Evidence of the Environmental Kuznets Curve for atmospheric pollutant emissions in Southeast Asia and implications for sustainable development: A spatial econometric approach

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Abstract

Southeast Asia has one of the fastest rates of industrialisation and urbanisation in the world. While this has brought economic benefits to the region, it has also resulted in considerable environmental and health impacts associated with air pollution. This study presents the first spatial econometric assessment of the Environmental Kuznets Curve (EKC) for Southeast Asia. Spatial panels, while important in studies involving geographical units, have to date been underutilised in many EKC studies. Here, the income-pollution trajectories of three air pollutants—nitrogen oxides (NO_x), sulfur dioxide (SO_2) and fine particulate matter ($PM_{2.5}$)—are examined through standard and spatial EKC models that regress per capita emissions on several socioeconomic indicators. The econometric assessment utilises data from 1993–2012 for nine Southeast Asian countries at varying levels of economic development. An inverted U-shaped curve is found for all pollutants, thus confirming the existence of an EKC. Spatial spillovers are not found for NO_x emissions but are supported for SO_2 and $PM_{2.5}$ emissions. While an EKC is supported, most countries are still on the upward sloping portion of the inverted U-shaped curve. This highlights the urgent need to establish and enforce effective policies to abate emissions in light of the current extent of health issues associated with ambient air pollution in the region. In particular, results presented here point to policies that increase the share of renewable energy as a potentially effective emissions abatement strategy as regional policymakers attempt to steer a path towards sustainable development.

Keywords: Air pollution; economic growth; EKC; Southeast Asia; spatial panels; sustainable development

1. Introduction

With an annual growth rate of 5.2% since 2000 and primary energy demand increasing by approximately 70% over the same period, Southeast Asia has one of the fastest rates of industrialisation and urbanisation in the world (International Energy Agency, 2017). While this has brought economic benefits to the region, it has also resulted in considerable health and environmental impacts associated with air pollution. The World Health Organisation attributes more than 149,000 premature deaths in the region to ambient air pollution annually and this is expected to double over the next two decades with rising energy demand and fossil fuel consumption (UN Environment, 2017). An examination of the relationship between economic growth and environmental pollution in Southeast Asia is therefore both timely and essential, especially because doing so can provide important guidance as policymakers in the region attempt to steer a path towards sustainable development.

Over the past few decades, a sizable portion of literature exploring the environment-development nexus has focused on the Environmental Kuznets Curve (EKC) hypothesis. The EKC was first proposed by Grossman and Krueger (1991), who theorised that environmental quality deteriorates in the early stages of economic growth, after which an increase in wealth prompts economic restructuring towards less pollution-intensive industries, technological improvements to methods of production, and attitudinal changes towards a cleaner environment (Maddison, 2006; Ward et al., 2016). If this were to hold, one might expect the EKC to depict an inverted U-shaped curve, whereby environmental degradation increases as a country begins to develop until a turning point is reached, beyond which environmental quality improves with continued economic growth (Dinda, 2004; Kaika & Zervas, 2013).

Grossman and Krueger's (1991) work was underpinned by the concept of trade liberalisation. The authors identified three mechanisms through which trade can lead to the realisation of the EKC: (i) the scale effect, whereby increased market access drives the expansion of economic activity, (ii) the composition effect, whereby countries restructure their economies to specialise in sectors they enjoy comparative advantage in, and (iii) the technique effect, whereby trade facilitates changing techniques of production and promotes the sharing of greener production technologies among countries. The turning point of the EKC is theoretically attained when the effects of increased productive efficiency and changes in the composition of an economy towards more environmentally friendly sectors offset the pollutive effects of economic growth. Nevertheless, Cole (2004) asserts that in the event that economic restructuring results in the offshoring of pollution-intensive industries from high income economies to lower income economies with less stringent environmental regulations, overall net pollution levels do not decline but are instead displaced. This displacement, leading to the creation of pollution havens, has been cited as a key reason for an overly optimistic view presented by the EKC (Cole, 2004; Kearsley & Riddel, 2010).

Several studies have attempted to account for the existence of pollution havens by incorporating a trade-reflection variable in their econometric models (e.g., Atici, 2009; Baek, 2016; Chandran & Tang, 2013; Chang, Yeh, & Chen, 2014; Ertugrul, Cetin, Seker, & Dogan, 2016; Friedl & Getzner, 2003; He, 2006; Jayanthakumaran, Verma, & Liu, 2012; Lau, Choong, & Eng, 2014; Sun, Clottey, Geng, Fang, & Amissah, 2019; Wagner & Timmins, 2009). The findings have, however, been mixed at best, with some studies suggesting the existence of pollution havens and others not. These studies also yield inconclusive results regarding the final shape of the EKC (e.g., positive linear relationship; inverted U-shaped relationship; U-shaped relationship; N-shaped relationship; no relationship). A recent strand of literature attributes these inconsistencies to the failure to account for spatial relationships among countries despite empirical evidence suggesting geographical distance as a key determinant of trade (Anderson & van Wincoop, 2004) and technological diffusion (Keller, 2004). Omitting spatial controls from econometric models when spatial relationships exist would consequently result in biased estimates (Anselin, 1988; LeSage & Pace, 2009).

Aware of the potential dependence among countries with open economies, Maddison (2006) and Rupasingha, Goetz, Debertin, and Pagoulatos (2004) were amongst the first to incorporate spatial interactions in their EKC frameworks. The authors, along with several others who have since extended the standard EKC to include spatially weighted variables, arrived at a common conclusion that emissions in one country may indeed be strongly influenced by the economic standing of a neighbouring state (e.g., Balado-Naves, Baños-Pino, & Mayor, 2018; Kang, Zhao, & Yang, 2016; Wang, Kang, Wu, & Xiao, 2013). At present, spatial EKC studies are either highly generalised and pitched at a global scale (e.g., Balado-Naves et al., 2018; Maddison, 2006; Wang et al., 2013), centred on large nation states such as China (e.g., Ding, Zhang, Chen, Wang, & Nie, 2019; Ge, Zhou, Zhou, Ye, & Liu, 2018; Hao, Liu, Weng, & Gao, 2016; Hao, Wu, Wang, & Huang, 2018; Li et al., 2014; Meng & Huang, 2018; Xu et al., 2019; Zhang, Zhang, & Zhao, 2020; Zhu, Wang, & Zhang, 2019) and the United States (e.g., Burnett, Bergstrom, & Dorfman, 2013; Rupasingha et al., 2004; Tevie, Grimsrud, & Berrens, 2011), or considered for regional groupings of countries that are at relatively similar stages of economic development such as Europe (e.g., Maddison, 2007). This study contributes to the current literature by providing the first spatial assessment of the

EKC for Southeast Asia, an economically diverse region characterised by rapid urbanisation and industrialisation and widespread environmental degradation.

