ERIA-DP-2020-40

ERIA Discussion Paper Series

No. 367

How Is the Asian Economy Recovering from the COVID-19 Pandemic? Evidence from the Emissions of Air Pollutants

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March 2021

Abstract: *This study empirically examines how economic and social activities in Asia were affected by the COVID-19 pandemic by using the emissions amounts of various air pollutants to represent those activities. Review of the emissions data suggests that from 2019 to 2020, the amount of emitted air pollutants decreased in most subnational regions in Asia. Data also show how economic and social activities have restarted in some regions; regression analyses are used to uncover the regions that restarted early. Regional characteristics are identified by employing a remotely sensed land cover dataset (i.e. ESALC) and OpenStreetMap. Results reveal that for Association of Southeast Asian Nations (ASEAN) members, economic and social activities in cropland, industrial estates, accommodations, restaurants, education, and public services still have not returned to normal.*

Keywords: COVID-19; air pollutants; Asia

JEL Classification: I14; R11; R14

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[§] This study is conducted as a part of the 'COVID-19 and Its Implications for the Regional Economy' project undertaken at the Economic Research Institute for ASEAN and East Asia (ERIA). The authors wish to thank Alloysius Joko Purwanto for his invaluable comments. All remaining errors are those of the authors.

1. Introduction

Many countries and areas around the globe have imposed restrictions on people and businesses, including citywide or nationwide lockdown orders, to contain the spread of COVID-19. An example is the 'workplace-closing policy,' which requires closing all but essential workplaces (e.g. grocery stores). If such a policy bans factory operations, production activities stop entirely. For example, Japanese car manufacturers have suspended production in Japan for several days monthly since April 2020. Some industries, however, 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, are exempting export-oriented firms, firms in special economic zones, or industries that must produce to maintain supply-chain operations from these policies. Therefore, the recovery of economic activities is observed to be geographically uneven in each country.

This study examines how economic and social activities in East Asia and South-East Asia have been affected by the COVID-19 pandemic. The sample includes 10 Association of Southeast Asian Nations (ASEAN) members and six partners involved in free trade agreements with ASEAN. The magnitudes of economic and social activities in regions that resumed these activities early are measured through the emissions of various air pollutants. One advantage of using air pollution data is that the data are provided almost instantaneously (i.e. near real-time data) daily and with very high spatial resolution. The study then aggregates these data by months (i.e. from January to October 2019 and January to October 2020) and subnational regions. The amounts of emitted air pollutants related to economic or regional attributes, such as establishments or infrastructure, are then determined. Those regional characteristics are identified by employing a remotely sensed land cover dataset (i.e. ESALC) and OpenStreetMap (OSM).

It is important to note that this study relies solely on publicly available data; thus, anyone can conduct similar exercises. Furthermore, data employed are those available for most countries, including the least-developed ones. These data do not represent the official data collected or published by governments, so their availability is an important advantage for developing countries that have not collected sufficient official data.

Several studies have investigated the effect of lockdown orders on the number of confirmed COVID-19 cases (e.g. Ullah and Ajala, 2020; Askitas, Tatsiramos, and Berheyden, 2020; Ghosh, 2020), the number of deaths (e.g. Conyon, He, Thomsen 2020), unemployment insurance claims (e.g. Kong and Prinz, 2020), international trade (e.g. Hayakawa and Mukunoki 2021), and household spending and macroeconomic expectations (e.g. Coibion, Gorodnichenko, Weber 2020). Others have examined the effect of lockdown orders on air pollution, although most have investigated the effect on a specific country or region.[1] Some, however, have examined the effect of lockdown orders on the amounts of emitted air pollutants for a global sample (e.g. Deb, Furceri, Ostry, and Tawk, 2020; Dang and Trinh, 2020; Keola and Hayakawa, 2021). These studies have consistently found that lockdown orders decreased the amount of emitted air pollutants.

Unlike the aforementioned studies, this study presents an empirical way to uncover what is happening at the regional level. Indeed, it is important for governments to monitor the economic and social conditions to understand the effects of sudden shocks like the COVID-19 pandemic – including policy interventions against the shocks.

Section 2 introduces the air pollutants examined in this study. Section 3 presents the empirical framework. Section 4 shows the estimation results, and Section 5 concludes the paper.

2. Overview of Air Pollutants

Air pollutants are emitted from anthropogenic and natural sources; most economic activities emit air pollutants through the generation and consumption of energy. TROPOspheric monitoring instruments (TROPOMIs) mounted on Sentinel-5P, which was put into orbit by the European Space Agency in 2017, are

[1] Examples include Almond, Xinming, Zhang (2020); Shi and Brasseur (2020); Chen et al. (2020); Cole, Elliott, Liu (2020); Wang et al. (2020); Fan et al. (2020); and Pei et al. (2020) for China; Chang, Meyerhoefer, Yang (2020) for Taiwan; Mahato, Pal, Ghosh (2020) for India; Cicala et al. (2020) and Zangari, Hill, Charette, Mirowsky (2020) for the United States; Adams (2020) for Canada; Baldasano (2020) for Spain; Isphording and Pestel (2020) for Germany; Collivignarelli et al. (2020) for Italy; and Menut et al. (2020) for Western Europe.

providing unprecedented remotely sensed air pollution data with global coverage. The daily spatial and temporal resolution of TROPOMIs is 7×7 kilometres, which is considered high enough for this study. The amount of emitted air pollutants measured by TROPOMIs are thus used to represent the extent of economic and social activities. Data from 16 countries were obtained, including the 10 ASEAN members, plus Australia, China, India, Japan, Republic of Korea (henceforth, Korea), and New Zealand. Then, up to first-level subnational administrative units (ADM1) are aggregated, as defined by the Food and Agriculture Organization (2015). For example, ADM1 includes prefectures in Japan and provinces in China, Thailand, and Viet Nam.[2]

Three air pollutants are then used as indicators of air pollution: carbon monoxide (CO), formaldehyde (HCHO), and nitrogen dioxide (NO_2). CO is considered a major atmospheric pollutant in urban areas. Its primary sources are the combustion of fossil fuels, biomass burning, and atmospheric oxidation of methane and other hydrocarbons. HCHO is primarily emitted through biomass burning, vegetation, vehicle emissions, and industrial emissions. Seasonal variations in this pollutant are related to temperature and fire events. NO_2 is emitted through human activities, especially 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 (O_3) converts nitrogen monoxide (NO) into NO_2. Therefore, the NO_2 measured by TROPOMIs is sometimes referred to as NOx, implying a combination of NO and NO_2. The amount of these emitted pollutants is related to economic and social activities.[3]

The changes in the amounts of air pollutants emitted are then observed from 2019 to 2020. The sum of each pollutant emitted from January to October in each year is computed, and the log difference of this sum between 2019 and 2020 is taken. The results for CO are presented in Figure 1.

