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How is the Asian economy recovering from COVID-19? Evidence from the emissions of air pollutants

Kazunobu Hayakawa *, Souknilanh Keola

Development Studies Center, Institute of Developing Economies, Japan

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ABSTRACT

This study examines how economic and social activities in Asia were affected by the COVID-19 pandemic, using the emissions of various air pollutants as representative measures of those activities. Our review of emissions data suggests that the amount of air pollutants emitted decreased in most subnational regions from 2019 to 2020. We also determined that economic and social activities have restarted in some regions in many countries. Moreover, we conduct regression analyses to identify the types of regions that restarted earlier. Regional characteristics are distinguished by employing a remotely sensed land cover dataset and OpenStreetMap. Results reveal that in the case of the Association of Southeast Asian Nations (ASEAN) forerunners, economic and social activities in cropland, industrial estates, accommodations, restaurants, education, and public services have not yet returned to previous levels.

1. Introduction

Many countries imposed restrictions on the movement and activities of people and businesses, including citywide or nationwide lockdowns, to contain the spread of COVID-19. An example is workplace-closing policies, which require closing all-but-essential workplaces (e.g., grocery stores). If the workplace-closing policy banned factory operations, production activities would stop entirely. For example, Japanese car manufacturers have suspended their production in Japan for several days monthly since April 2020. However, some industries are permitted to operate if they observe adequate infection control measures (e.g., social distancing). Several countries, such as China, India, Malaysia, and the Philippines, allowed the operation of export-oriented firms, firms in special economic zones, or industries that must produce to maintain supply chain operations. Therefore, the recovery of economic activities has been observed to be geographically uneven in each country.

In this study, we examine how economic and social activities in East Asia and Southeast Asia were affected by the COVID-19 pandemic. The sample includes 10 Association of Southeast Asian Nations (ASEAN) nations and six partner countries of ASEAN free trade agreements (FTAs). Owing to these trade linkages, the countries under study may follow a common economic mechanism even during the pandemic era. We examine the regions that have resumed economic and social activities early. The magnitudes of those activities were measured using the emissions of various air pollutants. One advantage of using air pollution data is that the data are provided almost instantaneously (near real-time data) daily and with a very high spatial resolution. We then aggregate these data by months and subnational regions. Our study period is from January to October in 2019 and 2020. Using this measure, we determine

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* Correspondence to: Wakaba 3-2-2, Mihama-ku, Chiba-shi, Chiba 261-8545, Japan.
E-mail address: kazunobu_hayakawa@ide-gsm.org (K. Hayakawa).
how the quantity of air pollutants emitted is related to economic or regional attributes, such as establishments or infrastructure. Those regional characteristics are identified by employing the remotely sensed land cover dataset and OpenStreetMap (OSM).

Our analytical framework presents the empirical means to instantaneously uncover what is happening at a detailed regional level. This paper relies solely on publicly available data; thus, anyone can conduct similar investigations. Furthermore, the data used are available for most countries, including the least developed. In short, our data are not official data collected or published by governments. Nevertheless, the availability of such data is an important advantage for developing countries that do not collect sufficient official data. In particular, governments must immediately understand the effects of sudden shocks such as COVID-19. Such effects include not only those of the shocks per se but also those of policy interventions designed to address the shocks. Our empirical framework allows us to instantaneously examine those effects at a detailed regional level. In this study, we demonstrate how this framework is applied to examining COVID-19 shocks.

Furthermore, through this study, we contribute to the growing literature on the effects of lockdown orders during the COVID-19 pandemic. Several studies have investigated the effect of lockdown orders on the number of confirmed COVID-19 cases (Askitas, Tatsiramos, & Verheyden, 2020; Ghosh, 2020; Ullah & Ajala, 2020), the number of deaths (Conyon, He, & Thomsen, 2020), unemployment insurance claims (Kong & Prinz, 2020), international trade (Hayakawa & Mukunoki, 2021), and household spending and macroeconomic expectations (Coibion, Gorodnichenko, & Weber, 2020). Furthermore, many studies have also examined the effect of lockdown orders on air pollution. Although most of these studies investigated the effect for a specific country or region, some studies have examined the effect of lockdowns on the quantity of air pollutants emitted for a global sample (e.g., Dang & Trinh, 2020; Deb, Fuceri, Ostry, & Tawk, 2020; Keola & Hayakawa, 2021). These studies have consistently found that lockdown orders decreased the amount of air pollutants emitted. Unlike the aforementioned studies, this research particularly examines the geographical or economic attributes of regions that recovered early from the negative effects of lockdown orders.

The major findings can be summarized as follows. First, according to the emissions data from 2019 to 2020, the quantity of air pollutants emitted decreased in most subnational regions. Second, the change in emissions was not uniform across the regions in a country. In several countries, economic and social activities seem to have started in some specific regions. Third, the regression analyses indicate that in the case of ASEAN forerunners, economic and social activities in crops, industrial estates, accommodations, restaurants, education, and public services have not fully recovered. However, full recovery or increase in tourism sites is apparent. In the case of ASEAN latecomers, activities in accommodation and automotive sectors decreased and later returned to normal. More activities were found in restaurants in 2020. However, activities in education sites have remained low. In the ASEAN-1 FTA partner countries, no significant changes were noted in the economic and social activities in most locations, other than shops and sports sites, where activities decreased.

The remainder of this paper is organized into four sections. Section 2 introduces the air pollutants examined in this study. Section 3 presents the empirical framework. Section 4 shows the estimation results. Section 5 concludes the paper.

2. Overview of air pollutants

Air pollutants are emitted from both anthropogenic and natural sources. Most economic activities emit air pollutants through the generation and consumption of energy. The tropospheric monitoring instruments (TROPOMI) mounted on Sentinel 5P, which was put on the orbit by the European Space Agency (ESA) in 2017, provide an unprecedented number of remotely sensed air pollution data with global coverage. The daily spatial and temporal resolution of TROPOMI is 7 x 7 km, which is considered high enough for this study. We then used the amount of air pollutants emitted from the TROPOMI to represent the extent of economic and social activities. We obtained the data of 16 countries, namely, the 10 ASEAN countries, Australia, China, India, Japan, South Korea, and New Zealand. We then aggregated up to the first-level subnational administrative units (ADM1), as defined in the Global Administrative Unit Layers (GAUL) of the United Nations’ Food and Agriculture Organization (FAO). For example, ADM1 includes prefectures in Japan and provinces in China, Thailand, and Vietnam.

