Wealthy, Healthy and Green: Are we there yet?

Son Nghiem, PhD

Centre for Applied Health Economics, Griffith University, Australia
Corresponding author: 170 Kessels Rd, Nathan, QLD 4111, Australia.
Email: s.nghiem@griffith.edu.au Phone: +61-7-3735-3103

Bach Tran, PhD
Ha Noi Medical University, Hanoi, Vietnam. Email:bach@hmu.edu.vn

Clifford Afoakwah, PhD
Centre for Applied Health Economics, Griffith University, Australia.
Email: c.afoakwah@griffith.edu.au

Joshua Byrnes, PhD
Centre for Applied Health Economics, Griffith University, Australia.
Email:j.byrnes@griffith.edu.au

Paul Scuffham, PhD
Centre for Applied Health Economics, Griffith University, Australia.
Email:p.scuffham@griffith.edu.au

1. Introduction

Maintaining a balance between economic growth, environmental protection, and good health have been the main concerns of the international community. These concerns were reflected in 17 Sustainable Development Goals (SDG), which 193 countries agreed to achieve by 2030. Understanding the trends, patterns and inter-relationships between economic growth, health and environment across countries and over time can help formulate policies to achieve these SDGs.

The inter-dependent and dynamic relationship between economic growth, environment and health have been widely investigated in the literature. For example, economic activities and environmental quality were found to follow an Environment Kuznets Curve (EKC): environment quality decrease and eventually reverse as income increases (Grossman & Krueger, 1995; Torras & Boyce, 1998). Regarding human health, economic growth leads to improved life expectancy (Preston, 1975) and reduced child mortality rate (Strulik, 2004). However, economic growth is also associated with an increase in lifestyle-related diseases such as obesity and type-2 diabetes (Egger, 2009). The COVID-19 pandemic has provided more evidence of the inter-dependent relationship between health, economic growth and environment. The COVID-19 pandemic is associated with the way human interact with the environment and has resulted in severe economic consequences (Ficetola & Rubolini, 2020; Hepburn, O'Callaghan, Stern, Stiglitz, & Zenghelis, 2020; McKee & Stuckler, 2020).

In this study, we argue that technological progress ‒one of the main factors driving economic growth‒ will enable us to protect the environment and improve health outcomes. A balance of strong economic growth, a high-quality environment and good health outcomes will eventually be attainable across countries. Also, owing to technological diffusion, emergence countries will be able to shorten the divergence phase (i.e., economic growths create detrimental effects on the environment and health), and hence, the synergy between economic development, health and environment may occur sooner. This study tests the hypothesis that countries will converge in economic development, environmental quality and health outcomes. We then conduct panel data regressions to examine the interrelationship between economic, environmental and health outcomes.

2. Review of Literature

The pairwise relationships between economic growth, environment and health have been investigated widely in the literature. Except for environment and health, these pairwise relationships were bi-directional. Thus, this section focuses on reviewing studies that incorporate economic convergence hypotheses (Galor, 1996) to investigate the relationship between health, economic development and the environment.

2.1 Economic growth and environment

Grossman and Krueger (1991) conducted one of the earliest studies on the relationship between economic growth and the environment. The authors found that environmental pollution, proxied by various indicators, followed an inverse U-shape relationship with economic growth, proxied by real gross domestic product (GDP) per capita increase. The turning point for most pollutant occurred when GDP per capita reached $8,000-$10,000 (purchasing power parity, 1995 prices). The inverse U-shape curve between economic growth and environmental quality, also referred to as the Environmental Kuznets Curve (EKC), has been confirmed in various studies with different pollutants (Stern & Common, 2001), analytical methods (Agras & Chapman, 1999), and countries (Burnett, 2016; Jalil & Mahmud, 2009). However, some studies (Gangadharan & Valenzuela, 2001; Kaika & Zervas, 2013a, 2013b; Stern, 2004) found that the EKC hypothesis was not consistent with the choice of pollutants, study sample (i.e., study periods, countries).

In the reverse direction, numerous studies also found significant effects of environmental degradation on economic activities. The natural environment contains valuable resources (e.g., water, land, minerals), which are crucial production factors (El Serafy, 1991; R. Lopez, 1994). Environment quality also affects economic activities indirectly via labour productivity. For example, pollution makes people sick and become less productive (Graff Zivin & Neidell, 2012; Hansen & Selte, 2000).

2.2 Economic growth and health

Economic growth can affect health directly via the ability to purchase health inputs (e.g., medication, health services) or indirect via changes in the environment. Economic growth leads to improve income, which enables individuals to purchase crucial health inputs such as food, medication and health services, and hence achieve better health (Deaton, 2003;

Khanam, Nghiem, & Connelly, 2009). There is abundant evidence that health outcomes, such as infant mortality rates and life expectancy, improve with income (Ebenstein et al., 2015). However, the positive effects of economic growth on health, which was popularly referred to as the Preston curve (Preston, 1975), decreases as income rises. Thus, it is expected that as economic growth continues, health outcomes across countries may eventually converge.

In the reverse direction, health also affects economic growth positively. Health is considered an economic engine (Mirvis, Chang, & Cosby, 2008) as healthy individuals are more productive (Strauss & Thomas, 1998). A cross-countries comparison found that differences in health explain about 10% of variations in GDP per worker.

Overall, health and economic growth demonstrate a mutual reinforcement relationship that could lead to a synergy of good health and stable economic growth. Also, technology diffusion can lead to the convergence of this synergy across countries.

2.3 Environment and health

The effects of environmental quality on human health have attracted most studies with consensus finding. A healthy environment (e.g., clean air) led to a healthy workforce (Hall et al., 1992), while air pollution resulted in numerous detrimental health effects (Afoakwah et al., 2020; Brunekreef & Holgate, 2002; Landrigan, 2017; Sun & Gu, 2008).

Apart from the pairwise analyses reviewed above, some studies examine the inter-dependent relationships between economic growth, environmental quality and health outcomes. For example, Gangadharan and Valenzuela (2001) extended the Environmental Kuznets Curve (EKC) hypothesis by incorporating economic growth, environmental and social factors as inputs for a health production function. However, this study only focuses on cross-sectional data and hence was not able to test the convergence hypothesis. Sarwar, Alsaggaf, and Tingqiu (2019) extended the analyses of the relationship between economic growth, health and environment using panel data. However, this study also did not test the convergence hypothesis.

To our best knowledge, Klarl (2016) was the only study that applied an endogenous growth model to test the convergence hypothesis and investigated the relationship between health, economic development and environment. However, Klarl (2016) conducted a simulation study rather than analyzing empirical data. This study fills the literature gap by conducting a club convergence test to examine whether countries converge in health outcomes, economic development and environmental quality. In addition, we investigate this tri-directional relationship using a panel data analysis.

3. Data

Data used in this study were collected from the "Gap Minder" website (www.gapminder.org), which is an open data portal established by the late Professor Hans Rosling. The Gapminder hosts comprehensive data collections compiled from publicly available sources such as the World Bank, the World Health Organization, and the United Nations. Air pollution data were collected from the Emissions Database for Global Atmospheric Research (EDGAR, 2020). This data set contains total annual emissions of nine pollutants, including carbon monoxide (CO), Sulfur dioxide (SO2), Organic Carbon (OC), Black Carbon (BC), Ammonia (NH3), Non-Methane Volatile Organic Compounds (NMVOC), Nitrogen Oxides (NOx), fine particle matters less than 2.5 microns (PM2.5), and less than 10 microns (PM10) across more than 200 countries in the 1970-2015 period. Apart from individual pollutants, we also aggregate all nine pollutants to establish an overall measure of air pollution.

Health outcome data were collected from the global burden of diseases 2019 (IHME, 2020). Particularly, we select the rate of disability-adjusted life years (DALY) of respiratory infection and tuberculosis per 1000 population (hereafter referred to as respiratory DALY). This health outcome was selected because the respiratory system is likely to be affected by air pollution. DALY is the total life-year loss due to premature death or living with disability/diseases (Rushby & Hanson, 2001; Sassi, 2006). The respiratory DALY data, however, only are only available from 1990 to 2015.