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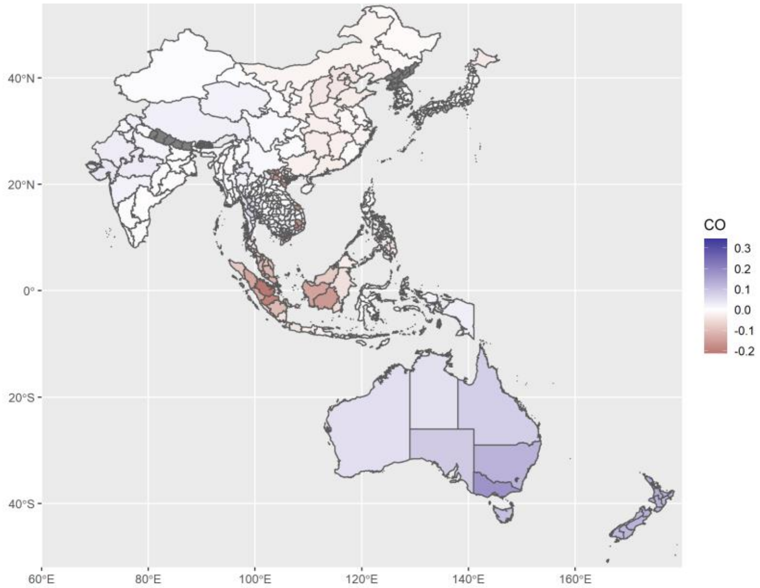
[2] The numbers of ADM1 are as follows: Australia, 9; Brunei Darussalam, 4; Cambodia, 25; China, 31; India, 34; Indonesia, 33; Japan, 47; Korea, 15; Lao People's Democratic Republic (Lao PDR), 17; Malaysia, 15; Myanmar, 17; New Zealand, 14; Philippines, 17; Singapore, 9; Thailand, 76; and Viet Nam, 64.

[3] The data on sulphur dioxide (SO_2) and methane (CH_4) are also available in the original dataset; however, in the sampled countries, many observations had negative values, which indicate noise. Therefore, these two pollutants are not examined.

Figure 1: Log Difference of Carbon Monoxide Emissions, January to October 2019 and January to October 2020



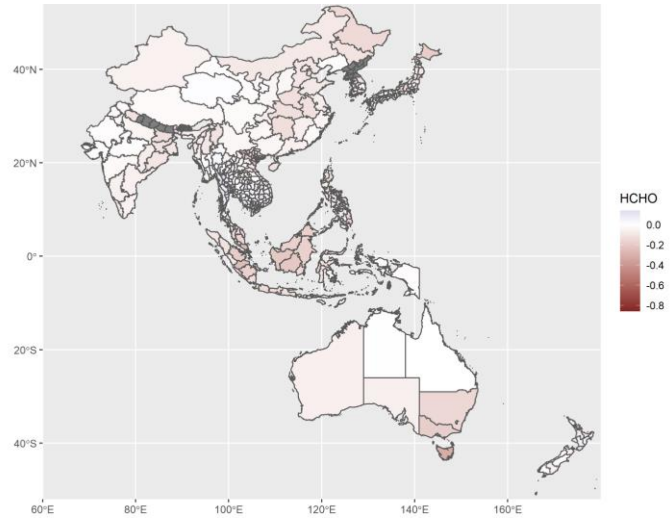
CO = carbon monoxide.
Source: Authors' compilation using TROPOMIs.

Australia, New Zealand, Western China, Western India, and parts of continental ASEAN (i.e. Cambodia, the Lao People's Democratic Republic [Lao PDR], Myanmar, Thailand, and Viet Nam) had a relatively large positive change in CO emissions from 2019 to 2020. By contrast, negative growth is observed in many subnational regions in Eastern China, Viet Nam, and maritime ASEAN (i.e. Brunei Darussalam, Indonesia, Malaysia, the Philippines, and Singapore). Moreover, CO emissions decreased in Korea and in the northern and western coastal areas of Japan (i.e. rural areas).

As stated previously, CO emissions are caused by, for example, a forest fire because of incomplete combustion (Vadrevu, Giglio, Justice 2013). In Australia, a series of unusual and intense forest fires broke out in autumn 2019 and lasted until spring 2020; thus, CO emissions increased in 2020 compared to 2019. Although unusual forest fires in Cambodia, Western China, India, Lao PDR, Myanmar, and Thailand in 2020 were not reported, an increase in rural populations due to lockdown measures in urban areas may have increased the use of inefficient stoves in rural areas, contributing to CO emissions because of incomplete combustion.

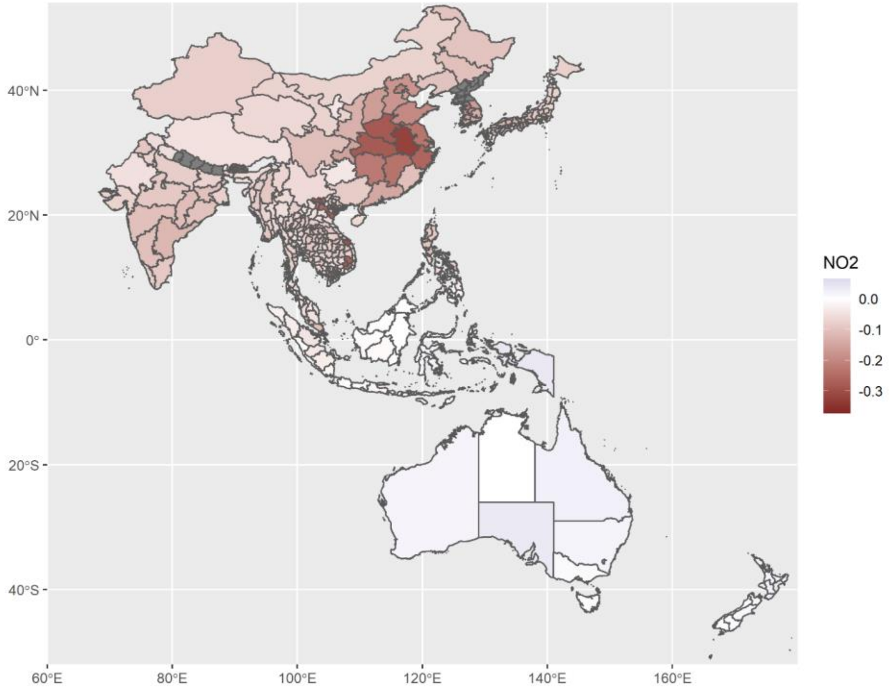
Figure 2 presents the changes in HCHO emissions, which show a more evident decrease compared to CO emissions. All subnational regions, except for those in Australia, experienced a considerable decrease. In addition, the decrease in NO_2 was also substantial, especially on the industrialised eastern coast of China (Figure 3). A slight increase is observed only in Australia, New Zealand, and the adjacent subnational regions in Indonesia. Biomass burning is one of the major sources of NO_2; hence, its emissions increase due to intense forest fires or use of inefficient stoves in rural areas, like CO (Lazaridis et al. 2008).