The research that underpins this paper focuses on the emissions of three criteria air pollutants—nitrogen oxides (NO_x), sulfur dioxide (SO_2) and fine particulate matter ($PM_{2.5}$). These three pollutants are closely associated with increases in fossil fuel combustion, power generation, as well as inland and maritime transportation in Southeast Asia, and have been implicated as the leading cause of respiratory-related diseases in the region (Koplitz, Jacob, Sulprizio, Myllyvirta, & Reid, 2017; Lee, Iraqui, & Wang, 2019; Shi et al., 2018). A recent global air quality report revealed that annual mean levels of $PM_{2.5}$—an indicator of overall air quality for Target 11.6 of the United Nations Sustainable Development Goals (SDGs)—across all Southeast Asian countries considerably exceeded limits set by the World Health Organisation (IQAir, 2019). Notwithstanding the well-documented environmental and health impacts of NO_x, SO_2 and $PM_{2.5}$ (United States Environmental Protection Agency, 2016; World Health Organisation, 2018), EKC-oriented studies in Southeast Asia have, to date, relied on carbon dioxide (CO_2) emissions as a proxy of environmental degradation (Table 1). While this is due to the limited availability of continuous, long-term data for other pollutant types, the general consensus is that the inverted U-shaped relationship does not hold for CO_2 emissions in any meaningful way (Ansuategi & Escapa, 2002; Arrow et al., 1995; Holtz-Eakin & Selden, 1995; Kaika & Zervas, 2013; Zhou, Ye, & Ge, 2017). This is because CO_2, once emitted, is widely dispersed in the atmosphere and the costs of pollution are easily externalised (Cole, Rayner, & Bates, 1997; Dinda, 2004). Consequently, CO_2 emissions tend to generate a relatively weak effect on local perceptions of environmental quality (Chen & Taylor, 2020) and on the responsiveness of policymakers and regulators (Cole, 1999; Gill, Viswanathan, & Hassan, 2018). Any observed declines in carbon emissions for each unit of capital stock—resulting from the shift towards cleaner fuels and technologies—have hence been largely motivated by concerns about the effects of local rather than global pollutants (Shafik, 1994). To this end, most studies either find a monotonically increasing relationship between CO_2 emissions and income, or report a high, out-of-sample turning point.

The current paper estimates two forms of the EKC: (i) a standard EKC that regresses per capita emissions on a range of variables reflecting the mechanisms originally proposed by Grossman and Krueger (1991), and (ii) a spatial EKC that augments the standard model by including spatially weighted variables. This permits assessment, for the first time, of whether the evidence for NO_x, SO_2 and $PM_{2.5}$ emissions in Southeast Asia is consistent with the EKC hypothesis, and the extent to which emissions in one country are associated with socioeconomic conditions in other countries within the region. We take advantage of and combine two 20-year country-level panels for the region, one on pollutant emissions and the other on aggregate economic metrics.

2. Data

A balanced panel dataset comprising nine countries in Southeast Asia[1] was used to assess the relationship between economic growth and environmental pollution. Panel data are generally preferred over time-series and cross-sectional data as they contain greater degrees of freedom and sampling variability, leading to improved accuracy and validity of parameter estimates (Hsiao, 2007). The nine countries referred to comprise a highly heterogeneous grouping in terms of economic standing, with Brunei and Singapore classed as high income economies,

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[1] Southeast Asia comprises Brunei, Cambodia, Indonesia, Lao PDR, Malaysia, Myanmar, Philippines, Singapore, Thailand, Timor-Leste and Vietnam. Myanmar was excluded from the analysis due to a large amount of missing data for several explanatory variables, while Timor-Leste was excluded as the country was only formed in 2002, midway through our study period. Pollutant emissions from Timor-Leste are expected to be very low, however, owing to its relatively small size and population and low level of economic development.

Malaysia and Thailand classed as upper-middle income economies, and Vietnam, Cambodia, Lao PDR, Philippines and Indonesia classed as lower-middle income economies (World Bank, 2019). No other region in the world supports such a wide diversity of per capita gross domestic product (GDP) among countries that are economically linked—in this case through various Association of Southeast Asian Nations (ASEAN) agreements—within such a small geographical area (Figure 1). This diversity permits the projection, albeit cautious, of the joint evolution of environmental quality and economic development for countries that are currently at relatively early stages of development (Stern, 2004).

The econometric analysis detailed here utilises 20 years of data from 1993 to 2012. Data on NO_x, SO_2 and $PM_{2.5}$ emissions were taken from the Emissions Database for Global Atmospheric Research (EDGAR v4.3.2; Crippa et al., 2018), while economic data were taken from the World Bank's World Development Indicators (data.worldbank.org/indicator) and the United Nations Conference on Trade and Development (unctadstat.unctad.org). The EDGAR database adopts a bottom-up, sector-specific[2] calculation methodology, but does not include emissions arising from large-scale biomass burning, land-use change and forestry (Crippa et al., 2018; Janssens-Maenhout et al., 2019), which can be substantial in countries like Indonesia and Malaysia (Streets, Yarber, Woo, & Carmichael, 2003; Vadrevu, Ohara, & Justice, 2014). To describe an EKC relationship, the main regressor of interest is per capita GDP and its squared term, measured in constant 2011 international dollars using purchasing power parity[3]. Scatterplots depicting both cross-country heterogeneity and time-series

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[2] Main categories of emission sectors comprise energy (including the production, combustion, handling and transmission of fossil fuels and biofuels), industrial processes (including non-combustion emissions from the manufacturing of chemicals and solvents or production of food, paper and ferrous and non-ferrous metals), agriculture (including agricultural waste burning), waste (including landfills, wastewater management and solid waste incineration) and others (including direct emissions from fossil fuel fires and indirect emissions from atmospheric deposition of NO_x). More details can be found in Crippa et al. (2018) and Janssens-Maenhout et al. (2019).

[3] All dollar values hereafter are expressed in constant 2011 international dollars using purchasing power parity.

variation in the key variables of interest (i.e., per capita GDP and per capita emissions) are presented in Figure 2. Additional control variables used in our analysis include:

(i) Level of urbanisation, calculated as the percentage of population living in urban areas out of the total population. As urbanisation levels increase, per capita emissions are expected to rise due to increased consumption and energy use (Dong, Lin, Huang, & Chen, 2020; M. Yang, Ma, & Sun, 2018). Urbanisation levels vary considerably among the nine Southeast Asian countries, from Cambodia, where a little over 20% of the population resides in urban areas, to Singapore with its entirely urbanised population.

(ii) Share of renewable energy consumption, calculated as a percentage of total final energy consumption. Energy generated from renewable sources is commonly associated with lower emission levels (Xie, Dai, & Dong, 2018). As the extent of renewable energy development is largely determined by a country's natural resource endowment (Carley, 2009), economies like land- and resource-challenged Singapore, and Brunei, with its substantial oil and liquefied natural gas reserves, meet less than 1% of their energy consumption through renewables. By comparison, countries like Cambodia and Lao PDR have been able to harness the Mekong River as a source of hydropower and thus generate a high proportion of their energy from renewable sources.

(iii) Share of the services sector (ISIC divisions 50–99)[4], expressed as a percentage of

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[4] ISIC divisions 50–99 include services in wholesale and retail trade (including hotels and restaurants), transport, and government, financial, professional and personal services such as education, healthcare and real estate services.

total GDP. An economy with a dominant services sector generally indicates a de-industrialisation stage characterised by the phasing out of more pollution-intensive industries (N. Yang et al., 2018). Singapore is the only country in our sample where the services sector accounts for more than 60% of GDP.