We expect that convergence is more likely to occur among countries of similar but high level of economic development, such as member countries of the Organization for Economic Co-operation and Development (OECD). Thus, the data set selected for this study consist of annual data on economic development (proxied by income per capita), environmental quality (proxied by emissions of air pollutants per capita), and health outcome (proxied by respiratory DALY per 1000 population) of 36 OECD countries in the 1990-2015 period.

Based on the literature and data availability, we selected a set of covariates, including population size, capital stock, the proportion of people engage in the workforce, human capital index, energy consumption, whether the universal health coverage is available, temperature variations, and the rate of Bacille Calmette-Guérin (BCG) vaccination to prevent tuberculosis. Population size can be a proxy for the scale economy of a country, which could affect economic development, health outcomes and environmental quality. The capital stock, human capital index and the rate of labour force engagement represent major factors of production. Regarding health determinants, we select the rate of BCG vaccination, which protect against tuberculosis, because it is directly related to respiratory DALY. Also, we select the number of doctors per 1000 population, which expect to contribute to reducing adverse health outcomes like respiratory DALY.

We selected energy production and consumption by sources of energy collected from the "Our Word in Data" portal (Ritchie & Roser, 2020) as determinants of air pollution. We expect that both production and consumption of energy, especially energy from fossil fuel, will have a positive association with the emission of air pollutants per capita.

Although we tried to select variables that have the least missing observations, this issue still occurred. Missing values were imputed using a nonparametric random forest approach (Stekhoven, 2015). This approach required no distributional and functional assumptions and was able to produce imputations with closer confidence intervals (Shah, Bartlett, Carpenter, Nicholas, & Hemingway, 2014).

4. Methods

4.1 Convergence hypotheses

We use the production function concept to illustrate the interdependent relationships and potential converge of economic development, health outcomes and environmental quality. The production function has been widely used to model the production of economic, health, and environmental outcomes. Effects of production factors on outcomes follow the law of diminishing marginal return. Thus, the growth of economic, health and environmental outcomes will slow down as countries increase production factors. The crucial role of technological progress in the production function allows us to argue that health, economic and environmental outcomes will eventually improve across countries. Technological progress also explains the potential synergy between economic development and environmental quality. Particularly, environmental pollution could be considered as a bad output of an economic production function. In the literature of productivity analysis, bad outputs can be considered as inputs, which can be reduced while maintaining or even increase outputs when as productivity increases. Economic development, thus, is associated with potential environmental degradation in the short run. However, the invention of new technology enables us to generate more outputs with fewer inputs or producing less bad outputs. Thus, the synergy between stable economic development and improved environmental quality is possible, at least in the long run. Also, technological progress will diffuse across countries, leading to the potential convergence of economic, health and environmental outcomes.

Traditionally, the economic growth literature refers mainly to two types of convergence, namely β- and σ- convergence. While the σ- convergence refers to the reduction of dispersion of income levels across countries, the β- convergence refers to a negative correlation between the initial level of economic development (e.g., GDP per capita) and its growth over time. The β- and σ- convergence, however, were based on a restrictive assumption that countries follow the same growth path. In this study, we apply the recently-developed club convergence hypothesis (Durlauf & Johnson, 1995; Quah, 1996), which allows country-specific growth paths. This hypothesis enables testing for overall convergence among all countries or club convergence among some countries.

4.2 Club convergence tests

Based on the production function concept, two groups of factors contribute to economic, health and environmental outcomes across countries: the common factor (e.g., common technology shared by all countries), and the country-specific factor (e.g., culture and geolocation of each country). To isolate the effects of business cycle, data were smoothed out using the bandpass filter (Christiano & Fitzgerald, 2003). We choose a maximum oscillation period of 10 years, which reflect the empirical estimates of 8-11 years (Inklaar, Jong-A-Pin, & De Haan, 2008) among OECD countries in the study period. The Hodrick-Prescott filter (Hodrick & Prescott, 1997), a common choice among convergence studies, could introduce spurious dynamic relations (Hamilton, 2018). The common factor is represented by the average growth rate of income, health outcomes and environmental quality. Thus, income, health outcomes and environment quality of countries converge if contributions of the common factor become substantially larger than that of country-specific individual factors. The decompositions of two growth factors can be represented as:

$$y_{it} = \delta_{it}\mu_t + \varepsilon_{it} \qquad (1)$$

where y is the proxies for economic development, health outcome and environment quality (e.g., income per capita, respiratory DALY rate, and emission of carbon monoxide per capita) of country i at period t; μ_t represent the common factor; and δ_{it} represent the country-specific factor, and ε_{it} represents random shocks. Assume that the cross-sectional average growth rate of all countries at any period represents the common growth factor (μ_t), we can isolate δ it by taking the ratio of a growth rate of a country and the average rate:

$$h_{it} = \frac{\delta_{it}}{\sum_{i=1}^{N} \delta_{it}/N} \qquad (2)$$

In this formulation, the overall convergence of all countries is achieved when $h_{it} \rightarrow 1$ for all i as $t \rightarrow \infty$. This convergence condition can also be expressed in the mean squared of relative transition differences:

$$H_t = \sum_{i=1}^{N} (h_{it} - 1)^2 / N \qquad (3)$$

In this representation, the growth rate of countries converges if $H_t \rightarrow 0$ as $t \rightarrow \infty$. The overall convergence hypothesis can also be represented in a semiparametric formulation as:

$$\delta_{it} = \delta_i + \sigma_i \tau_{it} / L(t) t^{\alpha} \qquad (4)$$

where δ_i is a time-invariant growth factor for country i, τ_{it} is identically and independently distributed with a mean of zero and variance of one, and $1/L(t)$ is a slow decay function such as the logarithm of t; σ_i is an idiosyncratic scale parameter, and $\alpha \geq 0$ is the decay rate. Equation (4) suggests that the condition for convergence is a slow decay component in the growth rate trajectories of individual countries. Under this specification, the null (convergence) and the alternative (non-convergence) hypotheses are expressed as:

$$\begin{aligned} &H_0: \delta_{it} = \delta \quad \text{for all } i \\ &H_A: \delta_{it} \neq \delta \quad \text{for some } i \end{aligned} \qquad (5)$$

The alternative hypothesis can also be specified to test for the formation of sub-convergence groups as:

$$H_A: \delta_{it} = \delta_i \quad \text{if } i \in G_i \text{ (i=1,2,..)} \qquad (6)$$

where $\delta_i = \lim_{N \rightarrow \infty} \sum_{i \in G_i} \delta_{it} / N$.

Using the limiting form for the quadratic difference $H_t \sim A/L(t)^2 t^{2\alpha}$ as $t \rightarrow \infty$ for a constant A>0 and setting the decay function L(t) =log(t), the overall convergence test can be simplified to a one-sided t-test for the parameter of log(t) to be non-negative in the following regression:

$$\log\left(\frac{H_1}{H_t}\right) - 2\log(logt) = \theta + \gamma logt + u_t \qquad (7)$$

Equation (7) is estimated using the quadratic spectral estimator by Andrews (1991) with fixed bandwidth to produce robust standard errors against heteroscedasticity and autocorrelation of unknown form. If the null hypothesis of overall convergence ($H_0: \gamma \geq 0$) is rejected, we can test the alternative hypothesis of club convergence using the following four steps:

1. Sort countries by y_{it}.
2. Form a core group of countries with the highest y_{it} using the overall convergence test.
3. Add the next country to the core group until the test rejects the null hypothesis.
4. Repeat steps 1–3 for the remaining countries. If the null hypothesis is rejected in Step 2 then the remaining countries do not form a convergent group.