Figure 2: Log Difference of Formaldehyde Emissions, January to October 2019 and January to October 2020



HCHO = formaldehyde.
Source: Authors' compilation using the TROPOMI.

Figure 3: Log Difference of Nitrogen Dioxide Emissions, January to October 2019 and January to October 2020



NO_2 = nitrogen dioxide.

Source: Authors' compilation using the TROPOMIs.

Changes in CO, HCHO, and NO_2 emissions mainly indicate a variation of economic and social activities, particularly in subnational regions, without substantial differences in natural and non-economic emissions between 2019 and 2020.

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

$$\sigma_t = \frac{SD_i(\ln Y_{it}^{2020} - \ln Y_{it}^{2019})}{SD_i(\ln Y_{i1}^{2020} - \ln Y_{i1}^{2019})}.$$

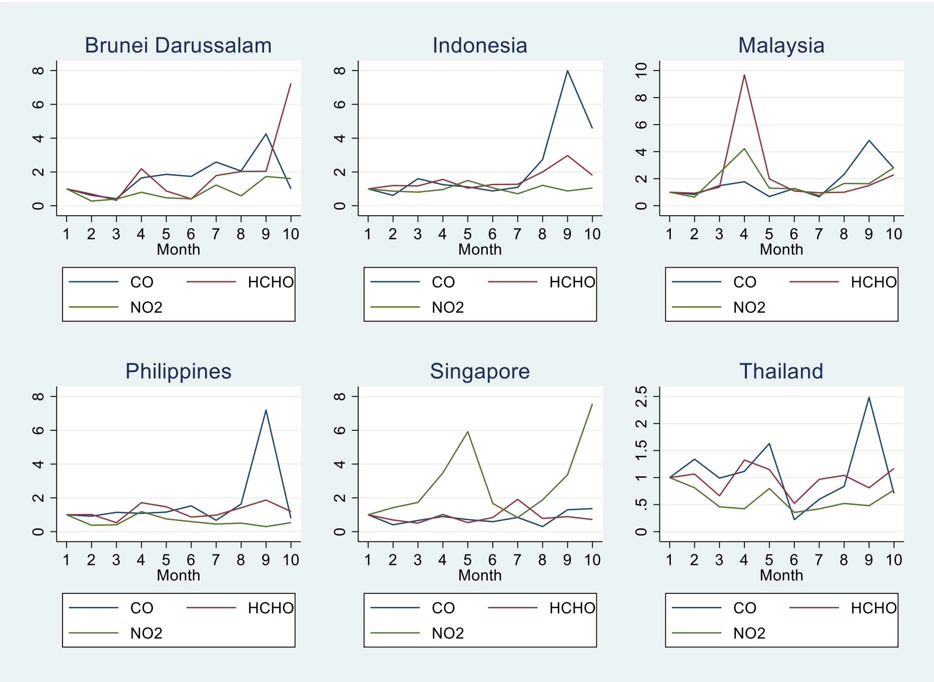
where:

Y_{it}^{2020} = the amount of emitted air pollutant in an ADM1-level region i in month t, and

$SD_i(\cdot)$ = a standard deviation operator over i.

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 the geographical concentration of economic and social activities changes in each country.

Figure 4: Standard Deviations of Brunei Darussalam, Indonesia, Malaysia, Philippines, Singapore, and Thailand

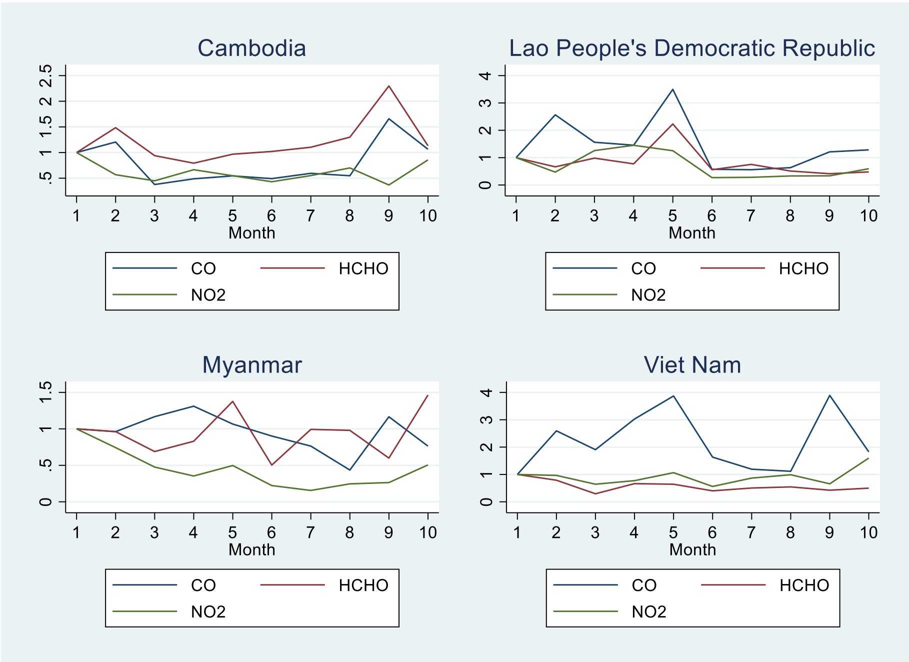


CO = carbon monoxide, HCHO = formaldehyde, NO_2 = nitrogen dioxide.
Notes: The standard deviation of each pollutant in the ADM1-level regions is shown by months and countries. The emission amount in a month is normalised by that of the same month in 2019. Furthermore, the standard deviation is rescaled for easy comparison amongst the pollutants so that the value in January becomes 1.
Source: Authors' compilation using the TROPOMIs.