We then assess three air pollutants as indicators of air pollution, namely, carbon monoxide (CO), formaldehyde (HCHO), and nitrogen dioxide (NO2). CO is considered a major atmospheric pollutant in urban areas. Its primary sources are the combustion of fossil fuels, biomass burning, and the atmospheric oxidation of methane and other hydrocarbons. HCHO is primarily emitted through biomass burning, vegetation, and vehicle and industrial emissions. Seasonal variations of this pollutant are primarily related to temperature and fire events. Finally, NO2 is emitted through human activities, particularly fossil fuel combustion, biomass burning,
and natural processes, such as microbiological processes in soils due to wildfires and lightning. During the daytime, a photochemical cycle involving ozone (O₃) converts nitrogen monoxide (NO) into NO₂. Therefore, the NO₂ provided by the TROPOMI is sometimes referred to as NOₓ, implying a combination of NO and NO₂. The volume of these pollutants is related to economic and social activities.⁵

We then review the changes in the quantity of air pollutants emitted from 2019 to 2020. We first compute the sum of each pollutant emitted from January to October in each year and then take the log difference of this sum between 2019 and 2020. The results for CO are presented in Fig. 1. Australia, New Zealand, the western part of China, Western India, and parts of continental ASEAN⁶ had a relatively large positive change in CO emissions from 2019 to 2020. In contrast, negative growth has been observed in many subnational regions in the eastern part of China, Vietnam, and maritime ASEAN.⁷ Moreover, CO emissions have decreased in South Korea and in the northern and western coastal areas of Japan (i.e., rural areas).

CO emissions derive from several sources. A major non-economic source of CO is combustion-related emissions that occur during forest fires. For example, a series of unusual and intense forest fires broke out in Australia in the autumn of 2019 and lasted until the spring of 2020, and CO increased in 2020 compared with 2019. Forest fires increase CO directly because of incomplete combustion (Vadrevu, Prasad, Giglio, & Justice, 2013). Although unusual, no forest fires were reported in Myanmar, Laos, Thailand, Cambodia, the western part of China, and India in 2020. The increase in rural population due to lockdown measures in urban areas may increase the use of less efficient stoves in rural areas and possibly emit CO because of incomplete combustion.

Fig. 2 presents the changes in HCHO, which reveal a more evident decrease in comparison to CO. All subnational regions, except for those mainly in Australia, experienced a considerable decrease. The decrease in NO₂ was also substantial in most subnational regions, particularly in the industrialized eastern coast of China (Fig. 3). Moreover, a slight increase is observed only in Australia, New Zealand, and adjacent subnational regions in Indonesia. Biomass burning is one of the major sources of NO₂; hence, its emissions increased in these countries due to intense forest fires or the use of less efficient stoves in rural areas, as in the above case of CO (Lazaridis et al., 2008). Although these non-economic sources exist, we expect that changes in CO, HCHO, and NO₂ mainly indicate variations in economic and social activities, particularly in subnational regions without substantial differences in natural and non-economic emissions between 2019 and 2020.

Next, the overtime changes in the σ-convergence index of economic activities are examined. We compute the standard deviation of the log difference of the monthly amount of each pollutant emitted from 2019 to 2020 in the ADM1-level regions within a country. Then, for easy comparison among the pollutants, we rescaled the standard deviation for January to 1. The σ-convergence index in month t in a country is given as follows:

\[ \sigma_{i} = \frac{SD_{i}(\ln Y_{i}^{2020} - \ln Y_{i}^{2019})}{SD_{i}(\ln Y_{i}^{2020} - \ln Y_{i}^{2019})}. \]

\( Y_{i}^{2020} \) refers to the amount of air pollutant emitted in an ADM1-level region i in month t. SD･(･) indicates a standard deviation operator over i.⁸ An increase in this index implies that the amount emitted is more diversified across regions in a country. If the amount changes only in some regions, this index increases. Thus, this index is used to examine how geographical concentrations of economic and social activities changed in each country.

Fig. 4 presents the changes in this index in the ASEAN forerunners (labeled as ASEAN6), comprising Brunei, Indonesia, Malaysia, the Philippines, Singapore, and Thailand. Its trend is not necessarily consistent across the three indicators of air pollution; however, we can observe fluctuations in the index in all countries over time, implying that the amount of air pollutants began to increase (or decrease) only in some specific regions. Compared with other countries, Thailand shows less fluctuation (notice the difference in the magnitude of the vertical unit across countries). This result might indicate that the within-country disparity in economic and social activities did not change that much in Thailand. In addition, the index of some air pollutants has increased significantly during lockdown and post-lockdown periods, that is, since March. These pollutants include HCHO in Brunei, CO in Indonesia and the Philippines, HCHO and NO₂ in Malaysia, NO₂ in Singapore, and HCHO, NO₂, and CO in Thailand. Pollutants with notable changes might be those emitted from major industries in each country. Depending on the lockdown orders, some regions experienced a sudden decline or bouncing back of the major pollutants.

Fig. 5 presents the changes in the index in ASEAN latecomers, comprising Cambodia, Laos, Myanmar, and Vietnam (labeled as CLMV). A gradual increase is noted in Cambodia, indicating that economic and social activities have started in some of its regions. Indeed, compared with other ASEAN countries, Cambodia did not introduce strict lockdown orders. In Laos, the index increased sharply in May, which might be due to the relaxation of lockdown orders in that month. In Myanmar, the index did not fluctuate much.

⁵ For example, Fig. A1 in the Appendix presents scatterplot graphs between a log of the annual quantity of emissions for each type of air pollutant and a log of GDP at the country level. The observations include those for our study: 16 countries in 2019. The data on GDP were obtained from the World Development Indicator. The three air pollutants are positively related to GDP.

⁶ Continental ASEAN refers to Cambodia, Laos, Myanmar, Thailand, and Vietnam.

⁷ Maritime ASEAN refers to Brunei, Indonesia, Malaysia, the Philippines, and Singapore.

⁸ Barro and Sala-i-Martin (2004) compute the cross-sectional standard deviation for the log of per capita personal income net of transfers for 47–48 U.S. states or territories as σ-convergence index. Rather than per capita income, we use the amount of air pollutants. Furthermore, to avoid calendar month-specific effects, we normalized their amount in a month in 2020 by that of the same month in 2019. We then rescaled this index for January to 1. As an additional measure, the coefficient of variance in the quantity of emissions in a month in 2020 was computed and normalized by that of the same month in 2019. The results are reported in Figs. A2–A4 in the Appendix and demonstrate a similar trend to those in the above σ-convergence index.
Fig. 1. The log difference of CO emission from January to October in 2019 and 2020.

Source: Authors’ compilation using the TROPOMI.
Fig. 2. The log difference of HCHO emission from January to October in 2019 and 2020.  
Source: Authors’ compilation using the TROPOMI.
Fig. 3. The log difference of NO2 emission from January to October in 2019 and 2020.