We further check the robustness of the club convergence finding by conducting a merging algorithm by Phillips and Sul (2009). This algorithm first estimates Equation (7) using the first two clubs; if the test result show confirmed convergence ($\gamma < 0$), add the next club. For sensitivity check, we also merge clubs using the modified algorithm by Von Lyncker and Thoennessen (2017). This algorithm first estimate Equation (7) using all adjacent clubs; if convergence presence and the absolute value of the t-statistics increases, merge the two clubs.

The clustering and merging algorithms above suggest that countries of the first club have higher outputs than those in subsequent clubs. Thus, we propose using club number as a score to rank countries on all three selected outputs (income, respiratory and air pollution) using the following three steps:

1. Reverse the score in income since the preference for selected outcomes are in contrast (higher values are better for income and lower values are better for DALY and air pollution) as $Reversed\ \ score = 1 + \max(original\ scores) - original\ sore$
2. Divergence countries depart from the common trend and thus are assigned the lowest score of zero.
3. Add scores of each country in all three outcomes as (since air pollution is represented by nine pollutants, the average score of these pollutants is used to represent environment): $Total\ score = Income_{Reversed} + Health + Environment_{Average}$

4.3 Panel data analysis

We specify the inter-dependent relationship between economic growth, health outcomes and environmental quality as

$$y_{ki,t} = \beta_0 + \beta_1 y_{k'i,t-1} + \beta_2 X_{it} + \beta_3 trend + \mu_i + \varepsilon_{it} \qquad (8)$$

where y_{kit} represents the set k that contain three outcomes of interest (economic growth, health and environment); k' represent remainder outcomes (e.g., if the outcome of interest is economic growth, the remainders are health and environment quality); $trend$ is the linear trend, representing technological progress; X represents a set of covariates; μ_i represents country-specific unobserved characteristics; ε_{it} is the random error, and βs are parameters to be estimated. Applying standard regressions to Equation 8 may result in biased estimated due to the presence of unobserved country-specific factors (μ_i) that included in the composite error term may be correlated with other covariates.

The treatment of (μ_i) using a fixed-effect estimator in Equation 8 will produce a consistent result, but it is not efficient if the country unobserved individual characteristics are randomly distributed. In this case, a random-effect estimator is preferred. A Hausman specification test (Hausman, 1978; Hausman & Taylor, 1981) is applied to select the appropriate estimator. If the null hypothesis that unobserved country effects are uncorrelated with other covariates were rejected, the fixed-effects estimator is preferred. We also conduct a series of tests for unit root, heteroscedasticity, cross-sectional dependent and serial autocorrelation. If the null hypotheses of stationarity, homoscedasticity, cross-sectional and serial independent are rejected, Driscoll and Kraay (1998)'s standard errors, which are robust to cross-sectional and serial dependent, will be applied. Finally, a stepwise-like approach is applied to select a concise set of covariates (i.e., covariates that were insignificant in most specifications were excluded from the final analysis).

5. Results and Discussions

5.1 Descriptive statistics

The descriptive statistics of outcomes and covariates in Table 1 shows substantial variations across countries and a clear trend of most variables. Particularly, income per capita increases significantly by $550 purchasing power parity (PPP) per person per year while adverse health outcomes and air pollution showed a significant decline trend. The respiratory DALY rate showed a substantial and significant reduction with 12.9 DALY per year, accounting for 4% of the mean value. Among the air pollutants, carbon monoxide was the most abundant, with an average of 46.5 kg per person, which reflect the fact that low-carbon energy accounts for only 27% of total energy consumption, on average (i.e., 13,117/49,234).

Among the selected covariates, only population size and labour force show substantial fluctuations (i.e., standard deviations are larger than means). However, only key production factors, namely capital stock, labour engagement rate, human capital index, show a significant increase over time. The number of doctors per 1000 population also increased significantly in the study period, but the magnitude is modest at three doctors per 100,000 population. The consumption of low-carbon energy also increased at a rate of 162 kwh/person per year, but it is only significant at 10%.

Table 1. Descriptive statistics

Selected variables	Means	Standard deviation	Linear trend	p-value of trend
Economic development				
Income per capita (1000 $PPP)	30.95	13.84	0.55	<0.01
Health outcomes				
Respiatory DALY per 1000 people	346.85	320.26	-12.9	<0.01
Environment: Air pollutants (kg/person)				
Particle matters <10 microns (PM10)	1.88	3.94	-0.34	<0.01
Particle matters <2.5 microns (PM2.5)	1.28	2.72	-0.23	<0.01
Carbon Monoxide (CO)	46.46	109.65	-8.35	<0.01
Non-Methane Volatile Organic Compounds (NMVOC)	8.36	17.20	-1.50	<0.01
Sulphur dioxide (SO2)	7.69	16.13	-1.39	<0.01
Black Carbon (BC)	0.19	0.41	-0.03	<0.01
Nitrogen Oxides (NOx)	8.77	19.33	-1.57	<0.01
Organic Carbon (OC)	0.34	0.74	-0.06	<0.01
Ammonia (NH3)	3.08	6.56	-0.55	<0.01
All pollutants	78.06	168.18	-14.02	<0.01
Covariates				
Temperature variations within a year (degree Celcius)	6.90	2.33	0.003	0.80
BCG vaccination rate	0.95	0.14	0.001	0.15
Labour force engagement (million people)	15.10	25.07	0.14	0.21
Population (million people)	33.77	52.97	0.25	0.28
Capital stock ($PPP/person)	143682	74629	4310	<0.01
Labour force engagement rate	0.45	0.06	0.001	<0.01
Human capital index	3.09	0.42	0.02	<0.01
Primary energy consumption (kwh/person)	49234	27074	134	0.26
Low-carbon energy consumption (kwh/person)	13117	20323	162	0.07
Doctors per 1000 people	2.83	0.85	0.03	<0.01

Note: see Table A0 in the Appendix for detailed sources of data

5.2 Club convergence test

Using the standard threshold for a one-side t-test (i.e., t-value≤ -1.65), we rejected the null hypothesis that countries across the globe have converged in income, health outcomes and some environment quality (i.e., γ parameter is significantly negative). Particularly, the emission rate of CO and NOx among OECD countries converged during the 1990-2015 period (Table 2). Since CO and NOx are the two main pollutants, the aggregated all pollutants also converge among OECD countries during the study period. However, the remaining pollutants, particularly PM2.5, PM10, BC, OC and NH3 showed substantial variations with many convergence clubs and many countries that diverge from the common trend. Income and respiratory DALY show a more similar trend among OECD countries with only 2-3 convergence groups and one divergence country.

Table 2. Club convergence test

Variables	Coef. (γ)	t- value	Convergence clubs	Divergence countries
Income	-0.40	-29.09	3	1
Respiratory DALY	-0.62	-34.29	2	1
PM10	-6.07	-6.04	9	9
PM2.5	-6.47	-6.37	7	15
CO	-0.34	-0.26	1	0
NMVOC	-4.27	-2.81	6	0
SO2	-4.24	-3.93	3	2
BC	-6.41	-5.72	5	14
NOx	-4.49	-1.61	1	0
OC	-7.84	-5.05	9	14
NH3	-5.84	-4.20	7	9
All pollutants	1.76	0.51	1	0

Note: convergence club=1 represent overall convergence.

The total ranking scores, estimated based on results of the club convergence test, show that European countries, including Belgium, Denmark, Sweden, Germany and Switzerland, lead the OECD countries in having the right balance between high income, good health and clean air (Table A1 in the Appendix). In contrast, Mexico, Chile, Australia, Turkey and Poland were the bottom five performers. Australia's main reason to be in the bottom five countries was due to its worst rank in most air quality indicators. This finding is surprising because Australia was ranked highly in the Better Life Index (Kasparian & Rolland, 2012), which included PM10. However, in this study, we use the average air pollutant per capita, which is a disadvantage for Australia because it is a large producer and consumer of coal (Della Bosca & Gillespie, 2018) while having a small population.

