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The effect of pollen exposure on economic activity: Evidence from home scanner data

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Abstract

Although seasonal allergies caused by airborne pollen are detrimental to physical and mental health and impair daily activity, discussion on their social cost is scarce in the economics literature. Large amounts of airborne pollen can not only increase health care costs and reduce worker productivity, but also cause people to stay at home, thereby stagnating economic activity. This study uses daily purchase records from scanner data to investigate the effect of pollen exposure on consumption behavior. Exploiting the daily variation in the pollen counts at 120 observation stations in Japan, I find that consumption expenditure decreases by about 2% on days when airborne pollen is unusually high. A reduction in consumption due to pollen exposure is also observed in estimates using weekly and monthly panel data. This finding suggests that exposure to pollen may reduce total expenditure as opposed to delay spending. The results highlight the overlooked economic burden of pollen and seasonal allergies. Hence, they underline the importance of urban planning to reduce airborne pollen and health policy to deal with seasonal allergies.

Keywords: Seasonal allergies, Pollen, Consumption, Scanner data, Hay fever

JEL classifications: Q51, D12, Q53, I10, E21, R11

1. Introduction

Seasonal allergy, also known as hay fever or pollinosis, is a common chronic condition and a global health problem (Bousquet et al., 2008). Seasonal allergy causes sneezing, nasal congestion, and itchy eyes, and its medications also bring about side effects such as sleepiness and lethargy (Jáuregui et al., 2009, Meltzer et al., 2012). The prevalence rates vary between country and region, but are generally 10% to 40% in developed countries, with an estimated 400 million sufferers worldwide (Greiner et al., 2011; Meltzer et al., 2012). Furthermore, numerous studies demonstrate that the prevalence is increasing (Caillaud et al., 2015; Linneberg et al., 2000; Nakae and Baba, 2010; Selnes et al., 2005) for a variety of reasons. Increases in temperature and precipitation due to global climate change increase pollen, which is the cause of seasonal allergy (Bajin et al., 2013; Shea et al., 2008; Todea et al., 2013; Zhang et al., 2015; Ziello et al., 2012). The urbanization and westernization of lifestyles also raise the prevalence of seasonal allergy (Kaneko et al., 2005; Krämer et al., 2010; Sakashita et al., 2010). Many developed countries are greening their cities to improve the air quality and landscape, which in turn leads to airborne pollen (Asero, 2002; Cariñanos and Casares-Porcel, 2011; Xu et al., 2016). Thus, since the burden of seasonal allergy can increase with economic activity, there is a need to study its social cost.

Despite the potential economic burden of seasonal allergy, economists pay little attention to pollen compared with pollutants. The medical and epidemiological literature indicates that seasonal allergy results in direct medical costs and indirect costs due to reduced labor productivity (Cardell et al., 2016; Hellgren et al., 2010; Lamb et al., 2006). However, these are not the only potential burdens of seasonal allergy. As with severe air pollution, pollen can also prevent people from going out (Graff Zivin and Neidell, 2009; Neidell, 2009) and affect their consumption behavior (Kang et al., 2019; Sun et al., 2019). High levels of airborne pollen make people stay at home, and the resulting loss of expenditure can be considered to be the economic cost of pollen. However, the relationship between airborne pollen and consumption behavior remains unclear.

To bridge this gap in the body of knowledge, this study investigates the impacts of pollen exposure on consumption behavior. By combining detailed purchase records from 2013 to 2019 based on home scanner data with daily pollen counts collected at 120 monitoring stations throughout Japan, I analyze changes in consumer spending due to daily pollen variations. The main results provide evidence that consumer spending declines by about 2% on days when airborne pollen is unusually high (above the 95th percentile). Considering that consumption expenditure accounts for about 55% of GDP in Japan, this decline has serious implications. The estimates using weekly and monthly panel data also show a decrease in consumption expenditure for each additional day of high pollen, suggesting that pollen exposure causes shopping to be canceled rather than postponed. To the best of my knowledge, this is the first research to investigate the relationship between daily pollen exposure and consumption expenditure.

An important contribution of this study is that it presents novel evidence that pollen exposure impedes economic activity, thereby revealing the economic benefits of pollen reduction. First, understanding the social costs of pollen is important when formulating urban planning or greening policies, as considering the negative externalities caused by pollen in urban planning can improve social welfare. In addition, it can take a long time from planting to pollen production. In Japan, cedar was artificially planted nationally after World War II; cedar pollen is the biggest cause of seasonal allergies today. Some types of trees such as Japanese cedar take decades to start producing pollen, so ignoring it could be a huge burden in the future. Second, quantifying pollen costs contributes to the climate change literature. As climate change affects the production, dispersion, and allergen content of pollen (Ziska et al., 2019), my results reveal a potential novel channel through which climate change can affect social costs. Finally, the effects of pollen should also be considered when using scanner data. High-frequency economic indicators using daily scanner data will become more common, and immediate policymaking using them could also increase in the future (De Haan and Van Der Grient, 2011; Melser, 2018). Although daily data are useful, they are susceptible to temporary exogenous variation. Considering the effects of pollen as well as daily weather and air pollution could thus allow for more accurate decision making.

The remainder of this paper is structured as follows. Section 2 explains pollen and seasonal allergies as well as related studies. Section 3 discusses the data and setting used in the study. Section 4 describes the empirical strategies. Section 5 presents the results, Section 6 explores their robustness, and Section 7 discusses the lasting effects of pollen. Finally, Section 8 concludes.

2. Background and related studies

2.1. Pollen and seasonal allergies

Seasonal allergy is a chronic disease caused by allergic pollen in the air. The causative plant and pollen season differ by country and region, but the symptoms are generally similar globally. Sufferers of seasonal allergies have an allergic reaction when they inhale airborne pollen. The most common reactions are allergic rhinitis such as sneezing, runny nose, and stuffy nose as well as allergic conjunctivitis such as itchy eyes and tears. In rare cases, asthma and atopy may also occur (Gonzalez-Barcala et al., 2013; Hanigan and Johnston, 2007; Sun et al., 2016). In the worst cases, it can cause bronchitis, bronchial asthma, pulmonary heart disease, and can even be life-threatening (Brunekreef et al., 2000; Weichenthal et al., 2016). In addition, allergy medications lead to side effects such as drowsiness, dryness, and lethargy (Jáuregui et al., 2009, Meltzer et al., 2012). These symptoms worsen sleep quality (Craig et al., 2004; Kremer et al., 2002; Santos et al., 2006), reduce cognitive performance (Bensnes, 2016; Marcotte, 2017), increase absenteeism (Hellgren et al., 2010; Lamb et al., 2006), and sometimes lead to suicide (Stickley et al., 2017). Thus, seasonal allergies reduce people's quality of life, affect their daily activities, and cause economic losses.

Seasonal allergy is a common disease, but the exact prevalence is difficult to ascertain because many sufferers use over-the-counter medications without visiting hospital or simply endure until the pollen season has passed because of the relatively mild and chronic symptoms. Several studies have estimated the annual per capita cost of seasonal allergies to be $600 to $1000, taking into account direct medical costs and indirect costs due to lost productivity (Cardell et al., 2016; Hellgren et al., 2010; Lamb et al., 2006). However, the burden of seasonal allergies may be underestimated.

A distinctive part of seasonal allergies is that sufferers' performance and behavior are strongly influenced by airborne pollen count on that day. More patients visit the asthma emergency department (Erbas et al., 2012) and more over-the-counter medications for allergies are sold (Ito et al., 2015; Johnston et al., 2009) on days with high pollen counts. Bensnes (2016), Marcotte (2015), and Walker et al. (2007) show that high airborne pollen on exam days reduces students' cognitive performance. Chalfin et al. (2019), who investigated pollen counts and crime, suggested that people may spend less time outdoors on high pollen days. They also found that not only outdoor crime but also indoor crime decreased on high pollen days, suggesting that high pollen may not only reduce outdoor activity, but also affect individual mood and behavior.

