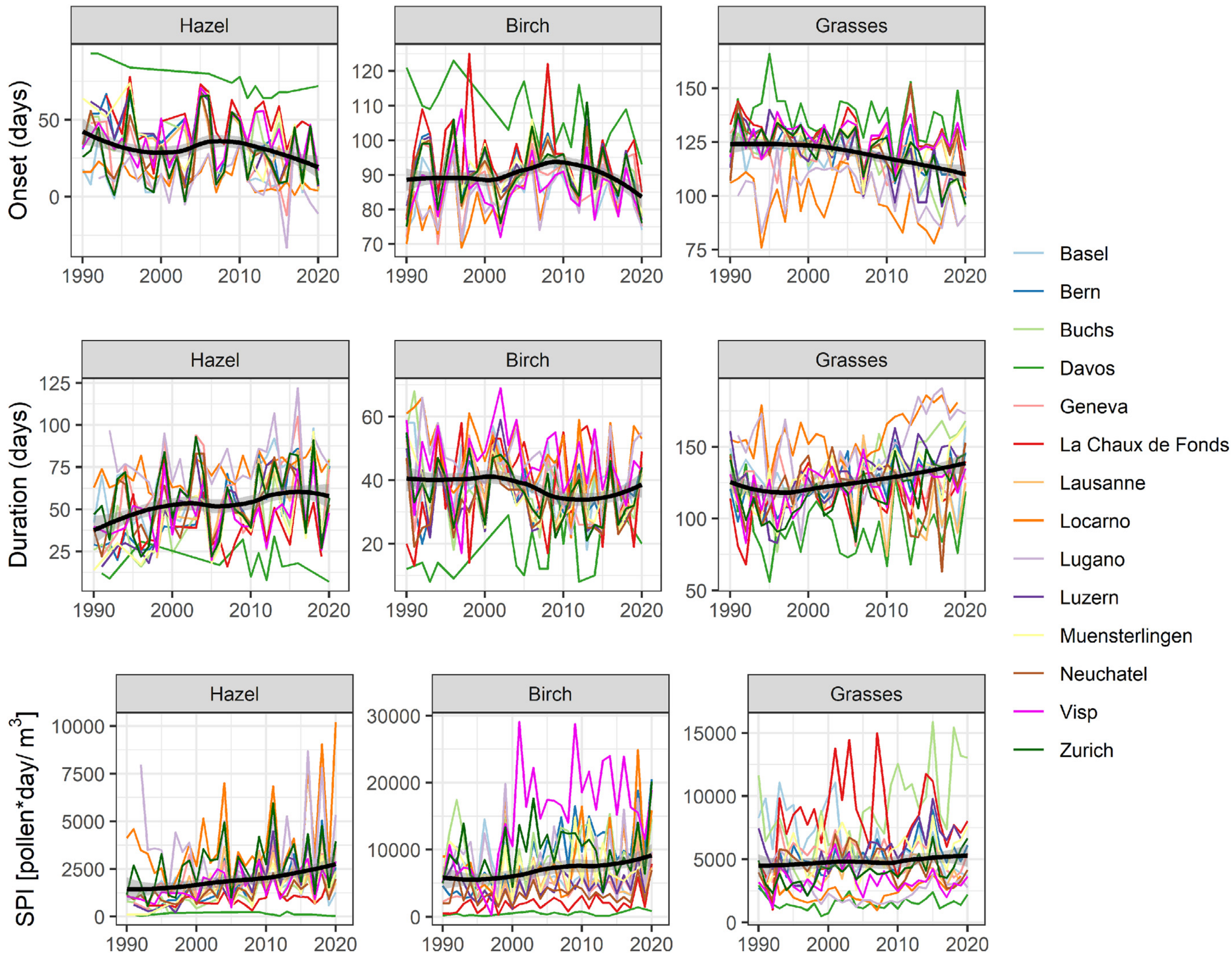

Fig. 4. Changes in MPS onset, duration, and SPIn for hazel, birch, and grasses using LOESS and Def6 (EAACI threshold-based definition) inclusive of data from 1990 to 2020. Black curves represent the national long-term trend in each MPS metric while colored lines represent the yearly station-level data from the individual 14 Swiss pollen monitoring stations. Segmental absence of colored lines indicative of years when data was unavailable or excluded (see Methods section). Shaded areas above and below the black splines indicate the 95% confidence interval of the national trend.

longer duration. Def5 most often produced an outlying result relative to the other definitions.