Figure 4 presents the changes in this index for Brunei Darussalam, Indonesia, Malaysia, the Philippines, Singapore, and Thailand. The trend is not necessarily consistent across the three air pollution indicators. However, the fluctuation of the index is evident over time in all of the countries, implying that the amount of air pollutants started to increase (or decrease) in only some regions. Compared with the other countries, Thailand shows less fluctuation; notice the difference in the magnitude of the vertical unit across countries. This result may 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 increased significantly during the lockdown and post-lockdown periods, that is, since March 2020. These pollutants include HCHO in Brunei Darussalam; CO in Indonesia and the Philippines; HCHO and NO_2 in Malaysia; NO_2 in Singapore; and HCHO, NO_2, and CO in Thailand. The pollutants with notable changes may be the ones emitted from major industries in each country. Depending on the lockdown orders, some regions experienced a sudden decline in or a bouncing back of major pollutants.

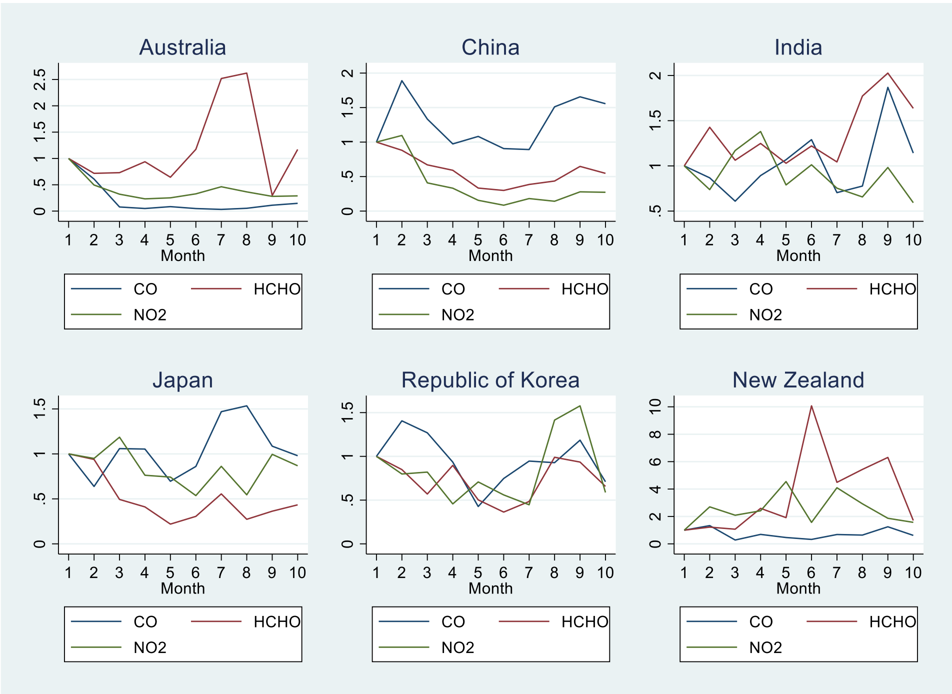
Figure 5: Standard Deviations in Cambodia, Lao People's Democratic Republic, Myanmar, and Viet Nam



CO = carbon monoxide, HCHO = formaldehyde, Lao PDR = Lao People's Democratic Republic, NO_2 = nitrogen dioxide.
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 normalised by that of the same month in 2019. Furthermore, the standard deviation is rescaled for easy comparison amongst the pollutants so that the value in January becomes 1.
Source: Authors' compilation using the TROPOMIs.

Figure 5 presents the changes in the index for Cambodia, Lao PDR, Myanmar, and Viet Nam. A gradual increase is noted in Cambodia, indicating that economic and social activities restarted in some of its regions. Indeed, compared with other ASEAN countries, Cambodia did not introduce strict lockdown orders. In the Lao PDR, the index increases sharply in May, which could be due to the relaxation of lockdown orders during that month. In Myanmar, the index does not fluctuate much and remains around a value of 1, indicating that the within-country disparity in economic and social activities did not change that much compared to those of the last year. Similarly, in Viet Nam, the index is relatively stable, except for CO. Moreover, Viet Nam's relatively small number of confirmed COVID-19 cases and deaths may not have changed its economic and social activities much. The fluctuations in CO may be due to its emission in relatively active regions.

Figure 6: Standard Deviations in Australia, China, India, Japan, Korea, and New Zealand



CO = carbon monoxide, HCHO = formaldehyde, NO_2 = nitrogen dioxide.
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 normalised by that of the same month in 2019. Furthermore, the standard deviation is rescaled for easy comparison amongst the pollutants so that the value in January becomes 1.
Source: Authors' compilation using the TROPOMIs.

Figure 6 presents the index in several partner countries of ASEAN, Australia, China, India, Japan, Korea, and New Zealand. In Australia, however, the HCHO index rises in July and August. In China, the index shows a declining trend up to July, after which it starts increasing gradually. Meanwhile, India has an increase around September. In Japan, it declines until around June, after which, it starts increasing gradually. A similar trend is also observed in Korea.

In contrast, New Zealand has a large fluctuation in the index; in particular, the HCHO index increases drastically in June. Note that New Zealand has been successful in terms of containing COVID-19. The study result may indicate that such containment was realised by stopping economic and social activities in some regions.

In summary, the change in the regional disparity in air pollutants is not uniform across countries. The extent of their regional disparity varies over time, particularly in Brunei Darussalam, Indonesia, Malaysia, New Zealand, the Philippines, and Singapore. The sharp rise of the index is observed regarding some pollutant indicators, indicating the restart (or stop) of economic and social activities in specific regions.