Club convergence tests are sensitive to the number of countries and the length of the observation period; convergence was less likely to achieve when the sample includes a large number of countries (Corrado, Stengos, Weeks, & Yazgan, 2018). We confirmed this finding as no convergence to any outcome was found when we extend the sample outside OECD countries, and the observation period to 1970-2015 (see Table A2 in the Appendix). The results remain relatively robust when we only extend the number of countries to 163 as overall convergence was still found on CO and NOx emission. However, when we only extended the study period to 1970-2015 the results changed considerably: overall convergence obtained in the emission of black carbon. However, the results were almost unchanged when we did not perform any treatment for missing value or outliers to the original data. This finding could be due to the good quality of data from the OECD countries in the most recent period of 1990-2015.

We also explore how the robustness of the club convergence test to the choices of estimation methods. We found that results were sensitive to filtering methods. For example, when choosing the Hodrick-Prescott filter with the λ value of 6.25 for annual data (De Jong & Sakarya, 2016; Ravn & Uhlig, 2002) we found that NOx no longer converges across all countries (see Table A3 in the Appendix). Results are also sensitive to the choice of the maximum oscillation period in the Christiano and Fitzgerald filter. For example, when choosing the maximum oscillation period of seven years, NOx also no longer reaches overall convergence. The results are also sensitive to the choice of trimming period. We also found that NOx no longer converges across all countries when we reduced the trimming period from 1/3 to 1/4. This finding suggests that convergence studies should use the trimming period of 1/3 as recommended by Phillips and Sul (2007). However, the remaining tests (e.g., using von Lyncker & Thoennessen merging algorithm or adaptive quadratic spectral bandwidth) have negligible effects.

Overall, despite the similarity of economic development among OECD countries in the study period (1990-2015), there is no overall convergence of economic development (proxied by income per capita), health outcomes (proxied by respiratory DALY). However, overall convergence was achieved in environmental quality, proxied by CO, NOx or the sum of all pollutants. The club convergence test is sensitive to sample size (e.g., number of countries and study period), filtering methods, and the trimming period.

5.3 Panel data analysis

To examine the stationarity of data, we conduct a series of unit root tests Levin-Lin-Chu (LLC) (Levin, Lin, & Chu, 2002), Breitung (Breitung, 2001), Im-Pesaran-Shin (IPS) (Im, Pesaran, & Shin, 2003); Fisher- Dickey-Fuller (Fisher-DF) (Dickey & Fuller, 1979); and Fisher-Phillips-Perron (Fisher-PP) (Harris & Tzavalis, 1999; Phillips & Perron, 1988). All unit root tests were based on the null hypothesis that a unit root presence. The test results show that the unit root may present at the level outcome, especially when the Breitung test is used (Table 3). However, all unit test rejected the null hypothesis when the first difference is used. This finding suggests that a fixed-effect estimator, which is similar to a first-difference transformation, will generate stationary series.

Table 3. Unit root tests

	Test methods				
Outcomes	LLC	Breitung	IPS	Fisher-DF	Fisher-PP
Level					
Income	***-6.37	**-2.09	***-4.34	***186.3	***203.3
DALY	***-3.68	0.86	0.51	83.92	40.54
PM10	***-4.56	0.96	-1.22	***109.57	*92.47
PM2.5	***-4.44	0.82	*-1.5	***138.07	**100.79
CO	***-2.69	2.05	0.55	***119.29	71.69
NMVOC	***-5.23	-0.01	**-1.75	***120.59	**96.5
SO2	***-2.47	0.84	0.65	*91.26	83.12
BC	***-3.44	0.03	-1.16	***124.38	*88.41
NOx	***-3.37	0.97	-1.26	***161.75	**94.59
OC	***-5.43	0.82	*-1.36	***110.94	***119.95
NH3	***-4.36	2.2	**-2.03	***146.77	85.44
All pollutants	***-3.94	1.01	**-1.8	***170.61	***103.28
First difference					
Income	***-13.41	***-3.14	***-10.15	***289.16	***324.33
DALY	***-7.12	***-2.85	***-2.79	***130.64	***226.89
PM10	***-23.83	***-7.31	***-14.36	***456.54	***857.13
PM2.5	***-23.12	***-7.75	***-13.92	***433.8	***863.78
CO	***-19.48	***-5.36	***-9.3	***293.37	***638.61
NMVOC	***-17.09	***-5.38	***-7.43	***229.87	***556.36
SO2	***-19.69	***-6.77	***-11.13	***346.64	***760.18
BC	***-18.17	***-5.9	***-10.38	***305.61	***625.75
NOx	***-18.01	***-5.57	***-10.74	***312.32	***676.87
OC	***-20.9	***-6.79	***-14.36	***461.66	***883.56
NH3	***-19.38	***-6.61	***-11.43	***338.57	***607.82
All pollutants	***-19.16	***-4.57	***-11.01	***344.98	***729.2

Note: Significant levels are: ***=0.01; **=0.05, *=0.1

The Granger-causality test for panel data (L. Lopez & Weber, 2017) rejected the null hypothesis of no association between the lag of one outcome and the current value of other outcomes (Table 4). However, the association between air pollution in the previous period and respiratory DALY in the current period was only significant at the 10% level.

Table 4. Granger causality test

LHS \ RHS	Income	DALY	PM10	PM2.5	CO	NMVOC	SO2	BC	NOx	OC	NH3	All
Income		2.5	16.9	16.9	17.1	16.9	17.8	16.8	17	16.9	17	17.1
DALY	3.7		1.7 (.09)	1.7 (.09)	1.7 (.08)	1.7 (.08)	1.6 (.1)	1.7 (.08)	1.6 (.1)	1.9 (.06)	1.7 (.1)	1.7 (.09)
PM10	30.0	27.3		17.7	48.1	21.1	22.6	26.1	31.8	12.8	23.1	37.6
PM2.5	24.1	31.6	22.8		48.7	17.8	22.7	25.2	33.2	15.6	20.2	47.3
CO	109	158	219	276		98.4	89.2	212	168	287	176	135
NMVOC	80.9	129	123	96.2	44		86	57.3	33.5	62.7	122	67.7
SO2	44.6	75.6	73.5	78.1	38.1	46.9		65.4	42.1	64	62	42.1
BC	48.7	68	50.3	56.9	91.8	52.8	46.1		59.3	23.2	56.3	84.3
NOx	68.4	127	159	156	191	33	72.9	120		81.6	68.3	134
OC	20.6	23.6	20.8	22.4	26.6	17.6	19.2	10.2	14.8		20.2	24
NH3	49.3	65.9	28.4	31.8	38.8	36.6	39.3	23.7	22.5	24.6		38.4
All	130	134	229	274	119	76.4	71.8	255	140	144	130	

Note: The null hypothesis is that right-hand-side (RHS) variables do not Granger-caused left-hand-side (LHS) variables. The table presents the test-statistics. P-values are <0.01 unless presented in parentheses.

We also conducted a series of diagnosis and specification tests to select relevant estimators. Both F-test (fixed-effects) and Breusch-Pagan (BP) test (random effects) rejected the null hypothesis, and countries unobserved characteristics have no effects, and hence ordinary least squares (OLS) are not appropriate. The Hausman specification test also rejected the null hypothesis that unobserved country characteristics are uncorrelated with other covariates, and hence a fixed-effects estimator is preferred (Table 5, first panel). The diagnosis tests for the fixed-effects estimator show that the residuals are serially correlated, heteroscedastic and cross-sectional dependent (Table 5, second panel). Thus, we apply a fixed-effects estimator with Driscoll-Kraay standard errors (Driscoll & Kraay, 1998), which are robust to the general form of cross-sectional dependent and serial autocorrelation.