(iv) Primary energy intensity, measured by dividing total primary energy supply over GDP. Economies with lower energy intensity use a smaller amount of energy for every unit of output produced. Energy intensity is therefore often used as an indirect measure of technological progress as productive processes become cleaner and more efficient (Huang, Du, & Tao, 2017; Pan, Uddin, Han, & Pan, 2019).

(v) Foreign direct investment (FDI), expressed as an inward stock and as a percentage of GDP. The association between FDI and pollutant emissions depends on the nature of investment by multinational firms. For example, while FDI may assist in the transfer of technology and development of human capital when an economy shifts towards high value-added products and service industries, other economies that specialise in pollution-intensive industries may also attract FDI (Gardiner & Hajek, 2019; López-Menéndez, Pérez, & Moreno, 2014).

Table 2 provides additional details and summary statistics of the data.

3. Methodology

3.1. Standard EKC model specification

In its most basic form, the EKC hypothesises a quadratic relationship between economic growth and environmental pollution, with per capita income and its squared term serving as the only explanatory variables in a regression equation (Grossman & Krueger, 1995). This relationship is not to be interpreted as causal in the sense that changes in income would lead to a change in emission levels. Rather, a multitude of mechanisms are at play, whereby various economic actors respond endogenously to evolving incentives and institutions that shape both growth and emission levels. A key criticism of the basic model has been its lack of explanatory capacity and, in particular, the omission of key variables that are strongly associated with pollution dynamics. For example, critics assert that income alone does not reflect broader changes in the structural composition of an economy, nor does it fully capture the effects of technological progress (Dinda, 2004; Fonkych & Lempert, 2005; Stern, 2004). We have therefore selected variables that are not only important determinants of NO_x, SO_2 and $PM_{2.5}$ emissions, but that are also representative of the relationship between economic development and environmental pollution:

$$lne_{it} = \beta_1 lny_{it} + \beta_2 (lny_{it})^2 + \beta_3 UB_{it} + \beta_4 RE_{it} + \beta_5 SV_{it} + \beta_6 lnEI_{it} + \beta_7 FDI_{it} + \alpha_i + \eta_t + \varepsilon_{it} \quad (1)$$

where e_{it} = per capita emissions of NO_x, SO_2 and $PM_{2.5}$ for country i in year t, y_{it} = per capita GDP, UB_{it} = level of urbanisation, RE_{it} = share of renewable energy consumption, SV_{it} = share of the services sector, EI_{it} = energy intensity, and FDI_{it} = stock of inward FDI. Variables e, y, and EI enter in natural logarithms. α_i and η_t represent country and year fixed effects, respectively, while ε_{it} denotes the error term. If an EKC exists, the turning point[5] would be given by:

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[5] Estimated standard errors on the ratio of coefficients and thus 95% confidence intervals (CI) on the turning point are computed using the delta method.

$$y^* = exp\,(-\beta_1/2\beta_2) \tag{2}$$

3.2. Spatial EKC model specification

Spatial spillovers occur when changes in one or more explanatory variables in unit i impact the dependent variable in other units j, where $j \neq i$ (Halleck Vega & Elhorst, 2015). Given that all countries in our sample are part of ASEAN, which promotes and facilitates regional trade and economic integration (ASEAN Secretariat, 2015), there is likely to be some degree of spatial spillover arising among these member states. When such spillovers exist, LeSage (2014) stresses the importance of selecting an appropriate spatial regression specification to account for these relationships. In the current study, spatial relationships are accounted for by estimating three spatial regression models. The spatial Durbin error model (SDEM) allows for spatial lags of the explanatory variables and the error term. Its two nested forms, the spatial lag of X (SLX) model and the spatial error model (SEM), include, respectively, spatially lagged explanatory variables and a spatial autoregressive process in the error term (Halleck Vega & Elhorst, 2015; LeSage & Pace, 2009). Here, the SDEM model takes the following form:

$$lne_{it} = \beta_1 lny_{it} + \beta_2 (lny_{it})^2 + \beta_3 UB_{it} + \beta_4 RE_{it} + \beta_5 SV_{it} + \beta_6 lnEI_{it} + \beta_7 FDI_{it} + \theta_1 \sum_{j=1}^{N} w_{ij} lny_{jt} + \theta_2 \sum_{j=1}^{N} w_{ij} (lny_{jt})^2 + \theta_3 \sum_{j=1}^{N} w_{ij} UB_{jt} + \theta_4 \sum_{j=1}^{N} w_{ij} RE_{jt} + \theta_5 \sum_{j=1}^{N} w_{ij} SV_{jt} + \theta_6 \sum_{j=1}^{N} w_{ij} lnEI_{jt} + \theta_7 \sum_{j=1}^{N} w_{ij} FDI_{jt} + \alpha_i + \eta_t + u_{it} \tag{3}$$

$$u_{it} = \lambda \sum_{j=1}^{N} w_{ij} u_{jt} + \varepsilon_{it}$$

where $N = 9$ is the number of panel units or countries, θ_p represents the spillover effects for the p^{th} spatially weighted explanatory variable, u_{it} denotes the spatially dependent error term, and λ indicates the strength of spatial dependence among the errors. w_{ij} is the element at row i and column j of a pre-determined spatial weights matrix, W, which captures the strength of relationship among the nine countries. W is specified from Tobler's First Law of Geography, which states that everything is related to everything else, but things that are nearer are more related to one another than things that are farther apart (Tobler, 1970). Since geographical distance is an important determinant of trade, W was computed using inverse distances based on country capitals[6]. The use of country capitals is preferred for the region of Southeast Asia due to the predominance of island states and irregularly-shaped countries (Figure 1). Using country centroids would result in the centroids of several countries lying in the middle of the sea (e.g., Indonesia) or in another country's territory (e.g., Vietnam). Prior to its inclusion in the spatial EKC models, W was normalised by its maximum eigenvalue to remove unit dependence whilst preserving its internal weighting structure (Kelejian & Prucha, 2010).

3.3. Estimation methods, model tests and sensitivity analysis

The fixed effects (FE) estimator was used in our model estimations to account for individual heterogeneity. Individual FE capture any time-invariant, country-specific characteristics, such as climate and geography (Ge et al., 2018), while year FE control for common time-varying external shocks that may affect the variables in our model, such as the financial crisis or the implementation of or changes in regional policy (Kang et al., 2016). For the standard EKCs, four models were compared using ordinary least squares (OLS): (i) pooled OLS, (ii) individual FE, (iii) year FE, and (iv) two-way FE. A Hausman diagnostic test was included in our preliminary analysis to validate our choice of the FE estimator over the random effects (RE) estimator (Wooldridge, 2013). For the spatial EKCs, while the SLX model can be efficiently estimated using OLS regression, maximum likelihood (ML) techniques are used to

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[6] The diagonal of W contains zeros.

estimate the SEM and SDEM models (LeSage & Pace, 2009). We therefore proceeded by first estimating all three spatial models before employing likelihood ratio (LR) tests to determine if the SDEM model can be simplified to one of its nested forms. Accordingly, the LR SLX test poses a null hypothesis of H_0: $\lambda = 0$, while the LR SEM test poses a null hypothesis of H_0: $\theta_p = 0$, where $p = 1, \ldots, 6$.