Source: Authors’ compilation using the TROPOMI.
Fig. 4. $\sigma$-convergence Indices in ASEAN Forerunners. Notes: The standard deviation of each pollutant in the ADM1-level regions is shown by months and countries. The emission amount in a month is normalized by that of the same month in 2019. Furthermore, we have rescaled the standard deviation for easy comparison among the pollutants so that the value in January becomes 1.

Source: Authors’ compilation using the TROPOMI.
and did remain around a value of 1, indicating that the within-country disparity in economic and social activities did not change much, compared with those of last year. Similarly, in Vietnam, the index is relatively stable, with the exception of CO. Vietnam’s relatively small number of confirmed cases and deaths may not have changed economic and social activities much. However, fluctuations in CO may be due to emissions in the relatively active regions.

Fig. 6 presents the index in several partner countries of ASEAN+1 FTAs (labeled as Plus6), comprising Australia, China, India, Japan, Korea, and New Zealand. Considering the magnitude of the vertical axis, the indexes do not demonstrate a large fluctuation in Plus6, other than New Zealand, in comparison to those in ASEAN6; these indexes only changed within a small range. For example, in Australia, the HCHO index rises in July and August. In China, the index shows a declining trend up to July, after which it began to gradually increase. Meanwhile, India experienced an increase in September. In Japan, it declined until around June, after which it began to gradually increase. A similar trend was also observed in Korea. In contrast to these countries, New Zealand demonstrates a large fluctuation of the index; in particular, the HCHO index increased drastically in June. New Zealand has been successful in terms of containing the spread of COVID-19. Our result may indicate that such containment was realized by ceasing economic and social activities in specific regions.

In summary, the regional disparity in air pollutants was not uniform across the countries. The extent of regional disparity varied over time, particularly in Brunei, Indonesia, Malaysia, the Philippines, Singapore, and New Zealand. A sharp rise in the index of some pollutant indicators was observed, indicating the restart (or discontinuation) of economic and social activities only in specific regions. In the following sections, we further examine the activities that regions restarted earlier or continued restricting.

3. Empirical analyses

This section explains the empirical framework used to examine the types of regions that restarted economic activities early. We specify our model as follows:

$$\ln Y_{it} = X_i^\prime \beta_y + Z_i^\prime \gamma + \delta c + \epsilon_{it},$$

(1)

where $Y_{it}$ represents the pollutant indicators in region $i$ in country $c$ in month $t$, year $y$. As noted, the indicators of pollutants are CO, HCHO, and NO$_2$. A vector of $X$ includes various regional characteristics, which are time-invariant. $\beta_y$ is a vector of year-variant...
Fig. 6. $\sigma$-convergence Indices in Plus6. Notes: The standard deviation of each pollutant in the ADM1-level regions is shown by months and countries. The emission amount in a month is compared with that of the same month in 2019. Furthermore, we have rescaled the standard deviation for easy comparison among the pollutants so that the value in January becomes 1. 
Source: Authors’ compilation using the TROPOMI.
Table 1
Data and characteristics of subnational regions.

| Industry | Sources | Indicators | Examples |
|----------|---------|------------|----------|
| Primary  | ESALC   | Cropland   | Cropland |
|          | OSM     | Farm       | Rice field, plantation |
|          |         | Quarry     | Coal mine, copper mine, pit |
| Secondary| OSM     | Industrial site | Industrial estate, processing plant |
|          |         | Dirty-power plants | Coal, fire, waste power plant |
|          |         | Clean-power plants | Hydroelectric, solar, wind power plant |
| Tertiary | OSM     | Accommodation | Hotel, guesthouse, apartment |
|          |         | Automotive | Gasoline station, carpark, carwash |
|          |         | Business | Bank, office, company |
|          |         | Restaurant | Macdonald, Starbucks, cafe |
|          |         | Education | School, university, kindergarten |
|          |         | Health | Hospital, clinic |
|          |         | Public service | Ministry, post office, village office |
|          |         | Religious site | Temple, mosque, church |
|          |         | Settlement | Hamlet, village |
|          |         | Shop | Market, store, supermarket |
|          |         | Sport | Stadium, pool, court |
|          |         | Tourism | Beach, museum, theater |
|          |         | Transport | Road, station, port, airport |

Notes: All variables, except for Cropland, are measured by the number of sites. Cropland is measured by square kilometers.

Source: Authors’ compilation.

coefficients. These coefficients indicate the quantity of air pollutants emitted in each type of region in each year. For example, the changes in people’s behavior due to the spread of COVID-19 or government orders to avoid its spread will affect the amount of pollutant emissions. A vector of Z includes assorted time-variant, weather-related variables, and γ is a vector of fixed coefficients. The elements in these vectors are explained below. δ_c indicates country–month–year fixed effects. ε_{it} is a disturbance term.

We estimate the year-to-year version of Eq. (1); specifically, we calculate the difference between the years 2019 and 2020, as follows:

\[
\ln y_{it}^{2020} - \ln y_{it}^{2019} = X_i \beta + Z_i \gamma + \delta_{it} + \epsilon_{it},
\]

(2)

where \( \beta \equiv \beta^{2020} - \beta^{2019} \), \( Z_i \equiv Z_i^{2020} - Z_i^{2019} \), \( \delta_{it} \equiv \delta_{it}^{2020} - \delta_{it}^{2019} \), and \( \epsilon_{it} \equiv \epsilon_{it}^{2020} - \epsilon_{it}^{2019} \). Thus, the dependent variable is a log difference of the pollutant indicators in region i in country c in month t from 2019 to 2020, measuring the extent of recovery in economic activities. Country–month fixed effects (\( \delta_{it} \)) will control for COVID-19-related policy measures (e.g., a state of emergency or a policy measure to encourage domestic travel) at a country–month level, the strictness and timing of which may differ across countries. Although these measures might differ across subregions within each country at a detailed level, we control for these differences at least across countries and months. \( \epsilon_{it} \) is a disturbance term, which is assumed to be independent of X and Z. We estimate this equation using the ordinary least squares (OLS) method.

The variables that represent regional characteristics are derived from two data sources, ESALC and OSM. ESALC is a remotely sensed land cover dataset, compiled by the ESA that classifies each grid of approximately 500 × 500 m into 22 categories based on the classification system of the United Nations’ FAO. OSM is a free and editable world map powered by high-resolution satellite images that was built from scratch, was maintained by volunteers, and offers an open-content license. Volunteers worldwide have added spatial information, such as shapes of roads, buildings, and points of interest (POI). As of March 2020, approximately 6 million global users were registered, of which about 5000 have actively contributed to updating the OSM by uploading or editing spatial data daily. Moreover, POI has 14 categories and more than 200 subcategories. We use these data from 2019.