The results of Chalfin et al. (2019) suggest a new potential effect of airborne pollen. Similar to air pollution (Kang et al., 2019; Sun et al., 2019) and bad weather (Bloesch and Gourio, 2015; Parsons, 2001), the day's airborne pollen count may be associated with daily expenditure. In other words, airborne pollen not only causes people to avoid going out, but may also decrease the desire to consume due to apathy and lethargy. Additionally, consumer spending could decline to offset the higher medical costs caused by seasonal allergy. However, to the best of my knowledge, empirical evidence of the impact of daily pollen exposure on consumer spending is lacking.

2.2. Seasonal allergies in Japan

The main sources of seasonal allergies in Japan are cedar and cypress (Yamada et al., 2014; Yoshida et al., 2013). Cedar and cypress, which are not only suitable for the Japanese climate, but also have excellent characteristics for processing wood such as fast growth and easy shaping, were planted in large numbers during and after World War II when demand for materials was high but it was impossible to import timber. About 20% of Japan's land is covered by artificial cedar and cypress forests (MAFF, n.d.), thereby playing important roles in public health by improving soil, air, and water quality. However, cedar and cypress begin to produce allergic pollen when they are about 30 years old.

Most pollen in Japan is distributed from February to April. Since pollen can be dispersed more than 100 kilometers away and can stay in the air for more than 12 hours, almost the entire area, even in sparsely forested cities, can be contaminated (Yamada et al., 2014). The regional prevalence rate is mostly 10–40% except for Okinawa[1] (Okuda, 2003; Sakashita et al., 2010; Yamada et al., 2014). Similar to the global trend, the prevalence rate in Japan is increasing steadily (Kaneko et al., 2005; Okano et al., 2012). Prevalence is particularly high in urban areas; in Tokyo, the prevalence rate reached 48.8% in 2016 (Tokyo Metropolitan Institute of Public Health, 2017), rising from 19.4% in 1996. As wearing protective masks as well as cutting down artificial forests and converting them to trees with less pollen have only marginal beneficial effects, a better understanding of the burden of seasonal allergies is necessary to help

[1] The climate of Okinawa prefecture, the southernmost remote island in Japan, is different than that in other prefectures. The prevalence of seasonal allergies is low because there is almost no pollen. Therefore, Japan's 46 prefectures other than Okinawa are investigated in this study.

introduce effective policies and improve public health.

3. Data

To investigate the effect of daily airborne pollen count on consumption behavior, this study uses a combination of three types of data: pollen, weather, and individual purchases. The data period runs from February to June (pollen season) of each year, from 2013 to 2019. Data on air pollution are only used to check the robustness of the results because the available period is short (from 2013 to 2017).

3.1. Airborne Pollen

Daily pollen data were obtained from the pollen observation system (Hanakosan) operated by the Ministry of the Environment. There are 120 pollen monitoring stations in Japan, operating from February to May each year (until June in Hokkaido). Figure 1 shows the locations of pollen observation stations that except for sparsely populated areas cover most Japanese cities. Automatic pollen monitors in each station report the pollen count per cubic meter every hour.[2] The measured pollen count is automatically published on the website of the Ministry of the Environment to allow allergy sufferers to make decisions about medication use and outdoor activities based on real-time pollen information.

Table 1 shows the descriptive statistics. The mean pollen count is 43.327 and the standard deviation is 252.918, indicating that the variance is large.[3] This study uses the effect of pollen thresholds following the literature (Chalfin et al., 2019; Ito et al., 2015; Marcotte, 2015;

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[2] There is no distinction between cedar and cypress because of their close properties. There are some deficiencies in the data due to equipment failure, data communication errors, or unusual yellow sand.

[3] The maximum pollen count is 66403.792, which may seem like an outlier. This value is the maximum for 2013, but the maximum for the other years is around 2000 to 7000. However, the Ministry of the Environment reports that outliers are excluded before the release of the data. Hence, this study treats this value as a non-outlier. In any case, the main analysis uses dummy variables, so there is no major impact.

Sheffield et al., 2011). A day when the airborne pollen count is in the 95th percentile (158.167) or higher is defined as a high pollen day. Therefore, the main analysis captures the effect of extreme pollen counts. This is reasonable because the medical and epidemiological literature shows that symptoms of seasonal allergies can rise sharply with increasing pollen counts and flatten above the threshold (Caillaud et al., 2014; Erbas et al., 2007; Johnston et al., 2009). In addition, using the same threshold for all the monitoring stations is not problematic because, as mentioned in the previous section, pollen trees are distributed nationally and the variance of the average pollen count at each monitoring station is small.

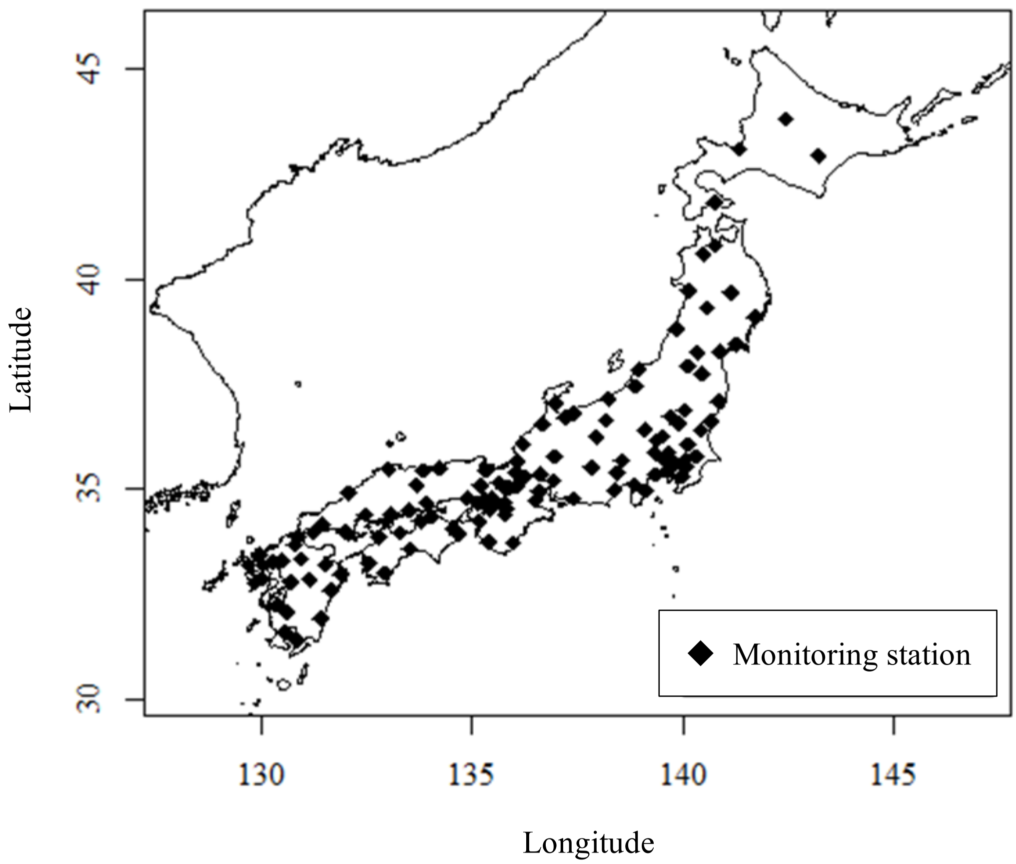

Figure 1. Pollen monitoring stations in Japan

Note: The black rhombus symbols represent pollen monitoring stations. Source: Ministry of the Environment.