The LOESS curves show the changes in national MPS duration to be typically non-linear over the three decades (Fig. 4 & Supplement Fig. S.5.A–L). Notably, the change in nettle/hemp duration has relatively plateaued since 2010. For ash, the decrease in national MPS duration appears to have started between 2000 and 2010.

3.4. Intensity of MPS (SPIn)

The outcomes for 31-year national change in SPIn were highly consistent between definitions (Table 3 & Fig. 3). The total pollen released during the defined season has significantly increased for hazel, birch, oak, beech, and nettle/hemp families across all definitions. The largest absolute increase is noted for birch (↑3055–3387 pollen*day/m^3/31 years), while the largest relative increases are noted for hazel (110–146%) and beech (162–237%). Alder, ash, hornbeam, grasses, and plantain demonstrate a non-significant trend toward increasing SPIn. There has been no appreciable change in pollen intensity for ragweed, while mugwort SPIn has generally decreased over the past three decades ($p < 0.05$ for Def1, 2, 3, and 6).

The LOESS curves for SPIn generally yielded similar findings as the linear regression results, excepting nettle/hemp families, mugwort, and ragweed (Fig. 4 & Supplement Fig. S.6.A–L). For nettle/hemp, the national median SPIn increased by a range of 1626–1858 pollen*day/m^3/31yr, however this 50–62% relative increase over the past 31 years is not visually represented by the cosine-shaped spline from the LOESS curves (Supplement Fig. S.6.J). For mugwort and ragweed, there were large proportions of non-analyzed species-station-year-definition permutations due to non-attainment of Def3–6 pollen thresholds (Table 2). Considering only the more complete data analyzed by Def1 and Def2, the mugwort and ragweed LOESS curve results approximated the linear regression results (Supplement Fig. S.6.K & L).

3.5. Systematic differences between the MPS definitions

We used Def6 (2017 EAACI threshold-based MPS definition) as the reference for an analysis of the systematic differences between definitions. Across all species and stations, Def2 and Def3 generally yielded pollen seasons with significantly earlier onset, 8 days and 2 days, respectively, while Def4 MPS onset was demarcated 3 days later (Table 4). The number of days difference in MPS onset relative to Def6 is

Table 4
Systematic differences (95% confidence interval) in MPS onset, duration, and SPIn, with Def6 (2017 EAACI threshold-based main pollen season definition) used as the reference definition (defined as having no bias).

	Def1	Def2	Def3	Def4	Def5	Def6 (reference)
Onset (days)	0.5 (−0.1, 1.2)	−7.6 (−8.3, −6.9)	−1.5 (−2.2, −0.8)	3.0 (2.3, 3.7)	−0.2 (−0.9, 0.5)	0
Duration (days)	−3.9 (−5.0, −2.9)	4.2 (3.1, 5.2)	2.7 (1.6, 3.8)	−8.1 (−9.3, −7.0)	5.5 (4.4, 6.6)	0
SPIn (pollen*day/m^3)	−218 (−316, −119)	−136 (−235, −38)	7 (−96, 109)	−48 (−152, 56)	−53 (−154, 47)	0

For onset, a negative value denotes a bias toward delineation of an earlier MPS relative to Def6; a positive value denotes a bias toward a later MPS onset. For duration, a negative value denotes a bias toward a shorter MPS relative to Def6; a positive value denotes a bias toward a longer MPS duration. For SPIn, a negative value denotes a bias toward a less intense MPS relative to Def6. All calculations corrected for station, location and species.

noted to be more pronounced for the percentage-based definitions (Def1 & Def2) in years with especially low APIn (Supplement Fig. S.7.A—E). There are also notable vulnerabilities for MPS onset of plantain and nettle/hemp families across all pollen season definitions when compared to Def6 (Supplement Fig. S.7.A—E).