OSM has both strengths and limitations. The strength of OSM is its openness. POI data in commercial search engines, such as Microsoft’s Bing or Google Maps, are generally better, are more accurate, are more up-to-date, and have wider coverage. Adequate financial resources and the considerable market power of these global companies are the sources of this better performance. Large and small enterprises worldwide voluntarily supply information to these search engines to increase exposure to more potential customers; however, the problem is that these are not free. Furthermore, the data cannot be downloaded in bulk; thus, this would require extensive time and likely prohibitively high cost and require sophisticated programs to compile comprehensive subnational data, even for our 16 countries.

In contrast, all raw data of OSM are available for download in bulk within around 48 h. Extracting data using a required spatial unit of analysis decreases time, cost, and computational resources; however, the limitation is the uneven coverage. OSM data need to be input by volunteers. Developed countries have more people with better internet access, sophisticated technical skills, and willingness to contribute. Tourists, scholars, and students traveling from developed countries to developing countries contribute substantially. Moreover, several global-scale activities (e.g., the Missing Maps movement) are aiming to increase the coverage of OSM.\(^9\) However,
currently, OSM’s coverage continues to be much better in higher-income countries than in developing ones. In our analysis, we address such differences in coverage across countries, as will be explained later.

The variables of regional characteristics were constructed using data from these two sources. Table 1 summarizes the indicators. First, based on the ESALC data, we aggregate the sizes (km²) of four cropland-related areas, including rain-fed cropland, irrigated cropland, and two cropland mosaics (larger and smaller than 50%), to construct a cropland indicator for this study. The numbers of farms and quarries (mineral-extracting activities) by subnational regions were derived from OSM. Secondary industry is divided into power generation and others. Power generation represents the number of power plants derived from the Global Power Plant Database and is further divided into dirty (e.g., biomass, coal, gas, oil, and waste) and clean generation (e.g., geothermal, hydro, nuclear, solar, and wind). Others represent the number of places tagged in OSM as “industrial,” and mostly represent factories and industrial estates.

Tertiary industry can be captured in detail with OSM. We use the number of places tagged as accommodations, automotive, business, restaurants, education, health, public service, religious, settlement, shop, sport, tourism, and transport. The major facilities under the automotive category include petrol stations, car parks, and highway rest areas, whereas health facilities mainly include hospitals, clinics, and pharmacies. The public service category captures post offices, police stations, ministries, and other types of government facilities. Transport comprises streets, roads, railways, ports, and airports. Tourism includes places such as beaches, parks, museums, and theaters. The rest are clear from the name. We then use the numbers identified and aggregated at an ADM1 level as the main independent variables.

A vector of $Z$ includes assorted weather-related variables. We control for the mean of temperature, precipitation, snowfall, and wind speed. These weather conditions also affect the amount of air pollutants emitted. For example, some studies demonstrate that rain reduces air pollutants by washing them to the ground (e.g., Guo et al., 2016; Kwak, Ko, Lee, & Joh, 2017). The data on weather were obtained from the Global Land Data Assimilation System (GLDAS), which can combine satellite and ground-based observational information to generate high-resolution weather data with global coverage. Although almost all countries have at least one ground station, this is not the case for subnational regions. However, since GLDAS can be used to compile weather data for virtually any subnational region, we combine this remote sensing data at the subnational level.

Eq. (2) is used to examine the regions that recovered from the negative impacts of the COVID-19 pandemic early. These regions include areas with large croplands, industrial bases, or business districts. To examine the changes in critical sites over time, we estimate Eq. (2) separately for March to June and July to October. The data for January and February are not included because of the low number of COVID-19 cases and deaths. The regional characteristic variables are time-invariant and defined in 2019. The sampled countries include the 16 previously listed countries. We pool all these countries for baseline estimation. In the later analysis, we separately regress the three groups of ASEAN6, CLMV, and Plus6.

We first review the regional characteristic variables. Table 2 presents the average number of each site type among the subregions in ASEAN6. Brunei had small numbers in almost all places compared with Indonesia, in which religious sites are relatively large in number. Malaysia has moderate numbers in most spots, whereas the Philippines has many crops, restaurants, settlements, and shops, but an interesting finding is the presence of many educational sites in the country. Singapore has a few dirty and clean power plants, but it has many restaurants, shops, and transportation sites. In Thailand, only a few tourism sites are found, which might be inconsistent with the public assumptions. Other than crops, the average number of all sites seems small.

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Table 2: Average Numbers of Each Type of Sites in ASEAN6.

| BRN | IDN | MYS | PHL | SGP | THA |
|-----|-----|-----|-----|-----|-----|
| Dirty-power plants | 147  | 1139 | 1042 | 708  | 23  | 451  |
| Clean-power plants | 0    | 178  | 138  | 350  | 0   | 66   |
| Cropland | 136  | 16,737 | 6214 | 8064 | 14  | 4074 |
| Farm | 2    | 2    | 18   | 57   | 6   | 2    |
| Quarry | 1    | 0    | 1    | 3    | 0   | 0    |
| Industrial site | 4    | 38   | 40   | 117  | 12  | 3    |
| Accommodation | 12   | 247  | 244  | 543  | 59  | 152  |
| Automotive | 17   | 110  | 279  | 476  | 107 | 73   |
| Business | 28   | 222  | 164  | 506  | 111 | 36   |
| Restaurant | 205  | 395  | 795  | 1353 | 585 | 250  |
| Education | 57   | 1161 | 464  | 2048 | 94  | 157  |
| Health | 16   | 312  | 167  | 524  | 64  | 50   |
| Public service | 46   | 569  | 211  | 907  | 65  | 48   |
| Religious site | 22   | 994  | 268  | 626  | 54  | 83   |
| Settlement | 81   | 2355 | 609  | 1934 | 24  | 245  |
| Shop | 484  | 746  | 979  | 2685 | 590 | 237  |
| Sport | 8    | 155  | 92   | 312  | 55  | 13   |
| Tourism | 22   | 766  | 235  | 717  | 152 | 60   |
| Transport | 23   | 93   | 167  | 347  | 600 | 41   |

Notes: All variables, except for Cropland, are measured by the number of sites. Cropland is measured by square kilometers.