	Mean	Std. Dev	Minimum	Maximum
Pollen and weather				
Pollen count	43.327	252.918	0	66403.792
High pollen day dummy	0.050	0.218	0	1
Rain dummy	0.365	0.481	0	1
Average temperature (°C)	13.286	7.250	-16	30.150
Average wind speed (m/s)	2.555	1.345	0	15.650
Daily home scanner data				
Total in-store purchases	107519.750	170719.621	0	1830594
Number of monitors purchased	68.894	110.525	0	844
Total in-store purchases per monitor	1599.797	727.673	0	30407
Total online and mail order purchases	11401.165	23078.241	0	902713
Total purchases of pollen-related goods	1179.982	2552.407	0	49742
Air pollution				
Average PM_{25} ($\mu g/m^3$)	14.389	8.198	0	86.028
Critical PM_{25} dummy	0.101	0.301	0	1
Average SO_2 (ppm)	1.835	1.742	0	63.297
Critical SO_2 dummy	0.001	0.025	0	1
Average NO_X (ppm)	13.303	9.847	0	340.500
Number of pollen monitoring stations		120		
Number of observation days		1051		
Observations		98361		

Table 1. Descriptive statistics

Note: Home scanner and air pollution data are aggregated for each pollen station within 15 km. The details of pollen-related goods are given in Appendix A. The number of observations is the number of pollen stations multiplied by the number of observation days minus the number of days when pollen data are missing.

3.2. Weather

As daily weather has a huge impact on consumer behavior (Bloesch and Gourio, 2015; Parsons, 2001), it must be controlled for. The weather data are obtained from the Automated Meteorological Data Acquisition System (AMeDAS) operated by the Japan Meteorological Agency. Pollen data and weather data can be matched one-to-one because pollen monitoring stations are intentionally located near AMeDAS stations. The variables used are a rain dummy (taking one when precipitation per hour is 15 mm or more), temperature (°C), and wind speed (m/s) (see Table 1). Intuitively, pollen counts are likely to be strongly influenced by rain;

however, the weather has a small impact on pollen counts in reality (D'Amato et al., 2007). Consistent with the results of Chalfin et al., (2019), the R-squared value is only 0.06 when regressing pollen counts on the weather variables and all the other fixed effects using the data in the main analysis.

3.3. Home scanner data

To measure daily consumption expenditure, I use home scanner data called Quick Purchase Report (QPR) from Macromill. This dataset aims to provide detailed marketing information by constructing nationally representative panel data on consumers' buying behavior. Since 2011, about 30,000 monitors[4] provided with barcode readers have reported daily purchasing data. Monitors scan all barcoded items purchased each day using handheld scanners and report the code, price, and quantity of each product. This dataset contains rich personal information about the monitors, including ZIP codes, age, income, and family structure, which is updated annually. Based on the ZIP code, I can combine the QPR data with the pollen station.[5] In addition, the QPR data include detailed information such as the date and time of the scan and location of the purchase (e.g., supermarket, mail order, vending machine) as well as the product name. An important feature of the QPR data is their high representativeness. Monitors are selected to ensure they represent the regional gender, age, marital status, and family structure shares based on the census. In addition, monitors are incentivized to scan correctly using rewards, and monitors who do not regularly scan are forced to leave; hence, the data are highly reliable.

However, as Leicester (2013), who compared home scanner data with other household survey data, pointed out, there are several problems with home scanner data. The most serious

[4] The QPR has maintained a sample size of about 30,000, replenished with individuals with similar characteristics when monitors drop out. Thus, it mitigates the problem of sample attrition, which is a serious shortcoming of daily purchasing data.

[5] A small number of monitors did not report the correct ZIP code and these were excluded from the sample.

is that the QPR data do not capture all household expenditure. Items without a barcode such as perishables, cars, and properties are not included in the data. Further, even if a barcode is attached, some products such as imported products cannot be used for the analysis because the unit price is unknown. Therefore, the consumption expenditure used in this analysis is less than the actual value. In addition, the monitor must scan every day, so the sample may be biased toward industrious people. However, such deficiencies and biases are likely to be uncorrelated with pollen exposure and seasonal allergies, and should not seriously bias the estimates.

In the main analysis, the data are used at the aggregate level of each pollen monitoring station.[6] The distance from the center of the ZIP code of the monitor to the nearest pollen monitoring station is calculated, and the QPR data are connected to the pollen and weather data. In the main estimation, data from monitors living within 15 km of the pollen monitoring station are aggregated and used as the consumption activity data in the area around the station. For each pollen monitoring station, I use the following daily information: total in-store purchases, number of monitors making purchases of at least one yen, per capita in-store purchases, total online and mail order purchases, and total purchases of pollen-related products.[7] Table 1 presents the descriptive statistics.

3.4. Air pollution

As with weather, air pollution levels can affect outdoor activities (Kang et al., 2019; Sun et al., 2019) and airborne pollen counts (D'Amato et al., 2007; Yamada et al., 2014). Therefore, air pollutants should be used as a control. The data on air pollutants are obtained from the National Institute for Environmental Studies. There are more than 2,000 automatic air quality

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[6] Another technical problem is that because of the huge sample size, it is difficult to control for the monitor-level fixed effects in the monitor's daily data and make estimates that account for the non-linearities caused by the many "zeros" (i.e., days when the monitor does not go shopping).

[7] Table A in the Appendix provides the definitions of pollen-related goods.

monitors in Japan, each reporting hourly airborne pollutants. In this study, air pollution is defined as the air quality at each pollen monitoring station (i.e., the average daily value reported by the air quality monitors within a certain distance of each pollen station). Unlike the pollen, weather, and purchasing data, the air pollution data are only available from 2013 to 2017. Therefore, they are not used in the main analysis, only in the robustness check.

Particulate matter (PM_{25}, μg/m3), sulfur dioxide (SO_2, ppb), and nitrogen oxides (NO_X, ppb) are used as the air pollution variables. Each pollutant is used not only as a value, but also as a dummy variable that takes one if it is above the critical threshold defined by the World Health Organization (WHO) (Bensnes, 2016). The threshold for PM_{25} and SO_2 is 25 or more per hour and 20 or more per hour, respectively (WHO, 2005). NO_X is only used linearly because there is no defined threshold. Table 1 shows the descriptive statistics of the pollutants used in the estimates.

4. Empirical strategies

To investigate the effects of pollen exposure on consumption expenditure, I estimate the following model:

$$P_{iymd} = \alpha + \beta Pollen_{iymd} + \gamma X_{iymd} + S_i + Y_y + M_m + D_d + W_{iy} + Z_{im} + \varepsilon_{iymd} \quad (1)$$

where, P_{iymd} represents consumption behavior in the catchment of pollen monitoring station i on day d, month m, and year y.[8] In the main analysis, consumption behavior is proxied by total in-store purchases. $Pollen_{iymd}$ is a dummy variable that indicates whether pollen is above the threshold and β is the coefficient of interest.[9] X_{iymd} is a control vector that

[8] One concern with home scanner data is the timing of the scan. If the timing of the scan is after midnight, the purchase amount is recorded on the next day. Therefore, I also analyzed purchases made before 8 a.m. on the next day as being purchases for that day (except for purchases made at 24-hour convenience stores and vending machines). The results are similar to the main results (see Appendix B).

[9] Estimates using alternative measures of pollen were also carried out (see Appendix C). Although there are

includes typical weather conditions such as daily average temperature, wind speed, and precipitation. For the robustness checks, air pollution levels are also included in X_{iymd}. S_i, Y_y, M_m, and D_d are the fixed effects of the pollen monitoring station, year, month, and day, respectively. W_{iy} and Z_{im} are the interaction of the station-year and station-month fixed effects, respectively, controlling the station-specific time trends. This allows us to address local economic trends and seasonality. To account for the serial correlation of the errors, standard errors are clustered at the station-year-month level. Controlling for the fixed effects in such detail allows me to identify the impact of exogenous variation in pollen on consumption behavior.