3. Empirical Analyses

To explain the empirical framework used in examining the types of regions that restarted economic activities early, the following equation is used:

$$\ln Y_{it}^{2020} - \ln Y_{it}^{2019} = \mathbf{X'}_i\boldsymbol{\beta} + \mathbf{Z'}_i\boldsymbol{\gamma} + \delta_c + \delta_t + \epsilon_{it}. \quad (1)$$

The dependent variable is a log difference of the pollutant indicators (i.e. CO, HCHO, and NO_2) in region *i* in country *c* in month *t* from 2019 to 2020. The dependent variable measures the extent of the recovery in economic activities; meanwhile, the vectors of **X** and **Z** include various regional characteristics and weather-related variables, respectively. Country fixed effects (δ_c) and month fixed effects (δ_t) are controlled for. ϵ_{it} is a disturbance term, which is assumed to be independent of **X** and **Z**. This equation is then estimated using the ordinary least squares (OLS) method.

The variables used to represent regional characteristics are from two data sources: ESALC and OSM. ESALC is a remotely sensed land cover data set, compiled by the European Space Agency. It classifies each grid of approximately 500 × 500 metres into 22 categories based on the classification system of the Food and Agriculture Organization. OSM is a free, editable world map powered by high-resolution satellite images. Built from scratch, it is maintained by volunteers, and was released with an open-content license. Volunteers worldwide have added spatial information, such as shapes of roads, buildings, and points of interest. As of March 2020, approximately 6 million global users of OSM were registered, out of which about 5,000 actively contribute to updating OSM by uploading or editing spatial data daily. Moreover, points of interest include 14 categories and more than 200 subcategories.

OSM has both strengths and limitations. The strength of OSM is its openness. Point-of-interest data in commercial search engines, such as Microsoft Bing or Google Maps, are generally better – more accurate, more up-to-date, and with wider coverage. Ample financial resources and the large market powers of these global companies are the sources of their better performance. Large and small enterprises worldwide voluntarily supply information to these search engines to increase their exposure to potential customers. However, these are not free, and the data cannot be downloaded in bulk; thus, it would have taken a long time, likely been prohibitively expensive, and required sophisticated programmes to compile comprehensive subnational data for this study.

By contrast, all raw data of OSM are available for download in bulk within 48 hours. Extracting data by a required spatial unit of analysis takes less time, money, and computational resources. However, the limitation is uneven coverage. OSM data need to be input by volunteers. Developed countries have more people with better internet access, higher technical skills, and willingness to contribute. Tourists, scholars, and students traveling from developed countries to developing countries do contribute substantially, however. Several global-scale activities (e.g. the Missing Maps movement) also aim to increase the coverage of OSM.[4]

[4] Missing Maps is a project in which anyone can help map areas for humanitarian organisations to

Table 1: Data and Characteristics of Subnational Regions

Industry	Source	Indicator	Example
Primary	ESALC	Cropland	Cropland
	OSM	Farm	Rice field, plantation
		Quarry	Coal mine, copper mine, pit
Secondary	OSM	Industrial site	Industrial estate, processing plant
		Emitting power plant	Coal, fire, waste power plant
		Clean-power plant	Hydroelectric, solar, wind power plant
Tertiary	OSM	Accommodation	Hotel, guesthouse, apartment
		Automotive	Petrol station, carpark, carwash
		Business	Bank, office, company
		Restaurant	McDonald's, 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, theatre
		Transport	Road, station, port, airport

OSM = OpenStreetMap.
Source: Authors' compilation.

By using the data from ESALC and OSM, the variables of regional characteristics were constructed (Table 1). First, based on the ESALC data, the sizes of four cropland-related areas were aggregated, comprising rain-fed cropland, irrigated cropland, and two cropland mosaics (i.e. larger and smaller than 50%), to construct a cropland indicator for this study. The numbers of farms and quarries (i.e. mineral-extracting activities) by subnational regions were also derived from OSM.

aid vulnerable peoples by tracing satellite imagery into OSM (Missing Maps 2021)..

The secondary industry was divided into power generation and others. Power generation represents the number of power plants derived from World Resources Institute (2021), which is further divided into emitting (e.g. biomass, coal, gas, oil, and waste) and clean (e.g. geothermal, hydro, nuclear, solar, and wind). The others represent the number of places tagged as ‘industrial’ in OSM, such as factories and industrial estates.

The tertiary industry has been captured in detail with OSM. The number of places noted as accommodation, automotive, business, restaurant, education, health, public service, religious, settlement, shop, sport, tourism, and transport are tagged. Major facilities under the automotive category include petrol stations, car parks, and highway rest areas, whereas health facilities include hospitals, clinics, and pharmacies. Post offices, police stations, ministries, and government facilities are under the public service category. Meanwhile, transport comprises streets, roads, railways, ports, and airports. Tourism comprises beaches, parks, museums, and theatres. Sizes or numbers of each site are identified and aggregated at an ADM1 level as the main independent variables.

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

Equation (1) is used to examine the regions that recovered from the negative impacts of the COVID-19 pandemic. They include areas with significant cropland, industrial bases, or business districts. To examine the changes over time in critical sites, Equation (1) is used for March to June and July to October separately. Data are not used for January and February due to few COVID-19 cases and deaths. The regional characteristic variables are time-invariant and are defined in 2019. The 16 countries are pooled for baseline estimation.

Table 2: Average Numbers of Each Site in Brunei Darussalam, Indonesia, Malaysia, Philippines, Singapore, and Thailand

	Brunei Darussalam	Indonesia	Malaysia	Philippines	Singapore	Thailand
Emitting power plant	147	1,139	1,042	708	23	451
Clean power plant	0	178	138	350	0	66
Cropland	136	16,737	6,214	8,064	14	4,074
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	1,353	585	250
Education	57	1,161	464	2,048	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	2,355	609	1,934	24	245
Shop	484	746	979	2,685	590	237
Sport	8	155	92	312	55	13
Tourism	22	766	235	717	152	60
Transport	23	93	167	347	600	41

Source: Authors' compilation using ESALC and OSM data.

The regional characteristic variables are first reviewed. Table 2 presents the average number of each site type amongst the subregions in six ASEAN countries. Brunei Darussalam has small numbers in almost all places compared to Indonesia, which has several religious sites. Meanwhile, Malaysia has moderate numbers in most spots. In the Philippines, there is a lot of cropland, restaurants, settlements, and shops, but an interesting finding is the presence of many educational sites. Singapore has few emitting and clean power plants but many restaurants, shops, and transport sites. In Thailand, only a few tourism sites are found. Except for crops, the average number of all sites seems small.