Bias in MPS duration was more widespread among the definitions, with Def1 and Def4 consistently yielding significantly shorter pollen seasons (↓4–8 days), while Def 2, Def3, and Def5 yielded longer pollen seasons (↑3–6 days). For SPIn, only the percentage-based MPS definitions (Def1 and Def2) were systematically different from Def6, with both measuring SPIn comparatively lower.

4. Discussion

Pollen sensitivity causes health effects in a large percentage of the population, and accurately understanding longitudinal changes in the timeframe of pollen release and the intensity of pollen exposure is a matter of public health importance. We analyzed 31 years of national pollen data collected by MeteoSwiss (1990–2020) using six MPS definitions, calculating and contrasting nationwide changes in pollen season onset, duration, and intensity. In doing so, we overcame three challenges which previous Swiss analyses faced: (1) uncertainty as to the extent that national trends mirror local pollen season changes; (2) analysis of sufficient plant species, particularly those relevant to health; and (3) inconsistent application of MPS definitions, leading to highly variable conclusions regarding long-term trends (Clot, 2001; Clot, 2003; Frei, 1998; Frei, 2008; Frei and Gassner, 2008a; Frei and Gassner, 2008b; Frei and Leuschner, 2000; Gehrig et al., 2015; Leuschner et al., 2000; Smith et al., 2014; Ziello et al., 2012). This study represents an important effort to analyze national pollen data from multiple decades and over the full geographic range, with consequential lessons learned about how longitudinal results are affected by choice of pollen season definition.

4.1. MPS definition functionality

We are unable to universally recommend either a percentage- or threshold-based MPS definition for longitudinal pollen trend investigation. Our results demonstrate that for hazel, alder, ash, birch, oak, grasses, and nettle/hemp families, no single MPS definition is superior with regard to successfully delimiting a pollen season. For hornbeam, beech, and plantain, Def1 and Def2 more often define the MPS, suggesting that a percentage-based definition may be preferable for studying long-term trends of these species. For mugwort and ragweed, all threshold-based definitions performed poorly due to low annual pollen accumulation at most stations. We propose that in Switzerland and other countries with relatively low mugwort/ragweed APIn, a percentage-based MPS definition be utilized for longitudinal study of these weeds.

The 2017 EAACI MPS definition (Def6) was developed for use in allergic rhinitis immunotherapy trials but has gained popularity in the aerobiologic research community, especially given recent validation against patient symptoms (Karatzas et al., 2018a; Pfaar et al., 2017; Pfaar et al., 2020). One limitation to this definition is that MPS criteria are specified only for birch, cypress, grasses, olive, and ragweed. At least one other study has modified the EAACI parameters for application to other species, using the birch MPS threshold for hazel and alder and the ragweed threshold for mugwort (Bastl et al., 2018). In this study, we applied the birch threshold to ash and nettle/hemp families, the grasses threshold to alder, beech, hazel, hornbeam, and oak, and the ragweed threshold to mugwort and plantain. Given that median rates of successful MPS demarcation for Def6 fell within the species-specific ranges established by the other three threshold-based definitions, our expansion of the EAACI definition may be similarly considered in future pollen studies.

The lack of a “gold standard” MPS definition allows for highly variable longitudinal trend results, confirming the findings from three prior side-by-side comparisons of MPS definitions which examined brief time periods (1–3 years) and a limited number of species (Bastl et al., 2018; Bastl et al., 2015; Jato et al., 2006). Bastl et al. suggested that two percentage-based MPS definitions (Def1 and Def2 in our analysis) were better correlated with patient symptom load (Bastl et al., 2015). European aerobiology societies have purposely deferred endorsement, as project outcome measures require flexibility in MPS definition choice (Galán et al., 2017).