To better understand the impact of pollen on purchasing behavior, I also make estimates using dependent variables other than total in-store purchases. First, the number of people who went out shopping is used as the dependent variable to examine whether the increase in pollen decreases outdoor activities. Second, to ensure that the results are not driven by the number of monitors assigned to each pollen monitoring station, I use the purchase amount per monitor. Third, using online and mail order shopping expenditure, I confirm that allergy symptoms caused by airborne pollen do not affect the accuracy and frequency of home scanner data. Since online shopping can be ordered without going out and delivery usually takes a few days, it cannot be affected by the pollen on that day. If airborne pollen affects scanning behavior rather than purchasing behavior, then spending on online and mail order shopping will also decrease. Finally, I investigate pollen-related goods to confirm whether people's behavior is affected by pollen. Since clinical studies such as Johnston et al. (2009) and Yamada et al. (2014) show that medication, masks, and glasses sell well on high pollen days, I define such products as pollen-related goods. The specific definitions are given in Appendix A.

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some differences in significance levels, the results consistently show the negative effect of pollen on consumption. This is also consistent with the relationship shown in the medical literature that it flattens when the threshold is exceeded.

When considering the economic burden of pollen, the key question is whether the decline in consumption will bounce back. Although bad weather and air pollution have a negative impact on outdoor activities and consumption, this may simply be a postponement (Bloesch and Gourio, 2015; Graff Zivin and Neidell, 2014; Sun et al., 2019). In other words, outdoor activity may be postponed while the bad conditions continue and then rapidly increase when they are over. This suggests that the negative effects of high pollen days are transitory and have no serious impact on the economy. However, it is difficult to verify the degree to which the economy bounces back from continuously bad pollen conditions. Since clear thresholds are lacking, it is hard to state concretely that the high pollen period is over. Moreover, pollen can affect sufferers the next day because allergy symptoms may not recover after one day and pollen can stay on clothes and indoor surfaces. Therefore, weekly and monthly data are estimated using the average pollen level and number of high pollen days. If people avoid going out on high pollen days and instead shop on low pollen days, then no negative effects of high pollen days should be observed at the weekly or monthly level. Conversely, if there is no bounce back effect, the number of high pollen days at the weekly or monthly level can have a negative effect.[10]

5. Main results

Table 2 presents the estimates of the impact of pollen exposure on in-store consumption expenditure. The treatment variable in each row is a dummy variable that takes one if the daily pollen count of a given monitoring station on a given day exceeds the 95th percentile (158.167). Each column reports the coefficients, their standard errors, and, for the variable of interest, the effect size as the percentage change in the dependent variable relative to its mean. Column (1)

[10] All the major analyses were performed at the level of pollen monitoring station, but weekly and monthly data were also used at the monitor level to confirm the robustness of the main results (see Appendix D and Appendix E).

shows the results estimated by controlling for only the basic fixed effects. When weather is not controlled for, there is no significant relationship between high pollen days and consumption expenditure. This is expected considering that the weather affects both consumption behavior and pollen dispersal, and this result emphasizes the need to control for the weather. Column (2) uses a specification with additional controls for weather conditions. The results show that consumer spending falls by 2.93% on high pollen days. Moreover, rainy days significantly reduce consumption, which is consistent with previous research (Parsons, 2001) and common sense. Columns (3) and (4) show the results with additional controls for the station-year and station-month fixed effects, respectively. Controlling for the time-fixed effects at the monitoring station level can reduce the bias caused by differences in the trends in the local climate, economic activity, and other unobserved factors. The results show that high pollen days significantly reduce consumer spending by about 1.9%. Column (5) additionally controls for the average pollen count in the weeks before and after the observation day to account for the effect of airborne pollen on adjacent days, which can affect purchasing behavior on the day in question. Column (5) indicates that even when controlling for pollen counts on adjacent days, there is no noteworthy change in the effect of high pollen days. It is also plausible that higher pollen levels in the previous week would slightly decrease consumer spending.

Hence, the main results show that regardless of the specification, store spending falls significantly on high pollen days. The effect size is 2–3%, in line with the findings of related studies that show that restaurant visitors decrease by about 4% on days with severe air pollution (Sun et al., 2019) and Citibike trips decrease by about 4% on days with high pollen counts (Chalfin et al., 2019).

	(1) Coeff. (Std. Err.) Eff. Size	(2) Coeff. (Std. Err.) Eff. Size	(3) Coeff. (Std. Err.) Eff. Size	(4) Coeff. (Std. Err.) Eff. Size	(5) Coeff. (Std. Err.) Eff. Size
High pollen day	-1261.277	-3150.088***	-2085.105***	-1995.053**	-2182.306*
	(879.019)	(885.615)	(616.992)	(640.979)	(893.465)
	-1.173%	-2.930%	-1.939%	-1.856%	-2.030%
Average pollen count for the previous week					-4.483*
					(1.866)
Average pollen count for the following week					0.690
					(2.821)
Weather					
Rain dummy		-9858.385***	-9842.177***	-10012.620***	-11457.877***
		(909.512)	(818.949)	(820.223)	(1142.275)
Temperature		892.839***	571.098***	603.265***	726.048***
		(60.650)	(50.717)	(51.954)	(71.750)
Wind speed		1059.979***	121.550	224.524	418.968*
		(149.792)	(136.870)	(138.942)	(188.590)
Fixed Effects					
Station	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES
Month	YES	YES	YES	YES	YES
Day of week	YES	YES	YES	YES	YES
Station × Year			YES	YES	YES
Station × Month				YES	YES
N	96437	96434	95738	95272	73160
Adjusted R^2	0.9022	0.9026	0.9363	0.9364	0.9358

Table 2. Effects of daily high pollen on consumption expenditure in stores

Note: *, **, and *** indicate statistical significance at 5%, 1%, and 0.1%, respectively. The effect size indicates the percentage change in the dependent variable relative to its mean on a high pollen day. Standard errors are adjusted for clustering at the station-year-month level.

6. Robustness checks

The main results are robust even when controlling for the various fixed effects discussed above. However, this section provides a series of robustness checks to address concerns about the main analysis, such as the composition of the sample and use of arbitrary thresholds.

6.1. Changing the explained variable

In this section, estimates with altered explained variables are conducted to investigate how people's behavior changes on high pollen days. Table 3 shows the results for different explained variables using the specification in column (4) of Table 2. Unless otherwise specified, this specification is used for all the subsequent estimations. Column (1) uses the number of monitors who purchased something in a store that day as the dependent variable. The results show that high pollen has no significant effect on the number of people who make purchases, which is somewhat unexpected considering that outdoor activities may be hampered by airborne pollen. One explanation is that people spend less time outside on high pollen days, rather than not going outside at all. For example, on a high pollen day, people might buy the essentials at a nearby convenience store instead of going to a suburban shopping mall or touring multiple stores.[11]

Column (2) presents the results using in-store purchase amount per monitor, showing that high pollen days significantly reduce per capita consumption expenditure, with effect sizes similar to the aggregated consumption expenditure in Table 2. This indicates that the main results are not sensitive to the number of monitors assigned to each monitoring station. Column (3) uses expenditure on goods purchased without going out, such as online and mail order

[11] Regrettably, the distance between the monitor's residence and place of purchase is not available from the data. To investigate outdoor activities, an analysis was conducted using the differences between weekdays and holidays. Although many people must go out on weekdays for work, holiday outings are arbitrary, suggesting that pollen may have a greater impact on outdoor activity in holidays. However, the results of the analysis showed no significant difference between weekdays and holidays.

shopping, as the dependent variable. As expected, online and mail order shopping is not significantly affected by high airborne pollen, emphasizing that the main results are not driven by changes in scanning behavior. Column (4) shows that spending on pollen-related goods increases significantly by about 32% on days when pollen is high. This exceptionally large effect presents evidence that people respond sensitively to pollen exposure.