To test the sensitivity of the estimated coefficients, we modified our regressions by dropping two covariates (share of the services sector and FDI) and interacting level of urbanisation with GDP and its squared term. This permits assessment of the robustness of an estimated EKC relationship to variations in model specification, and the dependence of the estimated turning points on the level of urbanisation specified; turning points were estimated using the 25th and 75th percentile of urbanisation levels across all countries (27% and 68%, respectively). No interactions were included in the spatially weighted variables to maintain model parsimony.

All model estimations and tests, including computation of W, were performed in the R language and environment (v3.5.0; R Core Team, 2018).

4. Results and discussion

4.1. Preliminary analysis

Supplementary Tables 1–3 present the results of the specification test for the standard EKC for per capita NO_x, SO_2 and $PM_{2.5}$ emissions, respectively. For all three air pollutants, the Hausman test rejects ($p < 0.01$) the null hypothesis that the RE estimator is more appropriate. The two-way FE model naturally provides the best fit of the data for each pollutant, as measured by a substantially higher log-likelihood compared to models with one-way FE. This is intuitive in light of Figure 1, which shows marked heterogeneity across countries coupled with within-country variation over time. We therefore focus our analysis on the two-way FE model estimations.

4.2. NO_x emissions

Table 3 presents the standard and spatial two-way FE estimations for NO_x emissions. For the standard model, the positive coefficient of lny and negative coefficient of $(lny)^2$, both of which are significant at the 1% level, point to an inverted U-shaped relationship between per capita income and NO_x pollution. This relationship is consistent with the findings of other studies (e.g., Cole et al., 1997; Panayotou, 1993; Selden & Song, 1994) and implies that increases in per capita GDP are associated with increases with per capita NO_x emissions until a turning point of \$10,957 (95% CI $=$ [\$4819, \$24,914]) is reached. This turning point is well within the observed income range in our sample, with the four most economically developed countries currently on the downward sloping portion of the EKC (Figure 3). Nevertheless, given that the remaining lower income economies are still relatively far from attaining this level of per capita GDP, NO_x emissions are expected to continue rising throughout much of the region in the years to come if current policies and business conditions are maintained.

The remaining explanatory variables exhibit statistical significance at the 1% level except for FDI, which is not significant even at the 10% level[7]. The standard model suggests that a percentage point increase in urbanisation levels is, on average, associated with a 2.8% increase in per capita NO_x emissions. This correlation is considerable and consistent with our

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[7] This lack of significance is likely due to the fact that, in this sample, FDI is already explained by countries' other economic characteristics that are included in the model.

expectations, as urbanisation tends to increase with primary energy demand, including that of transportation (e.g., diesel), which is a significant source of NO_x emissions (Ge et al., 2018). Energy intensity also has an expected positive association with the amount of per capita NO_x emissions produced; specifically, all else being equal, a 1% increase in energy intensity is associated with a 0.16% increase in per capita NO_x emissions. By contrast, a rising share of renewable energy is associated with lower emissions, with every percentage point shift in energy consumption towards renewable sources leading to a decline in emissions of equal magnitude. Emissions are also expected to decline by an average of 1.1% with every percentage point increase in the share of the services sector. This is due to the generally less polluting nature of the services sector relative to manufacturing and heavy industries (Levinson, 2009). Beyond offering an EKC assessment for Southeast Asia, the analysis informs the characteristics that drive emissions in different countries in the region.

For the spatial model, the null hypothesis for both the LR SLX and LR SEM tests is not rejected, even at the 10% level. This suggests that there is insufficient evidence to confirm the existence of spatial spillover effects of the errors and regressors for per capita NO_x emissions. After controlling for possible spatial relationships among countries, the estimated coefficients for all three spatial models are broadly similar to that of the standard FE model, suggesting that the level and composition of economic activity in neighbouring countries do not lend additional power to explain national NO_x emissions. A possible reason for this is that the largest contributors of NO_x emissions in Southeast Asia are the ever-growing public electricity production and transportation sectors (Vadrevu et al., 2014). These two sources, which are highly and positively associated with urbanisation levels, tend to be more local in nature as they reflect rising standards of living (Chang et al., 2018; Herrerias, Aller, & Ordóñez, 2017; Wang & Yang, 2019). As people migrate from rural to urban areas, they tend to demand greater mobility and better access to electricity. The resultant increase in per capita NO_x emissions therefore appears to be predominantly driven by increases in national energy and fuel consumption rather than changes in the energy intensity or sectoral composition of neighbouring countries, which would then be suggestive of pollution havens in NO_x sources.

Supplementary Table 4 investigates the sensitivity of estimated turning points to different urbanization levels. The standard and spatial EKC specifications for NO_x emissions are repeated, this time adding the interaction of urbanisation with GDP and the interaction of urbanisation with GDP squared while dropping the share of the services sector and FDI together with their spatial lags. The results indicate turning points of about \$5,000 to \$8,000 at lower levels of urbanization in the sample (25th percentile). At higher levels of urbanization (75th percentile), turning points are evaluated to be lower, between \$2,000 and \$4,000.

Although NO_x emissions in Southeast Asia are projected to rise for the foreseeable future, our results point to the potential effectiveness of policies targeted at minimising vehicular emissions. At present, Singapore, Thailand and Malaysia are the only countries in the region to impose a minimum of Euro IV-equivalent emission standards for light-duty passenger vehicles (ASEAN Secretariat, 2019; UN Environment, 2017). These countries are also found on the downward sloping portion of the estimated EKC. Given the positive association between urbanisation and vehicular ownership, and with our model indicating urbanisation levels having the largest influence on per capita NO_x emissions, measures to tighten vehicle emission standards and improve fuel quality—particularly in countries that are currently in the early stages of rapid urbanisation—will likely lower the current turning point of the EKC. This will help to reduce projected increases in transport-related NO_x

emissions, with the International Energy Agency (2017) expecting road transportation to account for 50% of all NO_x emissions in Southeast Asia by 2040 under a business-as-usual scenario. It will also contribute to regional efforts to achieve SDGs 3 (by reducing harmful vehicular emissions), 7 (by promoting energy efficient transport), 11 (by improving urban air quality and fostering sustainable mobility in cities) and 13 (by reducing greenhouse gas emissions).

4.3. SO_2 emissions

Table 4 presents the standard and spatial two-way FE estimations for SO_2 emissions. For the standard model, all variables were significant at the 1% level except for energy intensity and FDI stock, which was not significant, even at the 10% level. This model lends support to the inverted U-shaped EKC and estimates a relatively low turning point of \$4054 (95% CI $=$ [\$1863, \$8821]).

For the spatial model, the null hypothesis for the LR SEM test was rejected at the 1% level, while that for the LR SLX test was not rejected. These tests point to the significance of spatial spillovers in the form of spatially lagged observable economic aggregates. Notably, the significant negative coefficient of $WlnGDP$ and positive coefficient of $W(lnGDP)^2$ imply that, all else including national income being equal, economic growth in neighbouring countries is associated with a decline in national per capita SO_2 emissions until neighbouring countries attain a per capita GDP of \$20,969[8]. Thereafter, national per capita SO_2 emissions are expected to increase. One interpretation used in the literature suggests the existence of

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[8] This turning point is calculated using $WlnGDP$ and $W(lny)^2$ in Table 4: exp $\left(\frac{-1 \times -9.268}{2 \times 0.466}\right)$

pollution havens in Southeast Asia: as neighbouring lower income economies develop, national emissions decline—likely due to the outsourcing of pollution-intensive industries from higher to lower income economies—until a certain level of wealth is achieved (Ding et al., 2019). This pollution displacement is temporary, however, with national per capita SO_2 emissions rising again once lower income economies improve their economic standing.