Percentage-based methods capturing the pollen season tails may be advantageous for demarcating the main flowering period botanically; we show these definitions can also be beneficial for species with typically low APIn, such as ragweed. However, the MPS must be defined retrospectively. Percentage definitions have the further disadvantage in that their reliance on APIn, which fluctuates strongly from year-to-year, can exaggerate between-definition differences in MPS parameters. We observed that bias of MPS onset for Def1 and Def2 relative to Def6 (reference EAACI definition) was dependent on APIn, i.e. was negative with low APIn and positive with high APIn, especially notable for plantain, grass, and nettle/hemp families (Supplement Fig. S.7.A—B). For investigations of long-term trends of APIn, the percentage definitions are therefore biased and do not give an independent measure of onset and duration.

Threshold-based definitions allow for prospective delineation of MPS onset, and for studies which focus on the period when moderately-sensitive individuals with allergic rhinitis will show clinical symptoms, these methods can be more practical (Bastl et al., 2018). One drawback is that, in years when the pollen threshold is not surpassed, a MPS cannot be defined, which we noted as an influential limitation for particular plants (i.e. mugwort, ragweed) and at certain stations (i.e. Davos). All MPS definitions are vulnerable to missing data.

4.2. Onset of MPS

This study substantiates that MPS onset for hazel, oak, grasses, and nettle/hemp families has shifted to earlier in the calendar year over the past 31 years. Notably, the between-definition differences in Δonset were sizable, with the largest being 2-4× higher than the smallest difference for each of these species (Table 3). The definitions are inherently biased toward delimiting MPS start earlier or later relative to each other (Table 4). To this point, caution should be taken in future aerobiology studies to note that the magnitude of change in MPS onset is highly influenced by the definition chosen by investigators.

One unexpected finding is that median national MPS onset for birch remains unchanged since 1990. This contrasts with previous Swiss publications, which have noted an earlier birch season start at particular localities. Clot (2001) analyzed the birch MPS in Neuchâtel between 1980 and 1997, using a threshold-based MPS definition. This study reported birch MPS onset occurring 19 days earlier over the 18-year period 1980–1997 (Clot, 2001). In a 2003 publication, Clot reviewed 21 years of pollen data at Neuchâtel, this time utilizing a percentage-based MPS definition; in this report, birch MPS onset moved 17 days earlier for 1979–1999 (Clot, 2003). Frei (2008) examined 38 years (1969–2006) of birch pollen data from Basel using a different percentage-based MPS definition and found that MPS onset was occurring 15 days earlier (Frei and Gassner, 2008a). These historical findings, compared with our results, highlight the role that choice of MPS definition has on the directionality, magnitude, and significance of longitudinal changes in MPS onset. It also confirms that local station changes in MPS onset cannot be accepted as proxy for what is happening nationally.

A very important prerequisite for magnitude and sign of the trend is the duration and timing of the studied period. Near-surface air temperatures in Switzerland exhibit large interannual to decadal variability (Croci-Maspoli et al., 2018). Although the yearly mean temperature increased in Switzerland by 1.1 °C during the last three decades, the single months show different trends, many of them not significant (Supplement Table S.8.1). The start of the birch pollen season depends mostly on temperatures from January to March (Clot, 2001; Pauling et al., 2014). During the relevant period of our pollen data analysis, the January to March mean temperature did not increase in Switzerland, in contrast to the timeframes of the above mentioned studies, in which a clear trend toward higher January to March mean temperatures was found. Ash and hornbeam likewise depend on the pre-season temperature of a similar calendar period, which may offer explanation for the stagnation or even delay in MPS onset noted for these plants over the past 31 years (Table 3 & Fig. 3).