Source: Authors’ compilation using the ESALC and OSM data. BRN, Brunei Darussalam; IDN, Indonesia; MYS, Malaysia; PHL, Philippines; SGP, Singapore; THA, Thailand.
Note that the size of ADM1 varies significantly among these countries. ADM1 is much smaller in continental ASEAN than in maritime ASEAN. This finding is responsible for the small number of each type of facility in Thailand. In addition, the size and distribution of the population are essential in the numbers. As mentioned, OSM is built and maintained by volunteers; therefore, the volume of information depends on the internet environment and volunteers’ efforts, both of which naturally vary per country. In the regression analyses, these differences across countries are controlled by using the 1-year difference of regional-level pollutants as the dependent variable and introducing country fixed effects ($\delta_c$).

Table 3 reports the average numbers in CLMV. Cambodia has moderate numbers in most sites. Laos has similar numbers, but it has many more restaurants and settlements than Cambodia. This difference is reasonable since the population in Laos is more scattered than that in Cambodia. In Myanmar, the number of crops is outstanding. Among other countries in this group, Myanmar has the largest numbers in most types partly because the average size of ADM1 is largest in this country. Meanwhile, Vietnam has a relatively large number of dirty and clean power plants and many shops.

The average numbers in the Plus6 group are presented in Table 4. Compared with the numbers in the previous tables, we can see many large numbers in most sites. As noted, these large numbers are partly due to more volunteers entering information into OSM, and many people in industrialized nations having the capacity and technology to contribute to OSM. There are a large number of accommodations, sports, tourism, and transport sites in Australia. Similarly, China has several dirty and clean power plants and a large number of settlements. India has a relatively large number of health sites, and Japan has many education and public service sites.

Table 3
Average Numbers of Each Type of Sites in CLMV.

|                  | KHM | LAO | MMR | VNM |
|------------------|-----|-----|-----|-----|
| Dirty-power plants | 23  | 110 | 65  | 346 |
| Clean-power plants | 35  | 183 | 162 | 265 |
| Cropland          | 2799| 2390| 12,522| 2202|
| Farm              | 1   | 0   | 7   | 2   |
| Quarry            | 0   | 1   | 3   | 0   |
| Industrial site   | 2   | 2   | 10  | 8   |
| Accommodation     | 61  | 96  | 92  | 91  |
| Automotive        | 34  | 49  | 24  | 28  |
| Business          | 23  | 32  | 55  | 41  |
| Restaurant        | 72  | 124 | 182 | 179 |
| Education         | 35  | 25  | 133 | 83  |
| Health            | 12  | 19  | 88  | 90  |
| Public service    | 17  | 25  | 88  | 42  |
| Religious site    | 31  | 20  | 214 | 55  |
| Settlement        | 58  | 384 | 567 | 132 |
| Shop              | 54  | 77  | 269 | 241 |
| Sport             | 3   | 6   | 26  | 11  |
| Tourism           | 31  | 67  | 95  | 58  |
| Transport         | 14  | 10  | 171 | 72  |

Notes: All variables, except for Cropland, are measured by the number of sites. Cropland is measured by square kilometers.
Source: Authors’ compilation using the ESALC and OSM data. KHM, Cambodia; LAO, Lao People’s Democratic Republic; MMR, Myanmar; VNM, Vietnam.

Table 4
Average Numbers of Each Type of Sites in Plus6.

|                  | AUS | CHN | IND | JPN | KOR | NZL |
|------------------|-----|-----|-----|-----|-----|-----|
| Dirty-power plants | 5240| 29,882| 6712| 1320| 2489| 83  |
| Clean-power plants | 1333| 10,685| 1589| 1169| 1971| 394 |
| Cropland          | 24,771| 68,616| 61,668| 1845| 665 | 254 |
| Farm              | 53  | 1   | 3   | 1   | 7   | 9   |
| Quarry            | 61  | 0   | 0   | 0   | 0   | 4   |
| Industrial site   | 188 | 339 | 78  | 93  | 59  | 21  |
| Accommodation     | 1356| 300 | 431 | 316 | 610 | 269 |
| Automotive        | 1076| 221 | 195 | 852 | 554 | 147 |
| Business          | 564 | 229 | 477 | 398 | 403 | 100 |
| Restaurant        | 3004| 544 | 714 | 2863| 1282| 627 |
| Education         | 1445| 1078| 1224| 1661| 1361| 283 |
| Health            | 610 | 207 | 2472| 1137| 1391| 136 |
| Public service    | 1022| 404 | 505 | 1818| 931 | 140 |
| Religious site    | 480 | 157 | 997 | 879 | 390 | 203 |
| Settlement        | 2055| 8426| 4475| 764 | 1358| 216 |
| Shop              | 3884| 770 | 1538| 4171| 1470| 708 |
| Sport             | 1199| 152 | 154 | 411 | 297 | 129 |
| Tourism           | 2887| 691 | 394 | 1161| 680 | 679 |
| Transport         | 4866| 965 | 411 | 642 | 1539| 211 |

Notes: All variables, except for Cropland, are measured by the number of sites. Cropland is measured by square kilometers.
Source: Authors’ compilation using the ESALC and OSM data. AUS, Australia; CHN, China; IND, Indonesia; JPN, Japan; KOR, Republic of Korea; NZL, New Zealand.
Meanwhile, Korea has moderate numbers in most areas, whereas the average numbers in New Zealand are small.

4. Results

We estimate the model for the two periods separately, from March to June and July to October. In the interest of space, the results of weather-related variables are omitted. The estimation results of air pollutants in all countries are presented in Table 5. Overall, the significance and sign of the coefficients are inconsistent in the three indicators of air pollution. Regarding CO, emissions in the first period (March to June) decreased in accommodation, automotive, settlement, and transport sites. In the second period (July to October), the quantity of emissions in some of these sites either returned to normal levels or increased. Moreover, CO emissions significantly decreased in crop, industrial, restaurant, and education sites in the second period, but they significantly increased in farms, automotive sites, shops, and tourism sites. This decrease may be due to people’s continuous avoidance of crowded places even after stay-at-home orders were lifted. For example, many restaurants continued to observe social distancing measures, and online classes or a combination with onsite courses has remained a norm in many countries.

As in the case of CO, the amount of HCHO emissions in accommodation and settlement sites decreased in the first period. It also significantly decreased in sport sites. This decrease could be attributed to workplace-closing orders adopted in many countries disallowing operation of recreation and sports sites. However, in the second period, HCHO emissions in these sites returned to normal, perhaps because of the relaxation of workplace-closing orders. Meanwhile, HCHO emissions in quarry, restaurant, and education sites increased in the first period, but they significantly increased in farms, automotive sites, shops, and tourism sites. This decrease may be due to people’s continuous avoidance of crowded places even after stay-at-home orders were lifted. For example, many restaurants continued to observe social distancing measures, and online classes or a combination with onsite courses has remained a norm in many countries.