Note that the size of ADM1 varies significantly amongst these countries. ADM1 is much smaller in continental ASEAN than in maritime ASEAN. This fact is responsible for the small average number of each type of facility in Thailand. In addition, the size and distribution of the population are important. As mentioned previously, OSM is built by volunteers; therefore, the volume of information depends not only on the internet environment in a country but also on volunteer effort, 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 by introducing country fixed effects (δ_c).

Table 3: Average Numbers of Each Site in Cambodia, Lao People's Democratic Republic, Myanmar, and Viet Nam

	Cambodia	Lao PDR	Myanmar	Viet Nam
Emitting power plant	23	110	65	346
Clean power plant	35	183	162	265
Cropland	2,799	2,390	12,522	2,202
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

Lao PDR = Lao People's Democratic Republic.
Source: Authors' compilation using the ESALC and OSM data.

Table 3 reports the average number of sites in the remaining ASEAN countries. Cambodia has moderate numbers; Lao PDR has similar numbers but more restaurants and settlements. This difference is deemed reasonable since the population in Lao PDR is more scattered than that of Cambodia. In Myanmar, the number of crops is high. Indeed, Myanmar has larger numbers of most sites partly because the average size of an ADM1 is larger in this country. Meanwhile, Viet Nam has a relatively large number of power plants and many shops.

The average numbers in the last country group are presented in Table 4. Compared with the previous tables, sites are numerous. The number of accommodation, sport, tourism, and transport sites is high in Australia. Similarly, China has several power plants and settlements. India has a relatively large number of health sites, and Japan has many education and public service sites. Meanwhile, Korea has moderate numbers in most areas, whereas the average numbers in New Zealand are small.

Table 4: Average Numbers of Each Site in Australia, China, India, Japan, Korea, and New Zealand

	Australia	China	India	Japan	Korea	New Zealand
Emitting power plant	5,240	29,882	6,712	1,320	2,489	83
Clean power plant	1,333	10,685	1,589	1,169	1,971	394
Cropland	24,771	68,616	61,668	1,845	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	1,356	300	431	316	610	269
Automotive	1,076	221	195	852	554	147
Business	546	229	477	398	403	100
Restaurant	3,004	544	714	2,863	1,282	627
Education	1,445	1,078	1,224	1,661	1,361	283
Health	610	207	2,472	1,137	1,391	136
Public service	1,022	404	505	1,818	931	140
Religious site	480	157	997	879	390	203
Settlement	2,055	8,426	4,475	764	1,358	216
Shop	3,884	770	1,538	4,171	1,470	708
Sport	1,199	152	154	411	297	129
Tourism	2,887	691	394	1,161	680	679
Transport	4,866	965	411	642	1,539	211

Source: Authors' compilation using the ESALC and OSM data.

4. Empirical Results

The model for the two periods are estimated separately, from March to June and July to October. To save 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 regarding the three air pollution indicators. For CO, its emission in the first period (i.e. March to June) decreases in accommodation, automotive, settlement, and transport sites. However, in the second period (i.e. July to October), the emission amount at all of these sites either returns to normal or increases. Thus, on average, economic and social activities in these regions recovered from the impacts of the COVID-19 pandemic. Moreover, the CO emission in the second period decreases at crop, restaurant, and education sites, but it increases at 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 continue to apply social distancing measures, and online classes or their combination with onsite courses has remained the norm in many countries.

Table 5: Regression Results for All Countries by Air Pollutant

Pollution	CO	CO	HCHO	HCHO	NO_2	NO_2
Month	Mar – Jun	Jul – Oct	Mar – Jun	Jul – Oct	Mar – Jun	Jul – Oct
Emitting power plant	0.000	–0.001	0.000	0.000	0.000	–0.001
Clean power plant	0.000	0.001	0.004	–0.001	–0.001	0.001
Cropland	0.003	–0.009**	–0.003	–0.001	0.018***	0.010***
Farm	0.002	0.005	0.012	–0.002	–0.001	–0.004*
Quarry	0.003	–0.003	0.031*	–0.018	0.001	0.003
Industrial site	–0.001	–0.006	–0.001	0.000	–0.001	0.001
Accommodation	–0.005*	–0.008	–0.025***	–0.01	0.002	0.004
Automotive	–0.008**	0.009*	–0.004	0.025***	–0.021***	–0.021***
Business	–0.004	–0.001	–0.007	–0.020**	–0.001	–0.001
Restaurant	0.005	–0.012*	0.022**	–0.008	0.001	0.004
Education	0.003	–0.007**	0.010*	–0.001	0.001	0.003
Health	0.003	0.004	0.005	0.005	–0.005	0.000
Public service	–0.002	–0.002	0.01	0.000	0.003	0.000
Religious site	0.005*	0.005	0.005	0.009	0.002	–0.004
Settlement	–0.005**	0.000	–0.012**	–0.005	–0.001	–0.001
Shop	0.005	0.01	–0.006	0.022*	0.005	0.008
Sport	0.001	–0.004	–0.030***	0.001	–0.003	–0.002
Tourism	0.002	0.013***	0.005	–0.001	0.003	0.002
Transport	–0.005**	0.002	0.009	–0.007	–0.002	0.000
Number of observations	1,696	1,646	1,691	1,640	1,696	1,646
Adjusted R–squared	0.4536	0.4738	0.1399	0.3013	0.4163	0.3469

CO = carbon monoxide, HCHO = formaldehyde, NO_2 = nitrogen dioxide.
Notes: The estimation results using the ordinary least squares method are reported. ***, **, and * indicate 1%, 5%, and 10% levels of statistical significance, respectively. Robust standard errors are used to show statistical significance. In all specifications, country fixed effects and month fixed effects are controlled for. The results of the weather–related variables are omitted.
Source: Authors' compilation.

For HCHO, as for CO, the emission amount in accommodation, settlement, and sport sites decreases in the first period. This decrease could be attributed to workplace–closing orders adopted in many countries that also did not allow recreation and sport sites to operate. However, in the second period, HCHO emissions in these sites return to normal, perhaps due to the relaxation of workplace–closing orders. Meanwhile, HCHO emissions in quarry, restaurant, and education sites increase in the first period. Although reasons for this HCHO increase in restaurant and education sites remain unclear, activities in quarries, often conducted in an open air and uncrowded environment, could continue or even increase during the lockdowns. In the second period, the emission of HCHO decreases at business sites, probably because of the popularity of working from home even after the relaxation of the workplace–closing orders.