	Number of monitors (1) Coeff. (Std. Err.) Eff. Size	Purchases per monitor (2) Coeff. (Std. Err.) Eff. Size	Online shop & Mail order (3) Coeff. (Std. Err.) Eff. Size	Pollen-related goods (4) Coeff. (Std. Err.) Eff. Size
High pollen day	-0.072	-29.966**	-62.681	375.907***
	(0.126)	(10.448)	(156.374)	(34.115)
	-0.105%	-1.87%	-0.550%	31.857%
Weather				
Rain dummy	-4.449***	-37.644**	-74.835	-147.823***
	(0.213)	(12.048)	(160.741)	(23.022)
Temperature	0.162***	5.046***	25.436*	9.519***
	(0.010)	(0.726)	(12.336)	(1.749)
Wind speed	-0.127***	5.902**	23.685	10.958*
	(0.029)	(1.841)	(32.640)	(4.793)
Fixed Effects				
Station	YES	YES	YES	YES
Year	YES	YES	YES	YES
Month	YES	YES	YES	YES
Day of week	YES	YES	YES	YES
Station × Year	YES	YES	YES	YES
Station × Month	YES	YES	YES	YES
N	95272	95272	95272	95272
Adjusted R^2	0.9935	0.1958	0.7855	0.6979

Table 3. Effects of daily high pollen on other explained variables

Note: *, **, and *** indicate statistical significance at 5%, 1%, and 0.1%, respectively. The effect size indicates the percentage change in the dependent variable relative to its mean on a high pollen day. Standard errors are adjusted for clustering at the station-year-month level.

6.2. Data composition

One potential concern with the main results is how the dataset is created. In the main analysis, monitors are aggregated by pollen monitoring station, but the distance from the station is decided arbitrarily. While using monitors close to a station can reduce measurement errors for pollen exposure, it can also lead to bias by reducing the number of monitors aggregated. Columns (1)–(5) of Table 4 show the results using monitors living within 5, 10, 20, 25, and 30 km of a pollen monitoring station, respectively.[12] Column (6) also shows the estimation results using the data generated by assigning all monitors to the nearest pollen monitoring station. Despite the wide variation in the number of monitors aggregated, from about 13,700 to about 66,700, the effects of high pollen days are negative, significant, and their sizes are remarkably consistent in all the columns, confirming that the main results are not sensitive to the distance at which the monitors are aggregated.

[12] The data used in the main analysis are from monitors living within 15 km of a pollen monitoring station, which numbered 46,080 people.

	Monitors within 5 km	Monitors within 10 km	Monitors within 20 km	Monitors within 25 km	Monitors within 30 km	Full sample
	(1)	(2)	(3)	(4)	(5)	(6)
	Coeff.	Coeff.	Coeff.	Coeff.	Coeff.	Coeff.
	(Std. Err.)	(Std. Err.)	(Std. Err.)	(Std. Err.)	(Std. Err.)	(Std. Err.)
	Eff. Size	Eff. Size	Eff. Size	Eff. Size	Eff. Size	Eff. Size
High pollen day	-409.748*	-1258.720**	-2225.964**	-2516.903**	-2622.737**	-2788.157***
	(206.295)	(437.871)	(748.260)	(789.188)	(809.036)	(838.034)
	-1.310%	-1.721%	-1.715%	-1.786%	-1.757%	-1.676%
Weather						
Rain dummy	-2549.196***	-6619.283***	-12085.127***	-13057.422***	-13644.979***	-14553.022***
	(243.810)	(554.598)	(964.223)	(1033.277)	(1060.811)	(1098.126)
Temperature	146.355***	391.308***	744.026***	823.355***	883.805***	948.884***
	(16.426)	(35.158)	(61.790)	(65.674)	(67.505)	(70.089)
Wind speed	47.094	97.900	194.195	179.625	133.807	159.180
	(44.586)	(95.804)	(166.556)	(178.771)	(186.045)	(196.487)
Fixed Effects						
Station	YES	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES	YES
Month	YES	YES	YES	YES	YES	YES
Day of week	YES	YES	YES	YES	YES	YES
Station × Year	YES	YES	YES	YES	YES	YES
Station × Month	YES	YES	YES	YES	YES	YES
# of aggregated monitors	13705	32151	54581	58485	61302	66671
N	90339	94007	95867	95867	95867	95985
Adjusted R^2	0.8786	0.9289	0.9385	0.9374	0.9365	0.9340

Table 4. Estimates when changing the monitor catchment area

Note: *, **, and *** indicate statistical significance at 5%, 1%, and 0.1%, respectively. The effect size indicates the percentage change in the dependent variable relative to its mean on a high pollen day. Standard errors are adjusted for clustering at the station-year-month level.

6.3. Pollen threshold

The main analysis defines a high pollen day as a day with a pollen level in the 95th percentile or higher, but this is also arbitrarily determined. Here, I re-estimate the specification in column (4) of Table 2 by varying the threshold for high pollen days to each percentile from the 90th to 99th percentiles. Figure 2 illustrates that the impact increases as the threshold rises. Naturally, as the threshold increases, the number of days corresponding to it decreases, and thus the precision of the estimates falls. This indicates that the main results are not sensitive to threshold changes.

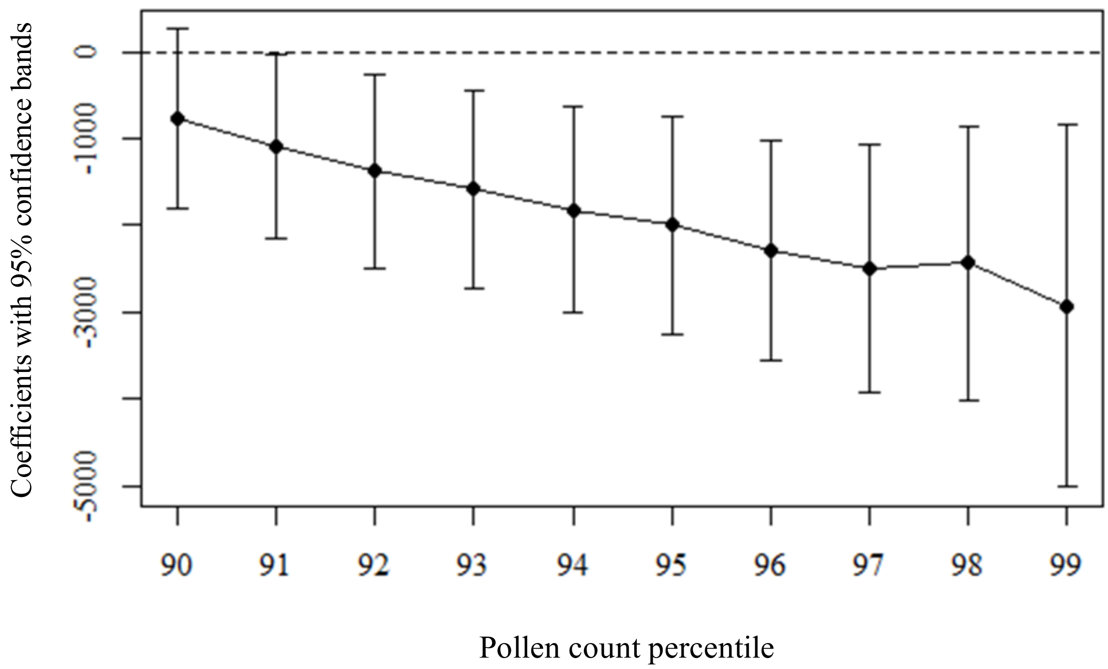

Figure 2. Sensitivity of the threshold for high pollen days

Note: Each point represents a coefficient for a high pollen day defined as a pollen level higher than the percentile indicated by the value on the horizontal axis. The confidence interval around the point estimate reflects the 95% confidence interval. The other control variables are the same as in column (4) of Table 2, with the rain dummy, mean temperature, and mean wind speed as well as the fixed effects of the pollen monitoring station, year, month, day, station-year, and station-month. Standard errors are adjusted for clustering at the station-year-month level.