Table 5. Specification and diagnosis tests

	F-test (fixed effects)			BP-test (random effects)			Hausman test		
	Income	Pollution	DALY	Income	Pollution	DALY	Income	Pollution	DALY
PM10	110.8	241.7	87.1	6055	7590	6110	45.8	17.7	12.7
PM2.5	111.5	226.6	88.9	6167	7722	6247	39.8	13.9	12.8
CO	143.2	98.8	92.8	6536	5354	6405	34.8	18.6	12.3
NMVOC	137.3	245.3	90.6	6307	7117	6293	54.3	36.9	10.5
SO2	107.9	147.0	102.1	6258	7242	6669	27.6	18.0	11.4
BC	133.9	274.8	90.4	6277	8026	6319	50.4	13.0	10.6
NOx	115.2	267.8	91.7	6404	8741	6445	24.9	15.6	8.4
OC	110.8	347.3	92.2	6345	8203	6408	36.7	16.1	10.8
NH3	104.1	769.0	90.9	6140	9890	6412	29.2	4.8	9.8
All pollutants	143.1	161.7	89.8	6486	6753	6246	38.9	14.5	15.2

	Heteroscedasticity			Cross-sectional dependent			Serial correlation		
	Income	Pollution	DALY	Income	Pollution	DALY	Income	Pollution	DALY
PM10	1102	435	317	-1.9 (0.05)	-2.4 (0.02)	-0.4 (0.67)	100	138	369
PM2.5	1082	715	321	-1.9 (0.06)	-2.4 (0.02)	-1.0 (0.3)	100	90	369
CO	1250	264	316	-2.8	-3.0	-0.4 (0.69)	99	190	370
NMVOC	1288	495	317	-2.3 (0.02)	-2.9	-0.4 (0.67)	111	109	370
SO2	966	543	424	-1.9 (0.06)	-3.0	-2.4 (0.02)	102	150	315
BC	1839	8352	318	-2.3 (0.02)	-2.9	-0.5 (0.64)	101	146	369
NOx	1072	614	352	-1.6 (0.1)	-3.0	-2.4	101	93	366
OC	1124	5155	322	-1.9 (0.06)	-2.5	-0.8 (0.44)	100	34	369
NH3	947	271	309	-1.9 (0.06)	-0.3 (0.76)	-1.2 (0.23)	97	142	374
All pollutants	1297	1224	320	-2.8	-2.8	-1.7 (0.09)	100	222	369

Note: The table presents the test-statistics. P-values are <0.01 unless presented in parentheses.

Results of the panel data analysis show that income per capita of OECD countries in the 1990-2005 period growth substantially at 10% per year (significant at 1%) when aggregated of all pollutants are used as a proxy for environment quality (Table 6). However, it is surprising that undesirable health and environmental outcomes (i.e., respiratory DALY & air pollution) in the past period were positively and significantly associated with income in the current period. One possible explanation is that air pollution in the previous was associated with economic activities, which lead to increase income at the expense of health outcomes and environmental quality. Among factors of production, human capital contributes most substantially to income with the elasticity of 0.67, followed by labour force participation rate (0.52) and capital stock per capita (0.22). The finding that human capital is the most crucial factor of economic growth is consistent with previous studies of economic growth convergence (Barseghyan & DiCecio, 2011; Klarl, 2016). Since the human capital index includes child survival, education and health components (Kraay, 2018), government policies that promote those factors would benefit economic development. Parameters of other covariates were sensitive to the choice of air pollutants. Particularly, the linear trend (proxied for technological progress) was insignificant in the scenario that PM2.5, SO2, NOx, OC and NH3 were selected as proxies for air pollution. This finding seems contradictory with the significance of a linear trend presented in Table 1, but that descriptive results were not controlled for any covariates such as factors of production and year dummies.

Regarding the environmental outcomes, the trend parameter shows that the emission of all air pollutants reduced significantly over time. The sign of income (positive) and income squared (negative) suggest the presence of an Environment Kuznets Curve (EKC) in most choices of air pollutants. However, evidence of the EKC is not significant when SO2 and NH3 were selected as proxied for air pollution, which confirms the finding of Gangadharan and Valenzuela (2001) that the finding of the EKC may be sensitive to the choice of pollutants. We further test the sensitivity of the EKC curve by alternating the samples. In the scenario that the study period covers 1970-2015 period, we still found non-significant evidence of the EKC for PM2.5, PM10 and OC, and contradictory evidence for NH3 (Table A4 in the Appendix). However, when we extended both the study period and the number of countries, the evidence of an EKC curve was consistent across all selected pollutants. Overall, empirical evidence of the EKC could be sensitive to pollutants and the study sample.

The consumption of low-carbon energy also has the expected significant negative association with the emission of most air pollutants. Few exceptions include PM2.5, PM10, and OC, where air pollution was not significantly associated with low-carbon energy consumption despite having the expected negative sign. We did not include lag of health outcome as the covariates for air quality in the current period because we believe that human health could not affect the environment.

Table 6. Interrelationship between economic development, environment quality and health outcomes

	Air pollutants									
	PM10	PM2.5	CO	NMVOC	SO2	BC	NOx	OC	NH3	All
Economic development: income per capita										
Linear trend	**0.05	0.04	***0.08	***0.16	-0.03	***0.15	0.04	0.03	0.02	***0.10
Lag of log DALY	0.02	0.03	**0.04	0.02	0.03	0.02	**0.04	0.02	0.02	**0.05
Lag of log air pollution	***0.13	***0.11	***0.18	***0.29	0.01	***0.23	***0.15	***0.07	0.02	***0.26
Log of capital stock	***0.24	***0.25	***0.23	***0.15	***0.29	***0.18	***0.27	***0.25	***0.28	***0.22
Log of labour participation rate	***0.51	***0.50	***0.60	***0.51	***0.51	***0.48	**0.37	**0.50	***0.50	***0.52
Log of human capital index	***0.81	***0.82	***0.56	***0.85	***0.90	***0.82	***0.75	***0.89	***0.92	***0.67
Environment quality: air pollution										
Linear trend	***-0.57	***-0.59	***-0.62	***-0.61	***-0.40	***-0.69	***-0.53	***-0.63	***-0.49	***-0.53
Lag of log income	***1.34	***1.51	***3.70	***3.00	-0.92	***1.67	***1.40	***1.16	*0.55	***2.69
Lag of log income squared	***-0.16	***-0.19	***-0.50	***-0.43	*0.22	***-0.17	***-0.15	***-0.13	-0.03	***-0.36
Log of low-carbon energy	-0.004	-0.01	**-0.04	**-0.02	***-0.07	***-0.05	*-0.01	-0.01	***-0.02	*-0.02
Health outcomes: respiratory DALY										
Linear trend	***0.20	***0.15	***-0.10	-0.04	***-0.22	***0.20	***-0.31	***0.19	*-0.18	***-0.20
Lag of log air pollution	-0.09	**-0.18	***-0.13	-0.03	***-0.32	-0.07	***-0.48	**-0.10	*-0.27	***-0.29
Lag of log income	**-0.17	-0.12	-0.08	*-0.20	***-0.21	-0.16	0.05	*-0.17	*-0.15	0.02
Log of doctors per 1000 people	***-0.32	***-0.33	***-0.31	***-0.31	**-0.15	***-0.32	***-0.25	***-0.32	***-0.30	***-0.31

Note: Fixed-effects estimator with Driscoll and Kraay (1998) robust standard errors are used. Parameters of year dummies are not reported for brevity. Significant levels are: ***=0.01, **=0.05, *=0.1. The sample size is 936 (36 countries in 26 years).

The fixed-effects results show that the number of doctors per 1000 people was the most significant and consistent predictor of adverse health outcomes (e.g., respiratory DALY) with the elasticity of -0.3 in most models. However, estimates of the remaining parameters are not consistent. For example, after controlling for year dummies (not shown), income, air pollution and the number of doctors, respiratory DALY is estimated to increase over time if PM2.5, PM10, BC and OC were selected to represent air quality. The negative sign of air pollution in the past period and respiratory DALY in the current period is also against expectation.

5. Conclusions

This paper has investigated the inter-relationship between income, health and environment using aggregated data from 36 OECD countries during the 1990-2015 period. The raw data show a significant trend of increasing income and reducing adverse health outcomes and air pollution.