Plant readiness to flower, flower opening, and pollen release are multifactorial processes, driven by a combination of light, day length, winter chilling, minimum temperature, accumulated temperature, humidity, and resource accumulation (Dahl et al., 2013). Online supplement Tables S.8.1—3 give an overview of trends of temperature, precipitation, and sunshine duration in Switzerland for 1990–2020. Increasing temperature during the pre-season period is the main driver for advancement of spring and early summer flowering plants, with plant-specific reactions to the changes (Menzel et al., 2020; Parmesan, 2007; Rojo et al., 2021). A recent North American study, evaluating continental pollen trends between 1990 and 2018, found that temperature was the strongest predictor of pollen season onset and explained 14–37% of the multi-decade variance (Anderegg et al., 2021). There are still many open questions in phenology modelling of the start of flowering, especially the influence of chilling and photoperiod and to how plants will react to increasing temperatures in the future (Basler, 2016; Fu et al., 2015; Güsewell et al., 2017). Given the profiles of the 31-year LOESS curves and in consideration of physiologic boundaries, it seems unlikely that MPS onset can transform boundlessly in relation to projected rising temperatures. Until today, winters in Switzerland are still cold enough, and a lack of chilling does not seem yet to play a role in the onset date of MPS and in spring plan phenology (Güsewell et al., 2017; Pauling et al., 2014).

4.3. Duration of MPS

A major endpoint for this study was quantifying the multi-decade change in MPS duration for the twelve species investigated. Only hazel, nettle/hemp, and ash exhibited a definitive change in national MPS duration, as evidenced by significant differences across all definitions. It is understood that MPS duration is influenced by temperature and water availability during the pollen season, [e.g. for grass pollen (García-Mozo et al., 2010; Gehrig, 2006) and for birch pollen (Grewling et al., 2012)], and thus climatic factors may be driving these changes (Dahl et al., 2013). Plant physiological processes such as duration of the reproductive cycle (Bock et al., 2014) or land management, for instance frequency of grass mowing in agriculture, may additionally play a role in MPS duration (Clot et al., 2012). Why some plant species are impacted differently than others is not yet well understood. A highly specific influence on ash MPS duration and intensity is a plant disease caused by the fungus *Hymenoscyphus fraxineus* and which is present in Switzerland since 2008 (Queloz et al., 2017). This dieback of the ash trees has caused a new pattern of pollen release with years of very low ash pollen production and therefore very short pollen seasons, alternating with high production years.

Even when there was inter-definition agreement for a significant change in national median MPS duration, the magnitude of the 31-year change was inconsistent between definitions. For instance, national hazel MPS duration may have increased by 10 days on the lower end and 29 days on the upper end. These differences are not trivial, strengthening the idea that directly comparing longitudinal results when authors use different MPS definitions is ill-advised. We also noted important outcome differences in 31-year Δduration with regard to Def5 (fourth day of the initial 4 consecutive days of non-zero pollen collection) (Ziska et al., 2019). Until future side-by-side comparisons between this threshold-based MPS definition and more established definitions are completed, caution should be exercised in utilizing this relatively new threshold-based framework in longitudinal studies of pollen season duration.

4.4. Intensity of MPS

The six MPS definitions generated the most consistent results for ΔSPIn, both in terms of directionality and magnitude of 31-year change. The findings for beech and hazel were striking, with both trees showing a 2- to 2.5-fold increase in national median SPIn in just 31 years. For birch and oak, the national median SPIn increased more modestly but still significantly compared to 1990 levels (57–68% for birch; 66–82% for oak). It is possible that some SPIn increase may be attributable to additional trees growing in proximity to pollen monitoring stations or long-range wind transport of pollen (García-Mozo et al., 2016). The more logical explanation, based on knowledge that pollen intensity is related to temperature, precipitation, and CO_2, is that climate change is impacting SPIn (Dahl et al., 2013; Ziello et al., 2012; Ziska et al., 2019).

We noted three species for which the linear regression results were different from the LOESS models. These disparities may have resulted from sizable differences in species-level SPIn between the 14 Swiss stations, fluctuating trends in SPIn over the past 31 years, and in the case of ragweed and mugwort, the considerable amount of excluded data due to sub-threshold pollen concentrations. The peak-valley alternating patterns of high-low pollen years also inherently limits the ability of a linear trend to fit pollen intensity data.