In addition, our results indicate that when spatial spillovers are accounted for, the estimated turning point drops from \$4054 (95% CI $=$ [\$1863, \$8821]) in the standard model to \$2616 (95% CI $=$ [\$1521, \$4499]) in the SLX model. This would suggest that all countries considered here, with the exception of Cambodia, are on the downward sloping portion of the EKC, and suggests that SO_2 emissions for the region as a whole may be on a decline. Such a trend is contrary to recent reports and observations, which indicate that SO_2 emissions in the region have been increasing and are expected to grow by 40% over current levels to 5.1 Tg in 2040 (International Energy Agency, 2017). Given that increased SO_2 emissions are primarily driven by a rising use of coal for power generation, and with coal projected to account for almost half of the total electricity generated in the region in 2035 (World Coal Association and ASEAN Centre for Energy, 2017), this discrepancy may be largely attributed to the inability of our models in capturing an out-of-sample increase in coal-fired electricity generation in Southeast Asia. This is particularly the case for Indonesia, Vietnam and the Philippines, where the number of coal-fired power plants is expected to grow from 147 to 323, 38 to 133 and 30 to 70, respectively, between 2011 and 2030 (Koplitz et al., 2017). Also relevant is the fact that the only two high income economies in Southeast Asia, Singapore and Brunei, do not rely on coal as a primary source of fuel. Hence, our models may have failed to account for a possible rise in per capita SO_2 emissions associated with an increasing reliance on coal-use as lower income economies grow. While this is indicative of model sensitivity to the data used, the results are fairly robust to econometric specification (Supplementary Table 5), particularly at lower levels of urbanisation.

4.4. $PM_{2.5}$ emissions

Table 5 presents the standard and spatial two-way FE estimations for $PM_{2.5}$ emissions. For the LR SEM test, the null hypothesis was rejected at the 1% level. We do not reject the null hypothesis for the LR SLX test, even at the 10% level. Thus, similar to the case for SO_2 emissions, the SLX model was found to best fit the data.

As with the earlier findings of NO_x and SO_2, the estimated turning point for $PM_{2.5}$ emissions is lower when spatial lags are accounted for. In particular, the results of the SLX model indicate the existence of an inverted U-shaped EKC with an estimated turning point of \$10,381 (95% CI = [\$4842, \$22,259]). This turning point likely reflects the switch from the traditional use of solid biomass to electricity and natural gas for cooking and heating, as indoor air pollution remains a major health risk, particularly in rural parts of Southeast Asia. In lower income economies such as Lao PDR, Cambodia and the Philippines, for example, 96%, 83% and 60% of the population, respectively, relies primarily on biomass as a fuel source (International Energy Agency, 2017). These countries are also found on the upward sloping portion of the EKC. The estimates, however, appear to be highly sensitive to model specification. Modifying the original model by allowing the income-pollution relationship to vary with urbanisation levels no longer results in an inverted U-shaped EKC (Supplementary Table 6). Evidence of an EKC for per capita $PM_{2.5}$ emissions is therefore much less robust than for NO_x and SO_2 emissions.

5. Conclusions and policy implications

This study provides the first confirmation of the EKC for NO_x, SO_2 and $PM_{2.5}$ emissions in Southeast Asia using a spatial econometric approach. While an EKC is found for all three air pollutants, most countries are still on the upward sloping portion of the inverted U-shaped curve. This finding highlights the urgent need to establish and enforce effective policies to abate emissions in light of the current extent of health issues associated with air pollution in Southeast Asia. In particular, results presented here point to policies that increase the share of renewables in the total energy mix as a potentially effective emissions abatement strategy. Rather than focusing on restructuring the composition of an economy—which has its limits as today's developing economies will find it more difficult to phase out or offshore pollution-intensive industries (Arrow et al., 1995; Stern, 2004)—Southeast Asian countries should work towards the development of renewable energy. The latter, however, requires careful thought and planning to avoid the potential pitfalls associated with it. For example, the expansion of oil palm plantations for the production of biofuels in Malaysia and Indonesia has, to date, taken place without due consideration of its negative impact on the environment (Mukherjee & Sovacool, 2014). This includes the large amount of carbon emissions and particulate pollution produced from the burning and conversion of forests and peatlands (Hayasaka, Noguchi, Putra, Yulianti, & Vadrevu, 2014; Nechita-Banda et al., 2018). The rapid development of hydroelectric dams throughout the region, which is, in part, driven by incentives to reduce energy dependence on fossil fuels, has also resulted in negative environmental impacts, such as declines in fish stocks and alterations to sediment and nutrient transport, as well in the loss of livelihoods and increased food insecurity (Hecht, Lacombe, Arias, Dang, & Piman, 2019). Tapping into renewable energy therefore requires a thorough evaluation of the trade-offs between the benefits of renewable energy and their potential, inadvertent ecological, social and environmental consequences. This remains a key regional challenge, especially in light of existing plans to expand the production and consumption of coal to meet future energy demands.

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Table 1. Summary of EKC studies for Southeast Asian countries.

			Variables			
Author(s)	Countries	Period	Dependent	Explanatory	EKC supported?	Spatial relationships considered?
Al-Mulali et al. (2015)	Vietnam	1981–2011	CO_2	GDP, exports, imports, non-renewable energy consumption, renewable energy consumption, labour force, capital	No	No
Apergis and Ozturk (2015)	14 Asian countries including Indonesia, Malaysia and Singapore	1990–2011	CO_2	GDP, population density, industry share, land area, political stability, quality of regulation, government effectiveness, corruption	Yes	No
Azlina et al. (2014)	Malaysia	1975–2011	CO_2	GDP, energy consumption, industrial structure, renewable energy consumption	No	No
Baek (2016)	ASEAN-5	1981–2010	CO_2	GDP, energy consumption, FDI	No	No

Chandran and Tang (2013)	ASEAN-5	1971–2008	CO_2	GDP, energy consumption, FDI	No	No
Chen and Taylor (2020)	Singapore	1950–2017	Cr	GDP, FDI, trade openness, environmental regulations	Yes	No
Dong et al. (2018)	14 Asia-Pacific countries including ASEAN-5 and Vietnam	1970–2016	CO_2	GDP, natural gas consumption	Yes	No
Heidari et al. (2015)	ASEAN-5	1980–2008	CO_2	GDP, energy consumption	Yes	No
Lau et al. (2014)	Malaysia	1970–2008	CO_2	GDP, FDI, trade openness	Yes	No
Le (2019)	ASEAN	1993–2014	CO_2	GDP, FDI, trade openness, level of urbanisation	No	No

Lean and Smyth (2010)	ASEAN-5	1980–2006	CO_2	GDP, electricity consumption	Yes	No
Liu et al. (2017)	Indonesia, Malaysia, Philippines, Thailand	1970–2013	CO_2	GDP, renewable energy consumption, non-renewable energy consumption, value-added of agricultural sector	No	No
Nasir et al. (2019)	ASEAN-5	1982–2014	CO_2	GDP, FDI, bank credit to bank deposit, international debt, number of listed companies	No	No
Saboori et al. (2012)	Malaysia	1980–2009	CO_2	GDP	Yes	No
Saboori and Sulaiman (2013)	ASEAN-5	1971–2009	CO_2	GDP, energy consumption	Yes (Singapore and Thailand); No (Indonesia, Malaysia and Philippines)	No