Finally, regarding NO\textsubscript{2}, few results indicate a significant difference between the quantity of emissions in 2020 and 2019. NO\textsubscript{2} emissions in automotive sites decreased in both periods but increased in crop sites. Cropland is identified on the basis of land cover data and often covers rural areas where most of the land is used for agriculture. Owing to the loose lockdowns adopted in our study countries, many people may have moved to and were active in rural areas. The quantity of NO\textsubscript{2} emissions on farms decreased in the second period.\textsuperscript{11}

Next, we estimate the model according to groups, that is, ASEAN6, CLMV, and Plus6. The estimation is focused on CO emissions.

\textsuperscript{11} Overall, a more dramatic decrease in emissions quantity may be expected in sports and tourist sites, particularly in the first period. Sites tagged as sports include open air facilities, such as sport fields, playgrounds, or golf courses. Parks and reserves are also included in Australia and New Zealand. Similarly, tourism locations include mountains, lakes, and parks. During the pandemic, people may have preferred walking around such open air places, causing emissions to be less likely to decrease.

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Table 5
Regression results for all countries by air pollutants.

| Pollution | CO Mar - Jun | CO Jul - Oct | HCHO Mar - Jun | HCHO Jul - Oct | NO\textsubscript{2} Mar - Jun | NO\textsubscript{2} Jul - Oct |
|-----------|-------------|-------------|----------------|----------------|----------------|----------------|
| Dirty-power plants | 0.000 | -0.001 | 0.000 | 0.000 | 0.001 | -0.001* |
| Clean-power plants | 0.000 | 0.001 | 0.004 | 0.000 | 0.001 | 0.001 |
| Cropland | 0.004** | -0.008*** | -0.003 | -0.002 | 0.018*** | 0.010*** |
| Farm | 0.001 | 0.005** | 0.011 | -0.004 | -0.002 | -0.004* |
| Quarry | 0.003 | -0.002 | 0.030** | -0.009 | 0.001 | 0.003 |
| Industrial site | -0.002 | -0.004* | 0.000 | -0.001 | 0.001 | 0.001 |
| Accommodation | -0.007*** | -0.008*** | -0.027*** | -0.011 | 0.000 | 0.004 |
| Automotive | -0.006** | 0.008** | -0.004 | 0.025*** | -0.019*** | -0.021*** |
| Business | -0.002 | -0.003 | -0.006 | -0.020*** | 0.001 | -0.001 |
| Restaurant | 0.006* | -0.011** | 0.022*** | -0.006 | 0.002 | 0.004 |
| Education | 0.003 | -0.006** | 0.010* | 0.000 | 0.001 | 0.003 |
| Health | 0.003 | 0.002 | 0.004 | 0.004 | -0.005* | 0.000 |
| Public service | -0.003 | 0.000 | 0.010 | 0.001 | 0.003 | 0.001 |
| Religious site | 0.006** | 0.002 | 0.005 | 0.009 | 0.001 | -0.005* |
| Settlement | -0.004** | 0.001 | -0.012** | -0.005 | 0.000 | -0.001 |
| Shop | 0.004 | 0.010** | -0.007 | 0.019* | 0.005 | 0.008* |
| Sport | 0.000 | -0.004 | -0.031*** | 0.002 | -0.003 | -0.002 |
| Tourism | 0.002 | 0.013*** | 0.005 | -0.001 | 0.003 | 0.002 |
| Transport | -0.004** | 0.003 | 0.010 | -0.005 | -0.001 | 0.000 |
| Number of observations | 1696 | 1646 | 1691 | 1640 | 1696 | 1646 |
| Adjusted R-squared | 0.654 | 0.7854 | 0.2017 | 0.4859 | 0.5645 | 0.4424 |

Notes: The estimation results using the OLS method are reported. ***, **, and * indicate 1%, 5%, and 10% levels of statistical significance, respectively. We use robust standard errors to show statistical significance. All independent variables reported in this table, except for Cropland, are measured by a log of (one plus) the number of sites. Cropland is measured by a log of (one plus) square kilometers. In all the specifications, we control for country-month fixed effects. The results of the weather-related variables are omitted.
likely because school opening restrictions were effective in these countries. Furthermore, the change in emissions was not uniform across countries China’s earlier recovery. Significant results are seen in the second period. CO emissions decreased in shops and sports sites but ‘activities did not change significantly during the first period, compared with those of last year. This result might be partly driven by pollutants emitted increased in both Australia and New Zealand, but decreased in most countries. Notably, a significant decrease was dramatically reduced CO emissions in transportation sites. The entry ban of foreigners, and thereby the decrease of air transportation services, may have also contributed to this decrease.

In the second period, the amount of CO emissions significantly reduced in crops, industrial estates, accommodations, restaurants, education, and public services. In ASEAN6, a decrease of economic and social activities in more types of sites is observed in the second period. Conversely, CO emissions was raised substantially in shops and tourist sites; hence, the decrease in the use of cars caused by workplace-closing policies dramatically reduced CO emissions in transportation sites. The entry ban of foreigners, and thereby the decrease of air transportation services, may have also contributed to this decrease.

In the CLMV group, CO emissions significantly increased in quarry sites in the first period, returning to normal in the second period. In contrast, CO emissions decreased in accommodation and automotive sites in the first period and returned to normal or increased in the second period. CO emissions in restaurants increased in both periods, indicating that people in CLMV did not refrain much from going to restaurants, even at the height of the pandemic. Meanwhile, CO emissions in education sites decreased in the second period, likely because school opening restrictions were effective in these countries.

In the Plus6 group, all the results for the first period, other than public services, were not significant. Thus, economic and social activities did not change significantly during the first period, compared with those of last year. This result might be partly driven by China’s earlier recovery. Significant results are seen in the second period. CO emissions decreased in shops and sports sites but increased in restaurant and religious sites. For example, in October, Japan introduced a program called “Go to Eat” to support the restaurant industry. Such government programs affected the amount of CO emissions.