Jochner-Oette et al. (2019) previously reported that linear models can be suboptimal for longitudinal evaluation of pollen intensity (Jochner-Oette et al., 2019). In their 30-year analysis of hazel, birch, and grasses from 6 Swiss monitoring stations, only hazel at two sites could be reliably trended with a linear model. In our national analysis, we note that national 31-year changes in SPIn for hazel, birch, hornbeam, oak, and grasses can be modeled well with linear regression, based on the roughly linear splines generated by LOESS technique. Future national analyses of pollen data may consider the use of a one change point Bayesian statistical model for other plant species, as proposed by Jochner-Oette.

4.5. Strengths and limitations

One strength of our study is the methodology employed in the systematic exclusion of incomplete species-station-year data from the analysis. Previous longitudinal studies of Swiss and European data have been more lenient, either including all data (regardless of the calendar position or number of days missing a pollen concentration), filling missing data with an annual average, or subjectively excluding individual data years based on less clear criteria (Clot, 2001; Clot, 2003; Emberlin et al., 2002; Frei, 1998; Frei and Gassner, 2008a; Frei and Gassner, 2008b; Leuschner et al., 2000; Sikoparija et al., 2017; Smith et al., 2014; Spieksma et al., 1995; Ziello et al., 2012; Ziska et al., 2019). We acknowledge that ecologic and climactic conditions are quite different between Switzerland's pollen monitoring stations, and one limitation of our study is that multi-decade national MPS trends which we report can misalign with local, longitudinal changes previously published. While pollen-sensitized individuals will likely show greater interest in local data, studying long-term national trends for the whole of Switzerland is highly relevant to public health and research communities, where population-level approaches to better understanding pollen-induced allergic disease are sought. The logical next step is to quantify how prevalence of specific pollen sensitization has changed in the Swiss population, and correlate this data with the multi-decade shifts in MPS duration and intensity.

A major goal of this study was to understand how choice of MPS definition can quantitatively affect longitudinal pollen trend results. It is beyond the scope of this paper to analyze the 31-year changes relative to specific climactic variables or to attribute a percentage of these longitudinal pollen trends to anthropogenic contribution. Future research may determine the attribution of altitude, climactic changes, and human-influenced factors on changes to MPS metrics, particularly the differential responses between trees, grasses, and weeds.

It should not be presumed that the results herein can predict future Swiss pollen trends, as the 31-year transformations have generally been non-linear, and plant adaptation to temperature, rainfall, and other climactic changes are finite. Information gained from this study may alter clinical guidance about the appropriate time to initiate rhinitis medication and enhance understanding about how pollen intensification has modulated the health effects of non-biologic air pollutants (Robichaud, 2020). These results may also be useful for improving pollen alert systems within Switzerland.

5. Conclusion

We analyzed pollen data from 14 Swiss stations over a 31-year period (1990–2020) studying the long-term trends in pollen season onset, duration, and intensity for 12 health-relevant species. We found that over the past three decades, significant shifts have occurred in pollen season at the Swiss national level, observing earlier pollen season onsets (hazel, oak, grasses, nettle/hemp); longer pollen season durations (hazel, nettle/hemp); a shorter pollen season duration (ash); and more intense pollen seasons (hazel, birch, oak, beech, nettle/hemp). The general trend toward significant net increase in pollen exposure from these five plants was not balanced out by significant or consistent decreasing trends for other species. We expect this may have adversely affected public health, especially the quality of life of the pollen-allergic population. Moreover, we compare national pollen trends delineated by two percentage- and four threshold-based MPS definitions, and conclude that the choice of such definition can lead to highly variable conclusions regarding multi-decade trends. We therefore suggest that long-term pollen aerobiologic studies take into account multiple MPS definitions, given the substantial differences in outcome measurements (magnitude, directionality, significance level) inherent to the chosen MPS definition.

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CRediT authorship contribution statement

Sarah Glick: Conceptualization, Methodology, Formal analysis, Investigation, Writing - Original Draft, Review & Editing

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Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.146382.

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