Tang and Tan (2015)	Vietnam	1976–2009	CO_2	GDP, energy consumption, FDI	Yes	No
Vincent (1997)	Malaysia	Late 1970s to early 1990s	TSP, BOD, COD, pH, NH_3-N, TSS	GDP, population density	No	No
Zhu et al. (2016)	ASEAN-5	1981–2011	CO_2	GDP, energy consumption, FDI, trade openness, industrial structure, financial development, total population	No	No

Note: CO_2 = carbon dioxide emissions; Cr = chromium emissions; GDP = gross domestic product; FDI = foreign direct investment; ASEAN-5 = five original member countries of the Association of Southeast Asian Nations comprising Indonesia, Malaysia, Philippines, Singapore and Thailand; TSP = total suspended particles in the air; BOD, COD, pH, NH_3-N and TSS are water quality parameters where BOD = biochemical oxygen demand, COD = chemical oxygen demand, NH_3-N = ammoniacal nitrogen and TSS = total suspended solids.

Table 2. Details and summary statistics of dependent and explanatory variables.

	Description	Min	Max	Mean	SD
Dependent variable, e					
NO_x	Per capita emissions of nitrogen oxides (kg)	2.69	58.28	16.62	15.27
SO_2	Per capita emissions of sulfur dioxide (kg)	0.84	120.67	15.32	25.62
$PM_{2.5}$	Per capita emissions of fine particulate matter (kg)	2.20	14.89	6.99	3.07
Explanatory variables					
y	Per capita GDP based on PPP (constant 2011 international $)	1031.66	86,433.81	20,917.13	27,837.58
UB	Share of population living in urban areas (%)	16.49	100.00	47.77	25.30
RE	Share of renewable energy in total final energy consumption (%)	0.00	86.93	34.88	29.43
SV	Share of services sector (ISIC divisions 50–99) over GDP (%)	25.25	69.21	45.76	9.40
EI	Primary energy intensity per unit GDP (MJ/$2011 PPP GDP)	2.51	11.92	5.16	1.51
FDI	Foreign direct investment inward stock as a percentage of GDP (%)	1.17	284.99	44.12	52.36

Note: Per capita emissions were calculated using data for total emissions from the EDGAR v4.3.2 database (Crippa et al., 2018) and data for total population from the World Bank's World Development Indicators. ISIC divisions 50–99 include services in wholesale and retail trade (including hotels and restaurants), transport, and government, financial, professional and personal services such as education, healthcare and real estate services.

Table 3. Non-spatial and spatial estimation results for per capita NO_x emissions.

	Two-way FE	SDEM	SLX	SEM
lnGDP	4.395***	4.139***	4.025***	4.294***
	(10.421)	(10.611)	(8.252)	(12.328)
(lnGDP)^2	–0.236***	–0.232***	–0.229***	–0.232***
	(–8.887)	(–9.628)	(–7.647)	(–10.574)
Urbanisation	0.028***	0.034***	0.035***	0.030***
	(7.046)	(6.694)	(5.416)	(8.577)
RenewableEnergy	–0.011***	–0.011***	–0.013***	–0.011***
	(–4.010)	(–3.764)	(–3.368)	(–4.898)
ServicesSector	–0.011***	–0.009***	–0.010***	–0.011***
	(–4.245)	(–3.484)	(–2.944)	(–4.799)
lnEnergyIntensity	0.158***	0.124*	0.104	0.130**
	(2.698)	(1.716)	(1.053)	(2.246)
FDI	0.001	–0.000	–0.000	0.001
	(1.278)	(–0.693)	(–0.305)	(1.311)
WlnGDP		–1.130	–2.618	
		(–0.651)	(–1.198)	
W(lnGDP)^2		0.041	0.087	
		(0.422)	(0.715)	
WUrbanisation		0.045**	0.052**	
		(2.306)	(2.224)	
WRenewableEnergy		–0.001	–0.022	
		(–0.040)	(–1.076)	
WServicesSector		0.007	–0.002	
		(0.548)	(–0.103)	
WlnEnergyIntensity		–0.154	–0.372	
		(–0.578)	(–1.109)	
WFDI		–0.000	0.000	
		(–0.222)	(0.168)	
Wu		–0.958***		–0.965***
		(–6.798)		(–6.864)
Log-likelihood	198.357	3.569	203.570	–0.448
LR SLX		–400.002		
LR SEM		8.033		

Turning Point ($)	10,957	7589	6525	10,321
95% CI	[4819, 24,914]	[4444, 12,960]	[3280, 12,981]	[6468, 16,469]

Note: t-statistics for the estimated coefficients are in parentheses; ***, ** *and* * *indicate significance levels of 1%, 5% and 10%, respectively. The dependent variable, per capita* NO_x *emissions, enters in its natural logarithm.*

Table 4. Non-spatial and spatial estimation results for per capita SO_2 emissions.

	Two-way FE	SDEM	SLX	SEM
lnGDP	8.089***	7.563***	7.195***	7.471***
	(9.856)	(11.550)	(8.668)	(11.882)
(lnGDP)^2	–0.487***	–0.465***	–0.457***	–0.438***
	(–9.412)	(–11.513)	(–8.965)	(–11.057)
Urbanisation	0.053***	0.060***	0.065***	0.054***
	(6.856)	(7.070)	(5.934)	(8.245)
RenewableEnergy	–0.023***	–0.025***	–0.031***	–0.021***
	(–4.496)	(–4.937)	(–4.616)	(–5.025)
ServicesSector	–0.015***	–0.006	–0.008	–0.012***
	(–2.968)	(–1.531)	(–1.349)	(–3.044)
lnEnergyIntensity	–0.138	0.300**	0.378**	0.073
	(–1.211)	(2.488)	(2.241)	(0.667)
FDI	0.000	–0.003***	–0.003**	0.000
	(0.448)	(–2.712)	(–2.041)	(0.226)
WlnGDP		–5.359*	–9.268**	
		(–1.842)	(–2.492)	
W(lnGDP)^2		0.317*	0.466**	
		(1.941)	(2.237)	
WUrbanisation		0.108***	0.143***	
		(3.327)	(3.615)	
WRenewableEnergy		–0.004	–0.057	
		(–0.133)	(–1.630)	
WServicesSector		0.020	0.005	
		(1.003)	(0.176)	
WlnEnergyIntensity		1.317***	1.520***	
		(2.952)	(2.660)	
WFDI		0.001	0.002	
		(0.291)	(0.656)	
Wu		–1.007***		–1.219***
		(–7.272)		(–9.782)
Log-likelihood	78.527	–90.103	107.870	–111.743
LR SLX		–395.947		
LR SEM		43.279***		

Turning Point ($)	4054	3402	2616	5026
95% CI	[1863, 8821]	[2271, 5097]	[1521, 4499]	[3432, 7360]

Note: t-statistics for the estimated coefficients are in parentheses; ***, ** *and* * *indicate significance levels of 1%, 5% and 10%, respectively. The dependent variable, per capita* SO_2 *emissions, enters in its natural logarithm.*

Table 5. Non-spatial and spatial estimation results for per capita $PM_{2.5}$ emissions.