6.4. Effects of air pollution

A critical concern with this study's identification strategy is that other variables that correlate with both daily pollen counts and purchasing behavior affect the results. Since pollen dispersal is a natural phenomenon, such variables are unlikely to exist other than weather, but air pollution could be a problem. If the main results are driven by a third factor such as air pollution, the explanatory power of pollen could be markedly reduced or disappear when controlling for the air pollution variables.

To address this concern, I re-estimate controlling for the air pollution variables. Columns (1) and (2) of Table 5 consider the air quality of each pollen monitoring station to be the average value of the pollutant level reported by the air pollution monitors within 15 km of each station. Column (1) includes the pollution variables as linear and column (2) includes them as dummies that take one if they are above the critical threshold defined by the WHO. However, only NO_X is inputted as linear in both columns because the threshold is undefined. The results show that even after controlling for the air pollution variable, the effect of high pollen days on store consumption expenditure remains negative and significant. There is a slight decrease in the effect size compared with the main results, but this may be due to a decrease in the sample period. Column (3) shows the results using the same sample from 2013 to 2017, but excluding the variable on air pollution, to check the impact of the shorter sample rather than air pollution. The effect size in column (3) is slightly less than that in the main results in Table 2, suggesting that the impact of controlling for air pollution is not considerable. Finally, columns (4) and (5) use the average pollution levels reported by air pollution monitors within 5 km and 25 km of a pollen monitoring station, respectively to ensure that the results are not sensitive to how the pollution variables are generated. Although the effect size changes because of the change in the number of available pollen monitoring stations, both coefficients of interest are negative and significant, indicating that the results are not sensitive to the way the pollution variables are generated. The results indicate that pollen has an effect independent of air pollution, enhancing the credibility of the identification strategy used in this study.

	Controlling air pollution (linear)	Controlling air pollution (dummy)	Restricted sample without air pollution	Air pollution monitors within 5 km	Air pollution monitors within 25 km
	(1)	(2)	(3)	(4)	(5)
	Coeff.	Coeff.	Coeff.	Coeff.	Coeff.
	(Std. Err.)	(Std. Err.)	(Std. Err.)	(Std. Err.)	(Std. Err.)
	Eff. Size	Eff. Size	Eff. Size	Eff. Size	Eff. Size
High pollen day	-1929.672*	-1975.793*	-2141.482*	-3223.326**	-2004.084*
	(924.830)	(925.496)	(928.093)	(1236.777)	(857.472)
	-1.515%	-1.551%	-1.681%	-2.193%	-1.675%
Weather					
Rain dummy	-10272.937***	-11243.053***	-12593.997***	-11692.467***	-9367.346***
	(1238.302)	(1227.657)	(1220.147)	(1567.545)	(1155.648)
Temperature	826.207***	942.390***	900.235***	914.711***	770.860***
	(80.479)	(80.468)	(80.037)	(103.323)	(74.761)
Wind speed	-17.582	-69.859	519.239*	-51.833	-130.087
	(209.977)	(209.434)	(202.124)	(247.846)	(198.679)
Air pollution					
PM_{25}	202.462***			265.099***	204.790***
	(30.335)			(36.168)	(28.921)
Critical PM_{25} dummy		2802.074***			
		(733.510)			
SO_2	837.724***			585.017***	1032.471***
	(129.987)			(162.680)	(142.832)
Critical SO_2 dummy		333.679			
		(3359.727)			
NO_X	-669.092***	-585.109***		-814.116***	-724.774***
	(50.144)	(45.954)		(55.767)	(53.166)
Fixed Effects					
Station	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES
Month	YES	YES	YES	YES	YES
Day of week	YES	YES	YES	YES	YES
Station × Year	YES	YES	YES	YES	YES
Station × Month	YES	YES	YES	YES	YES
# of aggregated air pollution monitors	1310	1310	NA	444	1731
N	55664	55664	55667	42168	59776
Adjusted R^2	0.9342	0.9341	0.9337	0.9348	0.9350

Table 5. Estimates when controlling for air pollution

Note: *, **, and *** indicate statistical significance at 5%, 1%, and 0.1%, respectively. The effect size indicates the percentage change in the dependent variable relative to its mean on a high pollen day. Standard errors are adjusted for clustering at the station-year-month level.

7. Transitory vs. lasting effects

To understand the economic impact, it is important to show whether the above-described negative effects of high pollen are lasting or transitory. One possible concern is that the decline in consumption due to high pollen may simply be a postponement, as studies of pollution and bad weather have shown (Bloesch and Gourio, 2015; Graff Zivin and Neidell, 2014; Sun et al., 2019). If consumption simply bounces back, the bounce back effect would cancel out the decline in consumption expenditure and pollen would have no lasting negative impact on the economy. High pollen usually does not continue for more than a few days; hence, if there is a bounce back effect, no negative effects of pollen should be observed at the weekly or monthly level. Alternatively, people might use online or mail order shopping instead of going out on a high pollen day. Because of the characteristics of online and mail order shopping, daily level data cannot analyze the impact of pollen. However, by using data at the weekly or monthly level, an alternative relationship between online and offline shopping due to high pollen levels may be observed. If the number of high pollen days in a week or month increases online consumption, the impact on total consumption expenditure may be limited, because pollen only changes the way of consumption. To determine whether the effects of pollen are transitory, this section thus examines in-store and online expenditure, using data aggregated at the weekly and monthly levels.

Table 6 shows the results using weekly data. In columns (1) and (2), the dependent variable is weekly in-store consumption expenditure and the control variables are the number of rainy days, average temperature, and average wind speed as well as the fixed effects of the pollen monitoring station, year, week, and station-year. Column (1) shows that a one standard deviation increase in average weekly pollen from the mean reduces in-store consumption expenditure by about 0.28%. Column (2) shows that one additional high pollen day reduces weekly in-store consumption expenditure by about 0.4%. The reduction in in-store consumption expenditure due to one additional high pollen day is about 3,000 yen, which is plausible given that the daily-level analysis shows a reduction in consumption on high pollen days of about 2,000 yen and that the effect of high pollen days stays for several days to some extent. In addition, the rainy day, which showed a large impact in the daily-level analysis, no longer has a significant effect on consumption expenditure. This indicates that rainfall only makes people postpone their purchasing behavior rather than reduce their weekly spending. Hence, in contrast to rainy days, the reduction in consumption caused by high pollen days does not bounce back, suggesting that the effects of pollen may be lasting.

Columns (3) and (4) present the impact of weekly pollen on weekly online and mail order shopping expenditure. The increase in pollen levels during the week reduces online spending. As shown in Column (4), one additional high pollen day significantly reduces weekly online spending by about 0.74%. One probable reason is the decrease in disposable income due to the increased medical costs of allergies (Erbas et al., 2012). Alternatively, a feeling of lethargy or depression caused by the allergy symptoms may reduce the desire to consume (Dahal and Fertig, 2013).

	Store purchase		Online shop & Mail order	
	(1)	(2)	(3)	(4)
	Coeff.	Coeff.	Coeff.	Coeff.
	(Std. Err.)	(Std. Err.)	(Std. Err.)	(Std. Err.)
	Eff. Size	Eff. Size	Eff. Size	Eff. Size
Average pollen count	-14.589*		-2.991	
	(6.004)		(1.571)	
	-0.279%		-0.538%	
# of high pollen days		-3055.505***		-591.722*
		(788.247)		(240.541)
		-0.405%		-0.737%
Weather				
# of rainy days	-153.404	-173.214	883.390	880.157
	(1732.342)	(1735.823)	(479.209)	(479.379)
Temperature	2286.123***	2442.636***	194.169	222.425
	(614.140)	(636.079)	(149.494)	(151.551)
Wind speed	2830.789	2643.319	1119.269**	1083.499*
	(1394.460)	(1392.457)	(429.666)	(430.478)
Fixed Effects				
Station	YES	YES	YES	YES
Year	YES	YES	YES	YES
Week	YES	YES	YES	YES
Station × Year	YES	YES	YES	YES
N	13354	13354	13354	13354
Adjusted R^2	0.9952	0.9952	0.9666	0.9666

Table 6. Estimates when using weekly data

Note: *, **, and *** indicate statistical significance at 5%, 1%, and 0.1%, respectively. The effect size of the average pollen count indicates the percentage change in the dependent variable relative to its mean when average weekly pollen increases by one standard deviation from the mean. The effect size of the number of high pollen days indicates the percentage change in the dependent variable relative to its mean when one additional high pollen day is added. Standard errors are adjusted for clustering at the station-year level.