We did not find evidence of overall convergence in income per capita, respiratory DALY and the emission of air pollutants except CO and NOx. However, countries tend to converge in these outcomes with their peers of the same clubs. We also found that the results of the convergence club test could be sensitive to the choice of sample and some methodological options, particularly the option to filter the business cycle.

In regression analysis, we confirmed that technological progress, proxied by a linear trend, contributes significantly to economic development and the improvement of health outcomes, but the evidence of its contribution to reducing air pollution was not consistent. We also found that human capital contributed most substantially to income growth, while the number of doctors per 1000 people was the biggest contributor to health outcomes. We confirmed that economic growth and environmental pollution followed an EKC, but this finding is also sensitive to the choice of pollutant and study sample.

Despite there was no clear evidence of global convergence, the finding of club convergence and significant inter-relationship between economic growth, health and environment suggest that we will eventually achieve SDGs. Our findings suggest that investment in human capital and technology could be crucial to attaining high income while reducing adverse health outcomes and improving environmental quality.

References

Afoakwah, C., Nghiem, S., Scuffham, P., Huynh, Q., Marwick, T., & Byrnes, J. (2020). Impacts of air pollution on health: evidence from longitudinal cohort data of patients with cardiovascular diseases. *The European Journal of Health Economics*, 1-14.

Agras, J., & Chapman, D. (1999). A dynamic approach to the Environmental Kuznets Curve hypothesis. *Ecological economics, 28*(2), 267-277.

Andrews, D. W. (1991). Heteroskedasticity and autocorrelation consistent covariance matrix estimation. *Econometrica: journal of the Econometric Society*, 817-858.

Barseghyan, L., & DiCecio, R. (2011). Cross-country income convergence revisited. *Economics letters, 113*(3), 244-247.

Breitung, J. (2001). *The local power of some unit root tests for panel data*: Emerald Group Publishing Limited.

Brunekreef, B., & Holgate, S. T. (2002). Air pollution and health. *The Lancet, 360*(9341), 1233-1242.

Burnett, J. W. (2016). Club convergence and clustering of US energy-related CO2 emissions. *Resource and Energy Economics, 46*, 62-84.

Christiano, L. J., & Fitzgerald, T. J. (2003). The band pass filter. *international economic review, 44*(2), 435-465.

Corrado, L., Stengos, T., Weeks, M., & Yazgan, M. E. (2018). Robust Tests for Convergence Clubs.

De Jong, R. M., & Sakarya, N. (2016). The econometrics of the Hodrick-Prescott filter. *Review of Economics and Statistics, 98*(2), 310-317.

Deaton, A. (2003). Health, income, and inequality. *National Bureau of Economic Research Reporter: Research Summary. Retrieved August, 15*, 2009.

Della Bosca, H., & Gillespie, J. (2018). The coal story: Generational coal mining communities and strategies of energy transition in Australia. *Energy policy, 120*, 734-740.

Dickey, D. A., & Fuller, W. A. (1979). Distribution of the estimators for autoregressive time series with a unit root. *Journal of the American statistical association, 74*(366a), 427-431.

Driscoll, J. C., & Kraay, A. C. (1998). Consistent covariance matrix estimation with spatially dependent panel data. *Review of Economics and Statistics, 80*(4), 549-560.

Durlauf, S. N., & Johnson, P. A. (1995). Multiple regimes and cross-country growth behaviour. *Journal of applied econometrics, 10*(4), 365-384.

Ebenstein, A., Fan, M., Greenstone, M., He, G., Yin, P., & Zhou, M. (2015). Growth, pollution, and life expectancy: China from 1991-2012. *American Economic Review, 105*(5), 226-231.

EDGAR. (2020). *Emissions Database for Global Atmospheric Research (EDGAR), release EDGAR v5.0 (1970 - 2015)*. Retrieved from: https://edgar.jrc.ec.europa.eu/overview.php?v=50_AP

Egger, G. (2009). Health, "Illth," and Economic Growth Medicine, Environment, and Economics at the Crossroads. *American Journal of Preventive Medicine, 37*(1), 78-83. doi:10.1016/j.amepre.2009.03.004

El Serafy, S. (1991). The environment as capital. *Ecological economics: The science and management of sustainability*, 168-171.

Ficetola, G. F., & Rubolini, D. (2020). Climate affects global patterns of COVID-19 early outbreak dynamics. *medRxiv*.

Galor, O. (1996). Convergence? Inferences from theoretical models. *The Economic Journal, 106*(437), 1056-1069.

Gangadharan, L., & Valenzuela, M. R. (2001). Interrelationships between income, health and the environment: extending the Environmental Kuznets Curve hypothesis. *Ecological economics, 36*(3), 513-531.

Graff Zivin, J., & Neidell, M. (2012). The impact of pollution on worker productivity. *American Economic Review, 102*(7), 3652-3673.

Grossman, G. M., & Krueger, A. B. (1991). *Environmental impacts of a North American free trade agreement*. Retrieved from

Grossman, G. M., & Krueger, A. B. (1995). Economic growth and the environment. *The quarterly journal of economics, 110*(2), 353-377.

Hall, J. V., Winer, A. M., Kleinman, M. T., Lurmann, F. W., Brajer, V., & Colome, S. D. (1992). Valuing the health benefits of clean air. *Science, 255*(5046), 812-817.

Hamilton, J. D. (2018). Why you should never use the Hodrick-Prescott filter. *Review of Economics and Statistics, 100*(5), 831-843.

Hansen, A. C., & Selte, H. K. (2000). Air pollution and sick-leaves. *Environmental and Resource Economics, 16*(1), 31-50.

Harris, R. D., & Tzavalis, E. (1999). Inference for unit roots in dynamic panels where the time dimension is fixed. *Journal of econometrics, 91*(2), 201-226.

Hausman, J. A. (1978). Specification Tests in Econometrics. *Journal of applied econometrics, 46*(6), 1251-1271.

Hausman, J. A., & Taylor, W. E. (1981). A generalized specification test. *Economics letters, 8*(3), 239-245.

Hepburn, C., O'Callaghan, B., Stern, N., Stiglitz, J., & Zenghelis, D. (2020). Will COVID-19 fiscal recovery packages accelerate or retard progress on climate change? *Oxford Review of Economic Policy, 36*.

Hodrick, R. J., & Prescott, E. C. (1997). Postwar US business cycles: an empirical investigation. *Journal of Money, credit, and Banking*, 1-16.

IHME. (2020). *Global Burden of Disease Study 2019 (GBD 2019) Results.* Retrieved from: http://ghdx.healthdata.org/gbd-results-tool

Im, K. S., Pesaran, M. H., & Shin, Y. (2003). Testing for unit roots in heterogeneous panels. *Journal of econometrics, 115*(1), 53-74.

Inklaar, R., Jong-A-Pin, R., & De Haan, J. (2008). Trade and business cycle synchronization in OECD countries—A re-examination. *European Economic Review, 52*(4), 646-666.

Jalil, A., & Mahmud, S. F. (2009). Environment Kuznets curve for CO2 emissions: a cointegration analysis for China. *Energy policy, 37*(12), 5167-5172.

Kaika, D., & Zervas, E. (2013a). The Environmental Kuznets Curve (EKC) theory—Part A: Concept, causes and the CO2 emissions case. *Energy policy, 62*, 1392-1402.

Kaika, D., & Zervas, E. (2013b). The environmental Kuznets curve (EKC) theory. Part B: Critical issues. *Energy policy, 62*, 1403-1411.

Kasparian, J., & Rolland, A. (2012). OECD's 'Better Life Index': can any country be well ranked? *Journal of Applied Statistics, 39*(10), 2223-2230.

Khanam, R., Nghiem, H. S., & Connelly, L. B. (2009). Child health and the income gradient: evidence from Australia. *Journal of health economics, 28*(4), 805-817.

Klarl, T. (2016). Pollution externalities, endogenous health and the speed of convergence in an endogenous growth model. *Journal of Macroeconomics, 50*, 98-113.

Kraay, A. (2018). Methodology for a World Bank human capital index. *World Bank Policy Research Working Paper*(8593).