Finally, regarding NO_2, few results indicate a significant difference between the emission amount in 2020 and 2019. The amount of emissions in both periods decreases at automotive sites but increases in cropland. Cropland is identified on the basis of land cover data and often covers rural areas where most land is used for agriculture. Due to the loose lockdowns adopted in many countries, many people may have moved to and were active in rural areas. The amount of NO_2 emission on farms decreases in the second period as well.

Next, the model is estimated according to country group, that is, ASEAN6 (i.e. Brunei Darussalam, Indonesia, Malaysia, Philippines, Singapore, and Thailand), CLMV (i.e. Cambodia, Lao PDR, Myanmar, and Viet Nam), and Plus6 (i.e. Australia, China, India, Japan, Korea, and New Zealand). CO emissions are the focus because Table 5 shows similar results for CO and HCHO, and most results for NO_2 are found to be insignificant.[5]

The results for CO are presented in Table 6.

[5] The results for HCHO and NO_2 are available in the Appendix.

Table 6: Regression Results of Carbon Monoxide Emission by Group

Group	ASEAN6	ASEAN6	CLMV	CLMV	Plus6	Plus6
Month	Mar – Jun	Jul – Oct	Mar – Jun	Jul – Oct	Mar – Jun	Jul – Oct
Emitting–power plant	0.000	0.001	–0.001	–0.001	0.000	0.000
Clean power plant	0.001	0.000	–0.001	0.000	0.001	0.001
Cropland	0.004	–0.024***	0.005	–0.007	–0.001	0.000
Farm	0.003	0.004	0.005	0.003	0.002	–0.004
Quarry	0.000	0.004	0.013*	0.003	–0.001	–0.006
Industrial site	0.002	–0.011*	–0.006	0.001	0.001	0.002
Accommodation	0.002	–0.013*	–0.014**	–0.008	–0.001	–0.007
Automotive	–0.009*	–0.001	–0.010*	0.009*	0.001	–0.004
Business	–0.001	–0.001	0.003	0.001	–0.011	0.002
Restaurant	–0.008	–0.030***	0.016**	0.012**	0.009	0.015**
Education	0.007*	–0.016***	–0.004	–0.010*	–0.006	0.01
Health	–0.006	–0.002	0.006	0.001	0.003	0.002
Public service	–0.004	–0.016**	–0.001	0.001	0.008	0.001
Religious site	–0.002	0.003	0.003	–0.001	0.003	0.011**
Settlement	–0.010*	0.003	–0.002	–0.002	–0.003	0.000
Shop	0.017**	0.051***	0.004	–0.007	0.000	–0.015*
Sport	0.007	0.004	0.002	0.002	–0.006	–0.017***
Tourism	0.000	0.012**	0.002	0.005	–0.002	–0.002
Transport	–0.006*	0.002	–0.006	0.001	0.001	0.003
Number of observations	612	612	492	442	592	592
Adjusted R–squared	0.4204	0.7652	0.5821	0.5381	0.5190	0.5252

ASEAN6 = Brunei Darussalam, Indonesia, Malaysia, Philippines, Singapore, Thailand; CLMV = Cambodia, Lao PDR, Myanmar, Viet Nam; CO = carbon monoxide; Plus6 = Australia, China, India, Japan, Korea, New Zealand.

Notes: The estimation results using the Ordinary Least Squares method are reported. ***, **, and * indicate 1%, 5%, and 10% levels of statistical significance, respectively. Robust standard errors are used to show statistical significance. In all specifications, country fixed effects and month fixed effects are controlled for. The results of the weather–related variables are omitted.

Source: Authors' compilation.

Some differences exist in major sites across the groups. Regarding ASEAN6, CO emission at automotive, settlement, and transport sites decreases in the first period but returns to normal in the second period. These countries include cities known to have severe traffic congestion (e.g. Manila, Jakarta, and Bangkok). One reason for such congestion is that people use cars to commute to work; hence, decreased use of cars caused by the workplace–closing orders dramatically reduced CO emission at automotive and transport sites. The amount of CO emission in the second period significantly falls in crop, industrial estate, accommodation, restaurant, education, and public service sites. Thus, in ASEAN6, economic and social activities at many kinds of sites have still not returned to normal. In the second period, on the other hand, CO emission is more significant at tourist sites, possibly because people enjoyed domestic traveling after the stay-at-home orders were lifted. Indeed, in July, Thailand introduced a programme to support domestic traveling, 'We Travel Together'.

In the CLMV group, CO emission significantly increases in quarry sites during the first period, which then returns to normal in the second period. By contrast, CO emission in accommodation and automotive sites decreases in the first period and returns to normal or increases in the second period. The emission of CO in restaurants increases in both periods, indicating that people in CLMV did not refrain from going to restaurants even during the pandemic. Meanwhile, CO emission in education sites decreases in the second period, possibly due to restrictions on school reopening.

In the Plus6 group, all results for the first period are insignificant. Thus, economic and social activities did not change significantly during the first period, compared with those of the last year. This result may be driven partly by China's earlier recovery. Significant results are seen only in the second period, as CO emission decreases at shops and sport sites but increases at restaurant and religious sites. For example, Japan introduced a programme to support dining out, 'Go to Eat', in October. Such government programmes do alter the amount of CO emission.

5. Conclusions

This study empirically investigates how economic and social activities were affected by the COVID-19 pandemic by using the emissions of various air pollutants to represent those activities. Review of the emission data suggests that from 2019 to 2020, the amount of emitted air pollutants increased in both Australia and New Zealand, but decreased in most other countries. However, a significant decrease is seen in Eastern China and Viet Nam. Furthermore, the change in emissions is not uniform across regions in a country. The regional disparity in emissions varies over time, particularly in Brunei Darussalam, Indonesia, Malaysia, New Zealand, the Philippines, and Singapore. A sharp rise of the regional disparity in some pollutant indicators is also observed, indicating that economic and social activities restarted (or stopped) in only specific regions.