Table 7 shows the results using monthly data. Columns (1) and (2) both use monthly in-store consumption expenditure as the dependent variable (average pollen level and number of high pollen days per month, respectively). The results are consistent with those using the weekly data, showing that high pollen levels reduce monthly consumption expenditure significantly. The magnitude of the coefficient is also reasonable, indicating that an additional high pollen day would reduce monthly consumption expenditure by about 6,700 yen (0.2%). Compared with the results of Kang et al. (2019), who found that one additional day of PM_{10} above the critical threshold reduces monthly retail sales by about 0.1%, the impact of an additional high pollen day is considerable. Columns (3) and (4) use monthly online and mail order shopping expenditure as the dependent variable. These results are also consistent with those obtained using weekly data, indicating that an increase in average pollen level and additional high pollen days significantly reduce online spending.

In summary, the reduction in consumer spending due to pollen does not bounce back. Furthermore, no shift from in-store consumption to online and mail order shopping occurs, indicating that high pollen levels can reduce consumption expenditure. This suggests that high pollen levels could have a lasting negative impact on the economy.

	Store purchase		Online shop & Mail order	
	(1)	(2)	(3)	(4)
	Coeff.	Coeff.	Coeff.	Coeff.
	(Std. Err.)	(Std. Err.)	(Std. Err.)	(Std. Err.)
	Eff. Size	Eff. Size	Eff. Size	Eff. Size
Average pollen count	-244.942**		-49.745*	
	(84.864)		(23.142)	
	-0.597%		-1.144%	
# of high pollen days		-6713.307**		-1757.858***
		(2511.847)		(475.079)
		-0.206%		-0.509%
Weather				
# of rainy days	146.982*	148.005*	16.756	17.025
	(70.317)	(70.247)	(10.577)	(10.549)
Temperature	9797.982*	10736.728*	51.969	482.501
	(4730.080)	(4774.747)	(1013.423)	(1008.089)
Wind speed	79113.635***	77581.535***	13889.132**	13453.891**
	(23417.727)	(23287.643)	(4482.359)	(4465.736)
Fixed Effects				
Station	YES	YES	YES	YES
Year	YES	YES	YES	YES
Month	YES	YES	YES	YES
Station × Year	YES	YES	YES	YES
N	2647	2647	2647	2647
Adjusted R^2	0.9949	0.9949	0.9879	0.9880

Table 7. Estimates when using monthly data

Note: *, **, and *** indicate statistical significance at 5%, 1%, and 0.1%, respectively. The effect size of the average pollen count indicates the percentage change in the dependent variable relative to its mean when the average monthly pollen increases by one standard deviation from the mean. The effect size of the number of high pollen days indicates the percentage change in the dependent variable relative to its mean when one additional high pollen day is added. Standard errors are adjusted for clustering at the station-year level.

8. Conclusion

To determine the impacts of pollen exposure on consumption behavior, this study used a combination of purchase records from 2013 to 2019 based on home scanner data and pollen counts recorded at monitoring stations throughout Japan to analyze changes in consumption expenditure due to daily pollen variations. The results provided robust evidence that in-store consumption expenditure decreases by about 2% on high pollen days. Furthermore, this effect is also observed using weekly and monthly data, showing the lasting effect of pollen on the consumption expenditure reduction.

This study presents novel evidence that pollen exposure inhibits economic activity, thereby revealing that pollen reduction has economic benefits. The magnitude of the impact of airborne pollen found is close to that of air pollution shown by previous studies (Kang et al., 2019; Sun et al., 2019). The study's findings emphasize that economists should pay as much attention to pollen as they do to air pollution. In addition, although pollen is a natural phenomenon, it can increase with human activity, suggesting that its potential negative effects could become even greater in the future. The results of this study may also be an underestimate, as the data used did not include expenditure on eating out and leisure activities. If pollen exposure has a greater impact on eating out and leisure activities, the negative effects of pollen would become even more critical.

The key findings of this study provide a new perspective that pollen should be considered, thereby adding to the literature in the fields of urban planning, climate change, public health, and environmental policy. Social welfare can improve by considering the negative externalities caused by pollen when conducting urban planning. Since many industrialized countries have greened their cities to improve living conditions and landscapes, ignoring the effects of pollen could result in an unintended public nuisance. The impact of pollen should also be considered in forestry given that the cause of seasonal allergies in Japan is the artificial planting policy pursued during the economic growth period. In addition, since it is difficult to remove the cause of the pollen once it has been produced, accurate forecasts about pollen dispersal may help seasonal allergy sufferers better prepare for it. There is also a need to develop and roll out medicines to relieve the symptoms of seasonal allergies. The effective prevention of pollen can not only improve people's well-being, but also promote economic activity.

Despite the series of fixed effects and robustness checks used in this study, there are some caveats and limitations to the results. First, the home scanner data used in this study do not represent total household consumption expenditure, as goods whose prices are unknown are excluded from the analysis. Therefore, if there is any association between the prevalence of seasonal allergies and characteristics of the products purchased, the results may be biased.

Second, this study uses weekly and monthly data to confirm that the effects of pollen are lasting, but does not discuss longer-term effects. The negative effects of bad seasonal weather such as cold summers and warm winters can bounce back the following season. Similarly, people may avoid purchasing in high pollen seasons and consume more in non-pollen seasons. This is a challenge for future research, as longer-term data are needed to examine this.

Finally, the identification strategy of this study does not reveal in detail the mechanisms that lead to the reduction in consumption. Is the decline in consumption due to less disposable income or less outdoor activity? If the latter, is it because people are avoiding pollen? Or are the allergy symptoms so painful that people cannot leaves their homes? To answer these questions, it would be fruitful to conduct an analysis with data that could identify seasonal allergy sufferers. The impact of pollen on outdoor activities may also be understood by using more detailed data on the location of product purchases. In addition, investigating the path of the decline in consumption is an interesting challenge. If less outdoor activity and fewer opportunities for consumption are being turned into savings, then enhanced online and mail order shopping might solve the problem. If seasonal allergies reduce labor productivity, which in turn lowers income and reduces consumption, then the problem is exacerbated. Using detailed data, including precise household income, savings, and health care costs, to identify the mechanisms by which airborne pollen affects individual behavior is thus another important future task.

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Goods category
Medical supplies
Eye, nose and ear care products
Oral allergy medication
Rhinitis medicine
Nasal congestion remedy
Anti-drowsiness drug
Tissue paper
Mask
Eye drops
Other hygiene and medical products
Other medicines for sensory organs
Other respiratory medicines
Glasses and contact lenses
Glasses
Spectacle lens
Glasses related products
Contact lens
Chemicals for contact lenses

Appendix A. List of pollen-related goods

Source: Macromill Inc.