Landrigan, P. J. (2017). Air pollution and health. *The Lancet Public Health, 2*(1), e4-e5.

Levin, A., Lin, C.-F., & Chu, C.-S. J. (2002). Unit root tests in panel data: asymptotic and finite-sample properties. *Journal of econometrics, 108*(1), 1-24.

Lopez, L., & Weber, S. (2017). Testing for Granger causality in panel data. *The stata journal, 17*(4), 972-984.

Lopez, R. (1994). The environment as a factor of production: the effects of economic growth and trade liberalization. *Journal of Environmental Economics and Management, 27*(2), 163-184.

McKee, M., & Stuckler, D. (2020). If the world fails to protect the economy, COVID-19 will damage health not just now but also in the future. *Nature Medicine, 26*(5), 640-642.

Mirvis, D. M., Chang, C. F., & Cosby, A. (2008). Health as an economic engine: evidence for the importance of health in economic development. *Journal of Health and Human Services Administration*, 30-57.

Phillips, P. C., & Perron, P. (1988). Testing for a unit root in time series regression. *Biometrika, 75*(2), 335-346.

Phillips, P. C., & Sul, D. (2007). Transition modeling and econometric convergence tests. *Econometrica, 75*(6), 1771-1855.

Phillips, P. C., & Sul, D. (2009). Economic transition and growth. *Journal of applied econometrics, 24*(7), 1153-1185.

Preston, S. H. (1975). The changing relation between mortality and level of economic development. *Population studies, 29*(2), 231-248.

Quah, D. T. (1996). Convergence empirics across economies with (some) capital mobility. *Journal of Economic Growth, 1*(1), 95-124.

Ravn, M. O., & Uhlig, H. (2002). On adjusting the Hodrick-Prescott filter for the frequency of observations. *Review of Economics and Statistics, 84*(2), 371-376.

Ritchie, H., & Roser, M. (2020). Our World in Data: Energy. Retrieved from https://ourworldindata.org/energy. https://ourworldindata.org/energy

Rushby, J. F., & Hanson, K. (2001). Calculating and presenting disability adjusted life years (DALYs) in cost-effectiveness analysis. *Health policy and planning, 16*(3), 326-331.

Sarwar, S., Alsaggaf, M. I., & Tingqiu, C. (2019). Nexus among economic growth, education, health, and environment: dynamic analysis of world-level data. *Frontiers in public health, 7*, 307.

Sassi, F. (2006). Calculating QALYs, comparing QALY and DALY calculations. *Health policy and planning, 21*(5), 402-408.

Shah, A. D., Bartlett, J. W., Carpenter, J., Nicholas, O., & Hemingway, H. (2014). Comparison of random forest and parametric imputation models for imputing missing data using MICE: a CALIBER study. *American journal of epidemiology, 179*(6), 764-774.

Stekhoven, D. J. (2015). missForest: Nonparametric missing value imputation using random forest. *Astrophysics Source Code Library*.

Stern, D. I. (2004). The rise and fall of the environmental Kuznets curve. *World development, 32*(8), 1419-1439.

Stern, D. I., & Common, M. S. (2001). Is there an environmental Kuznets curve for sulfur? *Journal of Environmental Economics and Management, 41*(2), 162-178.

Strauss, J., & Thomas, D. (1998). Health, nutrition, and economic development. *Journal of economic literature, 36*(2), 766-817.

Strulik, H. (2004). Child mortality, child labour and economic development. *The Economic Journal, 114*(497), 547-568.

Sun, R., & Gu, D. (2008). Air pollution, economic development of communities, and health status among the elderly in urban China. *Am J Epidemiol, 168*(11), 1311-1318. doi:10.1093/aje/kwn260

Torras, M., & Boyce, J. K. (1998). Income, inequality, and pollution: a reassessment of the environmental Kuznets curve. *Ecological economics, 25*(2), 147-160.

Von Lyncker, K., & Thoennessen, R. (2017). Regional club convergence in the EU: evidence from a panel data analysis. *Empirical Economics, 52*(2), 525-553.

Appendix:

Table A0. Data sources and selected variables

Source	Variable name	Descriptions
Gapminder (https://www.gapminder.org/data/)		
	Income	Income per capita at $PPP
	Doctors	Number of doctors per 1000 population
	BCG	BCG vaccination rate
	Pop	Population
EDGAR (https://edgar.jrc.ec.europa.eu/overview.php?v=50_GHG)		
	NOx	Nitrogen oxides
	BC	Black carbon
	CO	Carbon monoxide
	OC	Organic carbon
	NH3	Ammonia
	SO2	Sulfur dioxides
	NMVOC	Non-Methane Volatile Organic Compounds
	PM2.5	Fine particle matters less than 2.5 microns
	PM0	Fine particle matters less than 10 microns (In the analysis, air pollutants were converted to per capita using population data)
Global burden of diseases (http://ghdx.healthdata.org/gbd-results-tool)		
	DALY	Disability-adjusted life year of respiratory infection and tuberculosis
Penn World Table 10.0 (https://www.rug.nl/ggdc/productivity/pwt/?lang=en)		
	CN	Capital stock at $PPPs
	HC	Human capital index
	Emp	Number of persons engaged in labour force (in the analysis this variable was converted to labour force participation rate using population data)
Our world in Data (https://ourworldindata.org/explorers/energy)		
	Energy	Primary energy consumption
	Lowcarbon	Low-carbon energy consumption
Earth Data (https://earthdata.nasa.gov)		
	Temp	Monthly temperature (we use standard deviation of monthly temperature each year in the analysis)

Table A1. Convergence clubs and overall ranking

Countries	Income	Reversed Income	DALY	PM10	PM2.5	NMVOC	SO2	BC	OC	NH3	Total Scores
Belgium	1	3	2	7	5	3	2	2	9	4	9.57
Denmark	1	3	2	6	6	2	1	2	7	1	8.57
Sweden	1	3	2	5	4	2	2	0	8	4	8.57
Germany	1	3	2	6	5	2	1	0	4	5	8.29
Switzerland	1	3	2	0	0	1	3	5	9	5	8.29
Norway	1	3	2	4	3	1	2	0	7	5	8.14
France	1	3	2	5	5	2	2	0	5	2	8.00
Austria	1	3	2	6	5	2	2	0	0	3	7.57
Hungary	2	2	2	5	5	3	1	4	5	2	7.57
Portugal	2	2	2	0	0	5	2	3	8	7	7.57
UK	2	2	2	9	0	2	1	5	0	6	7.29
Iceland	1	3	2	3	2	1	1	0	6	2	7.14
Netherlands	1	3	2	9	0	3	0	0	0	3	7.14
Slovenia	2	2	2	4	4	2	1	2	6	3	7.14
Lithuania	1	3	2	0	6	2	1	0	4	1	7.00
Spain	2	2	2	8	0	4	2	2	0	5	7.00
USA	1	3	2	5	5	1	1	2	0	0	7.00
Colombia	3	1	1	7	7	4	0	4	5	7	6.86
New Zealand	2	2	2	7	5	1	3	2	0	1	6.71
Canada	1	3	2	2	1	1	1	1	2	3	6.57
Latvia	1	3	2	3	0	3	1	0	2	2	6.57
Finland	1	3	2	1	0	1	1	0	2	5	6.43
Japan	1	3	2	0	0	5	2	3	0	0	6.43
Czech Rep.	1	3	2	1	0	2	1	0	1	4	6.29
Luxembourg	1	3	2	2	1	1	1	0	0	4	6.29
Israel	2	2	2	8	0	2	1	5	0	0	6.29
South Korea	3	1	2	0	7	6	2	4	0	0	5.71
Italy	1	3	2	0	0	3	2	0	0	0	5.71
Greece	2	2	2	0	0	4	1	0	0	6	5.57
Slovakia	2	2	1	2	2	4	1	2	2	3	5.29
Estonia	2	2	2	0	3	1	1	0	2	1	5.14
Poland	3	1	2	3	0	4	1	3	3	0	5.00
Turkey	3	1	1	5	4	6	2	2	0	0	4.71
Australia	1	3	0	2	1	1	1	1	1	1	4.14
Chile	0	0	1	3	0	4	1	0	3	0	2.57
Mexico	3	1	1	0	0	2	2	0	0	0	2.57