	Two-way FE	SDEM	SLX	SEM
lnGDP	3.169***	2.697***	2.774***	3.490***
	(9.506)	(9.955)	(8.449)	(12.141)
(lnGDP)^2	–0.162***	–0.144***	–0.150***	–0.178***
	(–7.689)	(–8.624)	(–7.436)	(–9.791)
Urbanisation	0.014***	0.019***	0.019***	0.017***
	(4.582)	(5.368)	(4.502)	(5.771)
RenewableEnergy	0.006***	0.004*	0.004	0.006***
	(2.722)	(1.942)	(1.465)	(3.340)
ServicesSector	–0.004*	–0.001	–0.001	–0.003*
	(–1.838)	(–0.562)	(–0.360)	(–1.791)
lnEnergyIntensity	0.036	0.181***	0.172**	0.064
	(0.787)	(3.502)	(2.574)	(1.387)
FDI	0.000	–0.001*	–0.001	0.000
	(0.822)	(–1.914)	(–1.274)	(0.367)
WlnGDP		3.228***	3.186**	
		(2.664)	(2.166)	
W(lnGDP)^2		–0.220***	–0.216***	
		(–3.234)	(–2.626)	
WUrbanisation		0.056***	0.055***	
		(4.217)	(3.542)	
WRenewableEnergy		–0.013	–0.012	
		(–1.115)	(–0.880)	
WServicesSector		–0.008	–0.005	
		(–0.987)	(–0.497)	
WlnEnergyIntensity		0.469**	0.439*	
		(2.534)	(1.944)	
WFDI		0.003**	0.003*	
		(2.376)	(1.802)	
Wu		–0.729***		–0.804***
		(–4.911)		(–5.475)
Log-likelihood	240.676	70.997	274.820	36.225
LR SLX		–407.647		
LR SEM		69.543***		

Turning Point ($)	18,171	11,649	10,381	18,545
95% CI	[3605, 91,583]	[6063, 22,382]	[4842, 22,259]	[10,335, 33,276]

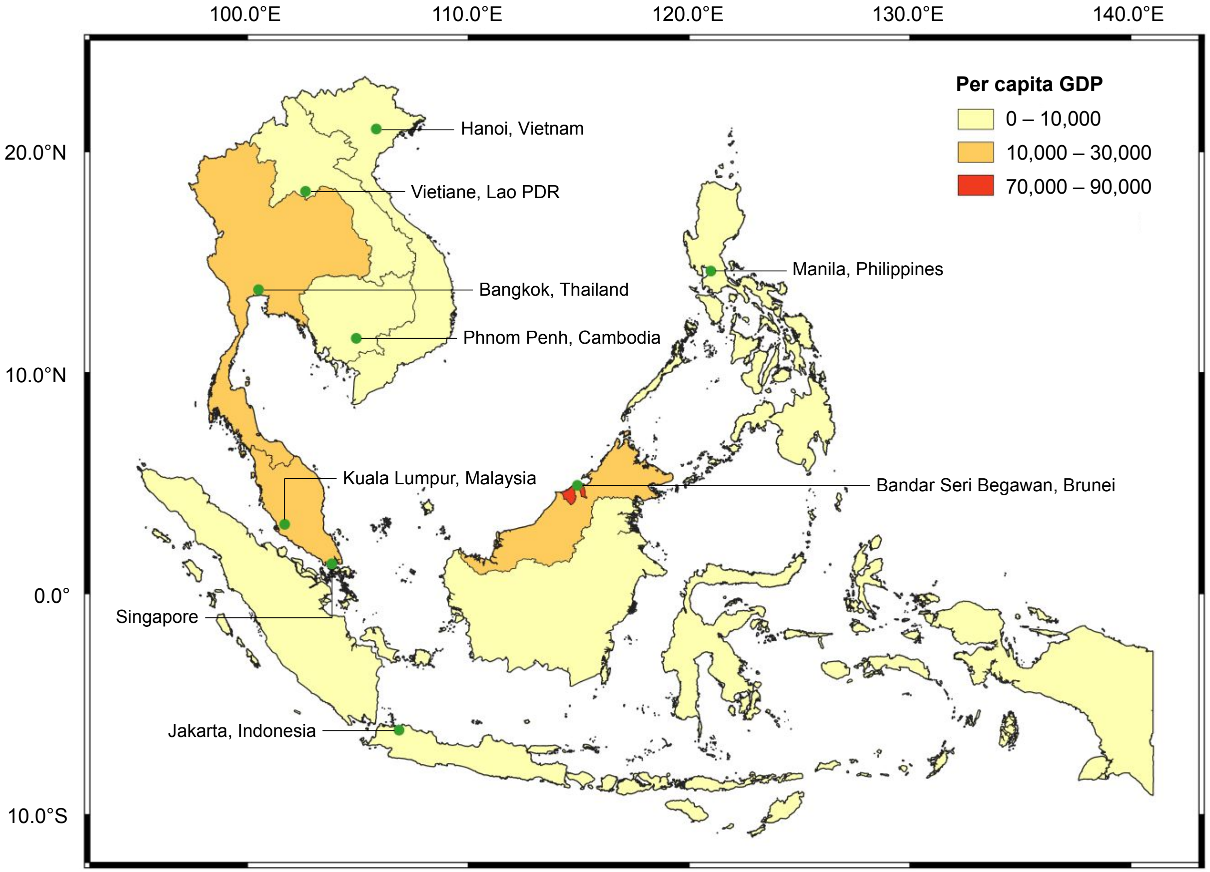
Note: t-statistics for the estimated coefficients are in parentheses; ***, ** *and* * *indicate significance levels of 1%, 5% and 10%, respectively. The dependent variable, per capita* $PM_{2.5}$ *emissions, enters in its natural logarithm.*

FIGURE LEGEND

Figure 1. Geographical location and 2012 income classification of the nine Southeast Asian countries included in the study. No country had per capita GDP ranging between \$30,000 and \$70,000 (expressed in constant 2011 international dollars using purchasing power parity).

Figure 2. Scatterplots of per capita NO_x, SO_2 and $PM_{2.5}$ emissions (kg) against per capita GDP (measured at constant 2011 international dollars using purchasing power parity) from 1993–2012 for the nine Southeast Asian countries.

Figure 3. Per capita GDP of the nine Southeast Asian countries in our sample from 1993–2012 (measured at constant 2011 international dollars using purchasing power parity). Estimated turning points for NO_x (standard two-way FE model), SO_2 (SLX model) and $PM_{2.5}$ emissions (SLX model) are indicated in dotted lines.