Regression analyses were conducted to examine the sites that recovered early. In Brunei Darussalam, Indonesia, Malaysia, Philippines, Singapore, and Thailand, economic and social activities in crop, industrial estate, accommodation, restaurant, education, and public services sites have still not returned to normal. In contrast, full recovery or an increase in tourism sites has been noted. For Cambodia, Lao PDR, Myanmar, and Viet Nam, activities in accommodation and automotive sites decreased but have since returned to normal. Although more activities are noticed at restaurant sites, activities at education sites are still low. Lastly, in Australia, China, India, Japan, Korea, and New Zealand, no significant changes are seen in economic and social activities at most sites. The exception is in shop and sport sites, where activities decreased.

This analysis does not aim to uncover the activity type that should start early, as economic and social activities may be well controlled by government policy or orders. For example, programmes to encourage domestic traveling or eating out seem to increase the emission of air pollutants in tourist or restaurant sites. Similarly, restrictions on school opening reduces emissions at education sites, while workplace-closing orders decreased the use of cars for commuting, thereby emissions at automotive and transport sites. In short, even during the pandemic, governments have controlled economic and social activities. Governments should still monitor various indicators, including the amount of the emitted air pollutants, when they open economic and social activities with adequate infection control.

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Appendix: Other Regression Results

Table A1: Regression Results of Formaldehyde Emissions by Group

Group	ASEAN6	ASEAN6	CLMV	CLMV	Plus6	Plus6
Month	Mar – Jun	Jul – Oct	Mar – Jun	Jul – Oct	Mar – Jun	Jul – Oct
Emitting power plant	–0.001	–0.002	–0.004*	–0.003	0.000	0.003
Clean power plant	0.007	0.002	–0.002	0.004	0.007	–0.015**
Cropland	–0.015	–0.021	0.01	–0.005	–0.011	0.034**
Farm	0.004	0.002	0.019**	0.000	0.02	–0.009
Quarry	0.000	0.01	0.028*	0.017	0.059**	–0.051
Industrial site	0.012	–0.005	–0.015*	0.000	0.008	–0.011
Accommodation	–0.003	–0.012	–0.01	–0.011	–0.060***	0.002
Automotive	–0.008	0.034***	–0.012	0.01	0.027	0.006
Business	–0.002	–0.023	0.003	–0.011	–0.052*	0.035
Restaurant	–0.003	–0.039*	0.028**	0.007	0.011	–0.004
Education	–0.002	–0.009	–0.006	0.013	0.009	0.03
Health	–0.028*	–0.008	0.023***	0.012*	–0.026	–0.019
Public service	0.008	–0.016	–0.003	0.002	0.029*	–0.015
Religious site	–0.003	0.024	0.007	–0.001	0.001	0.004
Settlement	0.008	0.002	–0.007	0.002	–0.009	–0.001
Shop	0.049**	0.051**	–0.004	–0.001	0.008	0.011
Sport	–0.032**	0.01	–0.013	–0.022*	–0.030*	0.005
Tourism	–0.007	–0.006	–0.001	0.001	–0.005	0.005
Transport	–0.017*	0.008	–0.011	0.001	0.054	–0.043
Number of observations	609	612	492	442	590	586
Adjusted R–squared	0.1127	0.4632	0.3794	0.4668	0.1258	0.2255

ASEAN6 = Brunei Darussalam, Indonesia, Malaysia, Philippines, Singapore, Thailand; CLMV = Cambodia, Lao PDR, Myanmar, Viet Nam; CO = carbon monoxide; Plus6 = Australia, China, India, Japan, Korea, New Zealand.
Notes: The estimation results using the Ordinary Least Squares method are reported. ***, **, and * indicate 1%, 5%, and 10% levels of statistical significance, respectively. Robust standard errors are used to show statistical significance. In all specifications, country fixed effects and month fixed effects are controlled for. The results of the weather-related variables are omitted.
Source: Authors' compilation.

Table A2: Regression Results of Nitrogen Dioxide Emissions by Group

Group	ASEAN6	ASEAN6	CLMV	CLMV	Plus6	Plus6
Month	**Mar – Jun**	**Jul – Oct**	**Mar – Jun**	**Jul – Oct**	**Mar – Jun**	**Jul – Oct**
Emitting power plant	0.002	0.001	0.000	–0.001	–0.001	–0.002**
Clean power plant	–0.001	0.000	0.000	0.000	0.002	0.002*
Cropland	0.031***	0.006	0.006	–0.006	0.006	0.013***
Farm	0.000	–0.001	0.001	0.007	–0.003	–0.005
Quarry	–0.005	0.007	0.008	0.004	–0.001	0.004
Industrial site	0.003	–0.001	–0.004	0.001	–0.002	–0.002
Accommodation	0.002	–0.003	0.002	0.001	0.008	0.017*
Automotive	–0.028***	–0.033***	–0.018***	–0.003	0.000	–0.002
Business	0.001	0.007	0.006	–0.006	–0.014	–0.019*
Restaurant	0.007	0.013	–0.001	–0.001	0.000	–0.008
Education	–0.003	–0.001	0.001	–0.002	0.008	0.019**
Health	–0.022***	–0.016**	0.002	0.003	–0.003	0.002
Public service	0.011*	0.006	–0.002	–0.003	0.001	–0.007
Religious site	0.006	–0.006	0.002	0.009*	0.005	–0.006
Settlement	–0.002	0.000	0.002	0.002	0.002	0.002
Shop	0.006	0.007	0.008	0.000	0.005	0.027***
Sport	–0.003	–0.002	–0.005	–0.007	–0.007	–0.005
Tourism	0.006	0.002	–0.001	0.001	–0.017**	–0.013*
Transport	–0.003	0.003	–0.002	0.004	0.000	–0.011*
Number of observations	612	612	492	442	592	592
Adjusted R-squared	0.5996	0.355	0.2479	0.4856	0.3617	0.3338

ASEAN6 = Brunei Darussalam, Indonesia, Malaysia, Philippines, Singapore, Thailand; CLMV = Cambodia, Lao PDR, Myanmar, Viet Nam; CO = carbon monoxide; Plus6 = Australia, China, India, Japan, Korea, New Zealand.
Notes: The estimation results using the Ordinary Least Squares method are reported. ***, **, and * indicate 1%, 5%, and 10% levels of statistical significance, respectively. Robust standard errors are used to show statistical significance. In all specifications, country fixed effects and month fixed effects are controlled for. The results of the weather-related variables are omitted.
Source: Authors' compilation.

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