Note: 0 represents divergence countries. CO, NOx and All pollutants attain overall convergence, and were not shown. Countries are list based on the ranking of the total score: Reversed Income+DALY+Average(pollutants)

Table A2. The robustness of the convergence test: changes samples

Outcomes	Use no treatment for missing value or outliers (Health=DALY)		Extend sample to 163 countries (Health=DALY)		Extended study period to 1970-2015 (Health=Life expectancy)		Extend both countries and period (Health=Life expectancy)	
	γ (t-value)	Convergence (divergence)	γ (t-value)	Convergence (divergence)	γ (t-value)	Convergence (divergence)	γ (t-value)	Convergence (divergence)
Income	-0.39 (-14.95)	3 (0)	-0.54 (-19.29)	6 (0)	-0.5 (-14.96)	4 (2)	-0.45 (-20.32)	5 (0)
Health	-0.62 (-34.29)	2 (1)	-0.67 (-33.81)	6 (0)	-0.84 (-52.15)	2 (1)	-0.66 (-26.1)	5 (0)
PM10	-6.03 (-6.02)	9 (10)	-6.63 (-4.78)	30 (17)	-0.8 (-9.73)	4 (0)	-0.71 (-40.43)	5 (0)
PM2.5	-6.43 (-6.38)	7 (15)	-6.65 (-6.48)	34 (25)	-0.67 (-9.6)	3 (0)	-0.67 (-35.31)	3 (0)
CO	-0.1 (-0.07)	1 (0)	-1.01 (-0.9)	1 (0)	-0.53 (-19.16)	3 (0)	-0.44 (-30.24)	4 (0)
NMVOC	-4.29 (-2.99)	6 (0)	-4.99 (-2.05)	5 (12)	-0.7 (-30.04)	4 (0)	-0.57 (-38.98)	5 (0)
SO2	-4.23 (-3.92)	4 (2)	-5.9 (-6.26)	25 (25)	-0.71 (-38.37)	3 (0)	-0.48 (-53.81)	5 (0)
BC	-6.34 (-5.8)	5 (18)	-5.36 (-8.58)	29 (12)	0.99 (2.47)	1 (0)	-0.34 (-8.75)	2 (0)
NOx	-4.79 (-1.23)	1 (0)	-5.62 (-5.38)	25 (19)	-0.78 (-30.68)	6 (1)	-0.36 (-19.27)	4 (0)
OC	-7.78 (-5.17)	10 (12)	-7.23 (-5.74)	43 (22)	-1.54 (-9.36)	3 (0)	-1.21 (-19.78)	2 (0)
NH3	-5.86 (-4.14)	8 (7)	-7.42 (-3.87)	37 (22)	-0.7 (-30.78)	5 (0)	-0.56 (-28.46)	6 (0)
All pollutants	1.87 (0.54)	1 (0)	0.1 (0.07)	1 (0)	-0.66 (-36.28)	4 (1)	-0.46 (-44.06)	5 (0)

Table A3. The robustness of the convergence test: changes estimation methods

Outcomes	Use Hodrick-Prescott filter with λ=6.25		Use Von Lyncker & Thoennessen (2017) merging method		Use Adaptive Quadratic Spectral Bandwidth method		Use time trim =1/4 instead of 1/3 (the recommended value)		Maximum oscillation period of 7 years in Christiano and Fitzgerald filter	
	γ (t-value)	Conv. (div.)	γ (t-value)	Conv. (div.)	γ (t-value)	Conv. (div.)	γ (t-value)	Conv. (div.)	γ (t-value)	Conv. (div.)
Income	-0.38 (-18.1)	3 (0)	-0.40 (-29.09)	3 (1)	-0.40 (-32.28)	3 (1)	-0.49 (-12.74)	4 (0)	-0.38 (-14.21)	3 (0)
DALY	-0.62 (-31.36)	3 (0)	-0.62 (-34.29)	2 (1)	-0.62 (-96.89)	2 (1)	-0.63 (-38.43)	3 (1)	-0.62 (-34.76)	2 (1)
PM10	-6.29 (-5.03)	7 (14)	-6.07 (-6.04)	9 (9)	-6.07 (-6.99)	8 (11)	-4.20 (-3.85)	9 (8)	-7.28 (-4.29)	7 (15)
PM2.5	-7.43 (-4.05)	10 (14)	-6.47 (-6.37)	7 (15)	-6.47 (-6.15)	6 (19)	-4.42 (-4.04)	9 (8)	-7.43 (-5.16)	8 (13)
CO	0.17 (0.12)	1 (0)	-0.34 (-0.26)	1 (0)	-0.34 (-0.17)	1 (0)	0.38 (0.31)	1 (0)	0.23 (0.16)	1 (0)
NMVOC	-3.46 (-2.98)	2 (0)	-4.27 (-2.81)	6 (0)	-4.27 (-2.01)	5 (1)	-3.07 (-2.65)	6 (1)	-3.29 (-2.95)	5 (0)
SO2	-3.71 (-1.93)	4 (2)	-4.24 (-3.93)	3 (2)	-4.24 (-4.05)	3 (1)	-3.13 (-3.75)	4 (3)	-3.43 (-3.46)	3 (3)
BC	-6.15 (-6.19)	7 (14)	-6.41 (-5.72)	5 (17)	-6.41 (-5.38)	5 (16)	-4.32 (-5.72)	7 (11)	-5.82 (-7.42)	6 (16)
NOx	-3.35 (-3.29)	2 (0)	-4.49 (-1.61)	1 (0)	-4.49 (-1.46)	1 (0)	-3.51 (-1.85)	5 (1)	-3.24 (-2.13)	1 (0)
OC	-7.41 (-6.64)	7 (21)	-7.84 (-5.05)	9 (14)	-7.84 (-4.29)	9 (13)	-5.25 (-3.91)	11 (9)	-7.37 (-9.06)	7 (19)
NH3	-5.55 (-5.95)	7 (8)	-5.84 (-4.2)	7 (9)	-5.84 (-4.1)	8 (8)	-4.17 (-3.45)	8 (8)	-6.90 (-2.4)	6 (10)
All pollutants	1.53 (0.98)	1 (0)	1.76 (0.51)	1 (0)	1.76 (0.59)	1 (0)	0.78 (0.34)	1 (0)	2.16 (1.04)	1 (0)

Table A4. The robustness of the Environmental Kuznets Curves

Air pollution	Main results (1990-2015 period, OECD)		Use 1970-2015 period for OECD		Use 1970-2015 period for 163 countries	
	Income	Income^2	Income	Income^2	Income	Income^2
PM10	***1.52	***-0.18	0.15	*-0.08	***0.44	***-0.07
PM25	***1.65	***-0.21	0.06	-0.05	***0.44	***-0.07
CO	***3.85	***-0.53	***2.09	***-0.33	***0.82	***-0.16
VOC	***2.88	***-0.42	***1.59	***-0.2	***0.61	***-0.07
SO2	*-1.29	**0.26	**0.37	***-0.2	***1.2	***-0.28
BC	***1.78	***-0.19	***0.74	-0.06	***0.45	***-0.05
NOx	***1.14	**-0.12	***0.57	**-0.06	***0.83	***-0.13
OC	***1.28	***-0.15	0.23	-0.03	***0.39	***-0.04
NH3	0.41	-0.02	***-0.42	***0.11	***0.28	***-0.06
All pollutants	***2.72	***-0.37	***1.28	***-0.2	***0.72	***-0.12

Note: Fixed-effects estimator with Driscoll and Kraay (1998) robust standard errors are used. Parameters other covariates are not reported for brevity. Significant levels are: ***=0.01, **=0.05, *=0.1.