	Store purchases	Number of monitors	Store purchases per monitor	Online shop & Mail order	Pollen-related goods
	(1)	(2)	(3)	(4)	(5)
	Coeff.	Coeff.	Coeff.	Coeff.	Coeff.
	(Std. Err.)	(Std. Err.)	(Std. Err.)	(Std. Err.)	(Std. Err.)
	Eff. Size	Eff. Size	Eff. Size	Eff. Size	Eff. Size
High pollen day	-1997.171**	-0.091	-29.123**	-49.831	362.333***
	(640.928)	(0.126)	(10.481)	(155.065)	(33.889)
	-1.876%	-0.134%	-1.819%	-0.444%	31.116%
Weather					
Rain dummy	-9971.891***	-4.429***	-37.375**	-63.327	-148.876***
	(818.505)	(0.213)	(12.077)	(159.431)	(22.781)
Temperature	587.790***	0.157***	4.871***	27.166*	9.505***
	(51.822)	(0.010)	(0.729)	(12.199)	(1.747)
Wind speed	230.173	-0.125***	6.387**	30.855	10.866*
	(138.655)	(0.029)	(1.836)	(32.311)	(4.754)
Fixed Effects					
Station	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES
Month	YES	YES	YES	YES	YES
Day of week	YES	YES	YES	YES	YES
Station × Year	YES	YES	YES	YES	YES
Station × Month	YES	YES	YES	YES	YES
N	95272	95272	95272	95272	95272
Adjusted R^2	0.9354	0.9934	0.1941	0.7826	0.6947

Appendix B. Estimation results when considering the scan lag

Note: *, **, and *** indicate statistical significance at 5%, 1%, and 0.1%, respectively. The effect size indicates the percentage change in the dependent variable relative to its mean on a high pollen day. Standard errors are adjusted for clustering at the station-year-month level.

Dependent Variable	level (1)	level (2)	log (3)	level (4)
Pollen count	-0.958			-2.635**
	(0.495)			(0.853)
ln(Pollen count)		-8.695	-5.952×10^{-4}	
		(136.001)	(29.084×10^{-4})	
Pollen count suqared				$3.317\times10^{-5*}$
				(1.289×10^{-5})
Weather				
Rain dummy	-9971.008***	-9955.701***	-0.114***	-10011.046***
	(931.941)	(822.566)	(0.017)	(819.997)
Temperature	591.264***	585.567***	0.005***	600.076***
	(58.646)	(52.466)	(0.001)	(51.959)
Wind speed	225.869	224.943	0.001	228.640
	(157.925)	(138.862)	(0.002)	(139.038)
Fixed Effects				
Station	YES	YES	YES	YES
Year	YES	YES	YES	YES
Month	YES	YES	YES	YES
Day of week	YES	YES	YES	YES
Station × Year	YES	YES	YES	YES
Station × Month	YES	YES	YES	YES
N	95272	95272	95272	95271
Adjusted R^2	0.9364	0.9364	0.8478	0.9364

Appendix C. Estimates of the alternative specification

Note: *, **, and *** indicate statistical significance at 5%, 1%, and 0.1%, respectively. The dependent variable in columns (1), (2), and (4) is in-store consumption expenditure. The dependent variable in column (3) is in-store consumption expenditure taken as the natural logarithm. Standard errors are adjusted for clustering at the station-year-month level.

	Store purchase		Online shop & Mail order		Pollen-related goods	
	(1)	(2)	(3)	(4)	(5)	(6)
	Coeff.	Coeff.	Coeff.	Coeff.	Coeff.	Coeff.
	(Std. Err.)	(Std. Err.)	(Std. Err.)	(Std. Err.)	(Std. Err.)	(Std. Err.)
	Eff. Size	Eff. Size	Eff. Size	Eff. Size	Eff. Size	Eff. Size
Average pollen count	-0.032*		-0.006		0.004***	
	(0.012)		(0.005)		(0.000)	
	-0.159%		-0.281%		1.804%	
# of high pollen days		-18.688***		-3.976*		5.001***
		(4.039)		(1.843)		(0.305)
		-0.410%		-0.821%		9.947%
Weather						
# of rainy days	-0.142	-1.019	2.957	2.768	-0.399	-0.146
	(5.762)	(5.768)	(2.729)	(2.730)	(0.335)	(0.334)
Temperature	9.754***	1.544***	0.784	1.173	2.270***	1.709***
	(2.166)	(2.208)	(0.990)	(1.011)	(0.130)	(0.131)
Wind speed	29.914***	28.992***	11.530***	11.334***	0.438	0.675
	(6.599)	(6.599)	(3.139)	(3.140)	(0.374)	(0.305)
Individual characteristics	YES	YES	YES	YES	YES	YES
Fixed Effects						
Station	YES	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES	YES
Week	YES	YES	YES	YES	YES	YES
Station × Year	YES	YES	YES	YES	YES	YES
N	2351629	2351629	2351629	2351629	2351629	2351629
Adjusted R^2	0.1916	0.1916	0.0256	0.0256	0.0124	0.0125

Appendix D. Estimates when using scan monitor-level data (weekly)

Note: *, **, and *** indicate statistical significance at 5%, 1%, and 0.1%, respectively. The effect size of the average pollen count indicates the percentage change in the dependent variable relative to its mean when the average weekly pollen increases by one standard deviation from the mean. The effect size of the number of high pollen days indicates the percentage change in the dependent variable relative to its mean when one additional high pollen day is added. Individual characteristics are controlled for: age, gender, marital status, presence of children, whether the individual is the head of the household, whether he or she is the main shopper in the household, occupation reported in 12 categories, family structure reported in five categories, housing type reported in six categories, household annual income reported in 14 categories, and family size reported in five categories. Standard errors are adjusted for clustering at the station-year level.

	Store purchase		Online shop & Mail order		Pollen-related goods	
	(1)	(2)	(3)	(4)	(5)	(6)
	Coeff.	Coeff.	Coeff.	Coeff.	Coeff.	Coeff.
	(Std. Err.)	(Std. Err.)	(Std. Err.)	(Std. Err.)	(Std. Err.)	(Std. Err.)
	Eff. Size	Eff. Size	Eff. Size	Eff. Size	Eff. Size	Eff. Size
Average pollen count	-1.461***		-0.186*		0.077***	
	(0.229)		(0.091)		(0.009)	
	-0.754%		-0.905%		3.621%	
# of high pollen days		-125.262***		-18.362***		5.022***
		(9.869)		(4.028)		(0.526)
		-0.643%		-0.889%		2.349%
Weather						
# of rainy days	325.967***	330.032***	36.269***	36.847***	2.950***	2.775**
	(21.827)	(21.824)	(8.969)	(8.974)	(0.878)	(0.877)
Temperature	590.198***	657.763***	54.003***	64.262***	20.418***	17.947***
	(22.901)	(23.684)	(8.202)	(8.407)	(0.857)	(0.869)
Wind speed	426.339***	406.439***	103.135**	100.209**	-3.923	-3.130
	(79.255)	(79.156)	(34.141)	(34.148)	(2.877)	(2.876)
Individual characteristics	YES	YES	YES	YES	YES	YES
Fixed Effects						
Station	YES	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES	YES
Month	YES	YES	YES	YES	YES	YES
Station × Year	YES	YES	YES	YES	YES	YES
N	578858	578858	578858	578858	578858	578858
Adjusted R^2	0.2888	0.2890	0.0549	0.0550	0.0398	0.0399

Appendix E. Estimates when using scan monitor-level data (monthly)

Note: *, **, and *** indicate statistical significance at 5%, 1%, and 0.1%, respectively. The effect size of the average pollen count indicates the percentage change in the dependent variable relative to its mean when the average monthly pollen increases by one standard deviation from the mean. The effect size of the number of high pollen days indicates the percentage change in the dependent variable relative to its mean when one additional high pollen day is added. Individual characteristics are controlled for: age, gender, marital status, presence of children, whether the individual is the head of the household, whether he or she is the main shopper in the household, occupation reported in 12 categories, family structure reported in five categories, housing type reported in six categories, household annual income reported in 14 categories, and family size reported in five categories. Standard errors are adjusted for clustering at the station-year level.