5. Concluding remarks

This study investigated how economic and social activities were affected by the COVID-19 pandemic using the emissions of various air pollutants to represent those activities. The review of the emissions data suggests that from 2019 to 2020, the amount of air pollutants emitted increased in both Australia and New Zealand, but decreased in most countries. Notably, a significant decrease was found mainly in the eastern part of China and Vietnam. Furthermore, the change in emissions was not uniform across countries’ regions. The regional disparity in emissions varied over time, particularly in Brunei, Indonesia, Malaysia, the Philippines, Singapore, and New Zealand. A sharp rise in the regional disparity was observed in some pollutant indicators, implying that economic and social

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**Table 6**

Regression results of CO emissions by groups.

| Group     | ASEAN6 | ASEAN6 | CLMV | CLMV | Plus6 | Plus6 |
|-----------|--------|--------|------|------|-------|-------|
| Month     | Mar - Jun | Jul - Oct | Mar - Jun | Jul - Oct | Mar - Jun | Jul - Oct |
| Dirty-power plants | 0.000 | 0.001 | -0.001 | -0.001 | 0.000 | 0.000 |
| Clean-power plants | 0.001 | -0.003 | 0.001 | 0.000 | 0.000 | 0.001 |
| Cropland  | 0.004 | -0.024*** | 0.005 | -0.007* | 0.001 | 0.000 |
| Farm      | 0.002 | 0.004 | 0.005 | 0.003 | 0.001 | -0.003 |
| Quarry    | -0.001 | 0.000 | 0.012* | 0.002 | 0.002 | -0.005 |
| Industrial site | 0.002 | -0.010** | -0.007 | 0.001 | 0.001 | 0.002 |
| Accommodation | -0.001 | -0.011** | -0.015** | -0.007 | 0.000 | -0.007 |
| Automotive | -0.004 | -0.001 | -0.011** | 0.009* | 0.000 | -0.004 |
| Business  | 0.001 | -0.002 | 0.004* | 0.001 | -0.010 | 0.001 |
| Restaurant | -0.009 | -0.030*** | 0.016** | 0.011** | 0.009 | 0.016** |
| Education | 0.006* | -0.014*** | -0.005 | -0.010** | -0.004 | 0.011 |
| Health    | -0.009* | -0.003 | 0.006 | 0.000 | 0.003 | 0.001 |
| Public service | -0.006 | -0.015** | -0.001 | 0.001 | 0.008* | 0.002 |
| Religious site | 0.004 | 0.005 | 0.003 | -0.002 | 0.002 | 0.010** |
| Settlement | -0.008* | -0.000 | -0.002 | -0.002 | -0.002 | 0.001 |
| Shop      | 0.016** | 0.050*** | 0.004 | -0.007 | 0.000 | -0.016** |
| Sport     | 0.004 | 0.003 | 0.002 | 0.002 | -0.005 | -0.017*** |
| Tourism   | 0.000 | 0.014** | 0.002 | 0.005 | -0.004 | -0.001 |
| Transport | -0.005** | 0.003 | -0.006 | 0.001 | 0.001 | 0.004 |
| Number of observations | 612 | 612 | 492 | 442 | 592 | 592 |
| Adjusted R-squared | 0.6617 | 0.8499 | 0.6512 | 0.6173 | 0.7216 | 0.6265 |

Notes: The estimation results using OLS method are reported. ***, **, and * indicate the 1%, 5%, and 10% levels of statistical significance, respectively. We use robust standard errors to show statistical significance. All independent variables reported in this table, except for Cropland, are measured by a log of (one plus) the number of sites. Cropland is measured by a log of (one plus) square kilometers. In all the specifications, we control for country-month fixed effects. The results of the weather-related variables are omitted.

because there were similar results for CO and HCHO, and most results for NO2 were found to be insignificant, as shown in Table 5.12 The results for CO are presented in Table 6. Some differences exist in the major sites across the groups. Regarding ASEAN6, CO emissions in health, settlement, and transportation sites decreased in the first period but returned to normal in the second period. The study countries include cities known to have extreme traffic congestion (e.g., Manila, Jakarta, and Bangkok). One reason for such congestion is people using cars to commute to work; hence, the decrease in the use of cars caused by workplace-closing policies dramatically reduced CO emissions in transportation sites. The entry ban of foreigners, and thereby the decrease of air transportation services, may have also contributed to this decrease.

In the Plus6 group, all the results for the first period, other than public services, were not significant. Thus, economic and social activities did not change significantly during the first period, compared with those of last year. This result might be partly driven by China’s earlier recovery. Significant results are seen in the second period. CO emissions decreased in shops and sports sites but increased in restaurant and religious sites. For example, in October, Japan introduced a program called “Go to Eat” to support the restaurant industry. Such government programs affected the amount of CO emissions.

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12 The results for HCHO and NO2 are available in Appendix.
activities restarted (or were applied) in only specific regions.

Regression analyses were conducted to examine the sites that recovered early. In the ASEAN forerunners, economic and social activities in crops, industrial estates, accommodations, restaurants, education, and public services have still not returned to normal levels. In contrast, full recovery or an increase in emissions at tourism sites were noted. For ASEAN latecomers, activities in accommodation and automotive sites decreased but later returned to normal. Although increased activity was found in restaurant sites, education sites remained low. In the ASEAN + 1 FTA partner countries, no significant changes were found in economic and social activities in most sites. The exception was shops and sports sites, where those activities decreased.

Our analysis does not aim to uncover the activity types that should start early. We simply presented the types of activities that started early. Nevertheless, economic and social activities may be well-controlled by governments’ policies or orders. For example, programs to encourage domestic traveling or eating out appeared to increase the emission of air pollutants in tourist and restaurant sites. Similarly, restrictions on school opening reduced emissions in education sites. Workplace-closing orders decreased the use of cars for commuting, which resulted in lowered emissions in automotive and transport sites. In short, our analyses demonstrate that governments seemed to control economic and social activities during the pandemic through introducing various restrictive orders or supporting programs.

It remains important for governments to monitor various indicators, including the amount of air pollutants emitted. Such monitoring will contribute to uncovering how and in what kinds of regions policy measures succeeded in altering economic and social activities. Although our analyses are conducted at an ADM1 level, the data are available at a more detailed level. Thus, when focusing on a single country, it will be invaluable to monitor at a more detailed regional level. Furthermore, the indicators may be related more closely with regional and time scopes of policy measures. Ordering business closures or shortened business hours might be effective only in specific regions or specific periods. Thus, analyses using the difference-in-differences method will uncover the causal effects of policy measures. We leave such analyses for future study.

Data availability

Data will be made available on request.

Appendix. Other results

(see Table A1).
(see Table A2).
(see Figs. A1-A4).