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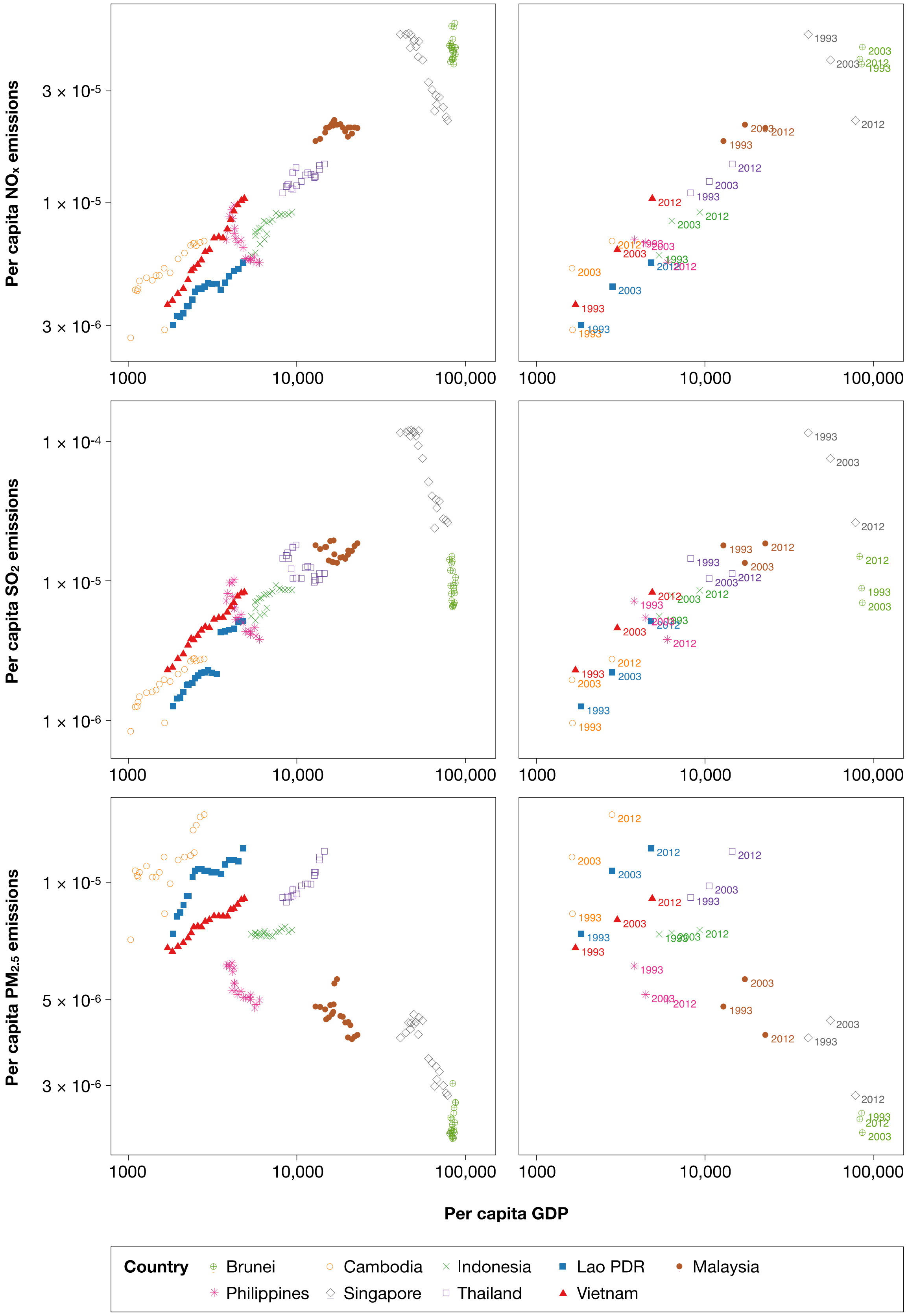

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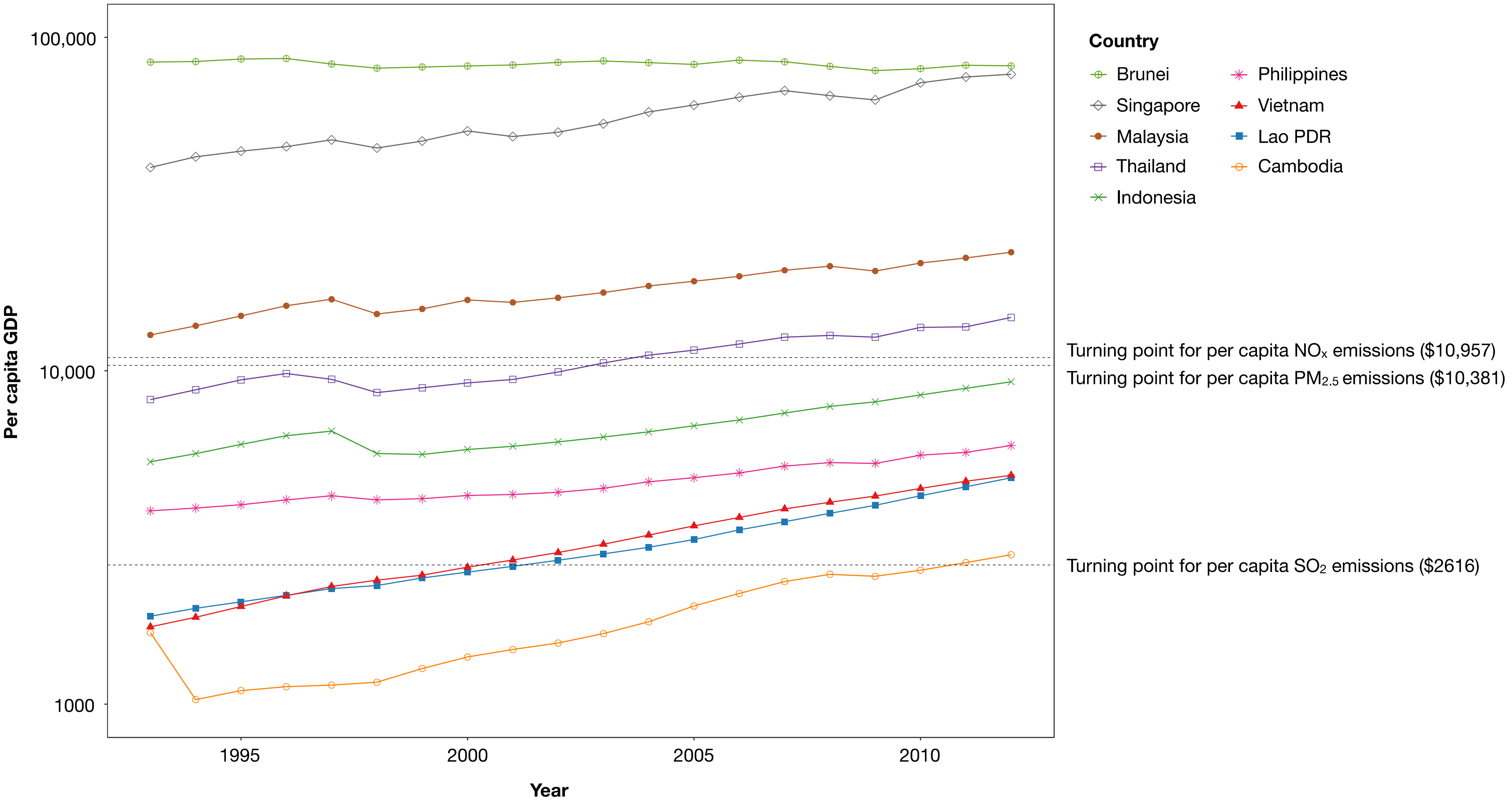

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