### Table A1
Regression results of HCHO emissions by groups.

| Group                | ASEAN6 | ASEAN6 | CLMV | CLMV | Plus6 | Plus6 |
|----------------------|--------|--------|------|------|-------|-------|
|                      | Mar - Jun | Jul - Oct | Mar - Jun | Jul - Oct | Mar - Jun | Jul - Oct |
| Dirty-power plants   | -0.001 | -0.002 | -0.004* | -0.003 | 0.000 | 0.003 |
| Clean-power plants   | 0.008  | 0.002  | -0.002 | 0.003 | 0.006 | -0.012* |
| Cropland             | -0.016 | -0.025** | 0.010 | -0.004 | -0.012 | 0.031** |
| Farm                 | 0.006  | 0.003  | 0.018** | 0.000 | 0.021 | -0.016 |
| Quarry               | 0.000  | 0.005  | 0.028** | 0.016 | 0.061** | -0.028 |
| Industrial site      | 0.012  | -0.003 | -0.016* | -0.001 | 0.007 | -0.010 |
| Accommodation        | -0.004 | -0.010 | -0.010 | -0.009 | -0.057*** | -0.003 |
| Automotive           | -0.006 | 0.030** | -0.013 | 0.008 | 0.026 | 0.011 |
| Business             | -0.003 | -0.024* | 0.004 | -0.011 | -0.056** | 0.024 |
| Restaurant           | -0.006 | -0.036* | 0.027** | 0.005 | 0.012 | -0.002 |
| Education            | -0.002 | -0.006 | -0.006 | 0.015 | 0.010 | 0.024 |
| Health               | -0.030** | -0.014 | 0.024*** | 0.012** | -0.026 | -0.008 |
| Public service       | 0.008  | -0.016 | -0.004 | 0.002 | 0.032** | -0.011 |
| Religious site       | 0.000  | 0.026* | 0.008 | -0.003 | 0.000 | 0.009 |
| Settlement           | 0.008  | -0.003 | -0.006 | 0.002 | -0.008 | -0.003 |
| Shop                 | 0.052** | 0.052** | -0.003 | 0.000 | 0.007 | 0.01 |
| Sport                | -0.033** | 0.009 | -0.014 | -0.021* | -0.028* | 0.003 |
| Tourism              | -0.007 | -0.005 | -0.001 | -0.001 | -0.007 | 0.006 |
| Transport            | -0.018* | 0.011  | -0.010 | 0.002 | 0.054 | -0.042 |
| Number of observations | 609  | 612  | 492  | 442  | 590  | 586  |
| Adjusted R-squared   | 0.1913 | 0.5731 | 0.4609 | 0.5397 | 0.1537 | 0.4339 |

Notes: This table reports the estimation results of the OLS method. ***, **, and * indicate 1%, 5%, and 10% levels of statistical significance, respectively. We use robust standard errors to show statistical significance. All independent variables reported in this table, except for Cropland, are measured by a log of (one plus) the number of sites. Cropland is measured by a log of (one plus) square kilometers. In all the specifications, we control for country-month fixed effects. The results of the weather-related variables are omitted.
Table A2
Regression results of NO2 emissions by groups.

| Group               | ASEAN6 Mar - Jun | ASEAN6 Jul - Oct | CLMV Mar - Jun | CLMV Jul - Oct | Plus6 Mar - Jun | Plus6 Jul - Oct |
|---------------------|------------------|------------------|----------------|----------------|----------------|----------------|
| Dirty-power plants  | 0.002            | 0.001            | 0.000          | -0.001         | -0.001         | -0.002**       |
| Clean-power plants  | -0.002           | 0.000            | 0.000          | 0.001          | 0.001          | 0.002*         |
| Cropland            | 0.031***         | 0.008            | 0.006          | -0.006         | 0.007*         | 0.013***       |
| Farm                | 0.000            | -0.001           | 0.000          | 0.007          | -0.004         | -0.006         |
| Quarry              | -0.006           | 0.007            | 0.007          | 0.004          | -0.001         | 0.004          |
| Industrial site     | 0.003            | -0.002           | -0.004         | 0.001          | -0.002         | -0.003         |
| Accommodation       | -0.001           | -0.004           | 0.003          | 0.003          | 0.007          | 0.018**        |
| Automotive          | -0.023***        | -0.032***        | -0.019***      | -0.003         | 0.000          | -0.003         |
| Business            | 0.002            | 0.008            | 0.007          | -0.006         | -0.014         | -0.019**       |
| Restaurant          | 0.004            | 0.011            | -0.002         | -0.002         | 0.000          | -0.006         |
| Education           | -0.004           | -0.001           | 0.001          | -0.002         | 0.009          | 0.019***       |
| Health              | -0.025***        | -0.012*          | 0.002          | 0.003          | -0.004         | 0.002          |
| Public service      | 0.010**          | 0.007            | -0.002         | -0.002         | 0.002          | -0.006         |
| Religious site      | 0.011**          | -0.006           | 0.002          | 0.009*         | 0.004          | -0.007         |
| Settlement          | 0.000            | 0.001            | 0.002          | 0.003          | 0.003          | 0.002          |
| Shop                | 0.007            | 0.007            | 0.008          | 0.001          | 0.005          | 0.025***       |
| Sport               | -0.006           | -0.003           | -0.005         | -0.006         | -0.007         | -0.006         |
| Tourism             | 0.007**          | 0.003            | 0.000          | 0.000          | -0.017**       | -0.012*        |
| Transport           | -0.004           | 0.002            | -0.002         | 0.004          | 0.002          | -0.009*        |
| Number of observations | 612             | 612              | 492            | 442            | 592            | 592            |
| Adjusted R-squared  | 0.7091           | 0.4732           | 0.3357         | 0.5042         | 0.5234         | 0.4675         |

Notes: This table reports the estimation results of the OLS method. ***, **, and * indicate 1%, 5%, and 10% levels of statistical significance, respectively. We use robust standard errors to show statistical significance. All independent variables reported in this table, except for Cropland, are measured by a log of (one plus) the number of sites. Cropland is measured by a log of (one plus) square kilometers. In all the specifications, we control for country-month fixed effects. The results of the weather-related variables are omitted.

Fig. A1. Relationships with GDP. Notes: This figure includes observations for our study 16 countries in 2019. The vertical axis is a log of the annual quantity of emissions for each type of air pollutant.

Source: Authors’ compilation using the TROPOMI and the World Development Indicator.
Fig. A2. Coefficients of Variance in ASEAN Forerunners. Notes: The coefficient of variance of each pollutant in the ADM1-level regions is shown by months and countries. The emission amount in a month is normalized by that of the same month in 2019. 
Source: Authors’ compilation using the TROPOMI.
Fig. A3. Notes: The coefficient of variance of each pollutant in the ADM1-level regions is shown by months and countries. The emission amount in a month is normalized by that of the same month in 2019.

Coefficients of Variance in CLMV
Source: Authors’ compilation using the TROPOMI.
Note: The coefficient of variance of each pollutant in the ADM1-level regions is shown by months and countries. The emission amount in a month is normalized by that of the same month in 2019.

Coefficients of Variance in Plus6

Source: Authors’ compilation using the TROPOMI.
