

Relationship between Urbanization and CO₂ Emissions Depends on Income Level and Policy

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S Supporting Information

ABSTRACT: We investigate empirically how national-level CO₂ emissions are affected by urbanization and environmental policy. We use statistical modeling to explore panel data on annual CO₂ emissions from 80 countries for the period 1983–2005. Random- and fixed-effects models indicate that, on the global average, the urbanization–emission elasticity value is 0.95 (i.e., a 1% increase in urbanization correlates with a 0.95% increase in emissions). Several regions display a statistically significant, positive elasticity for fixed- and random-effects models: lower-income Europe, India and the Sub-Continent, Latin America, and Africa. Using two proxies for environmental policy/outcomes (ratification status for the Kyoto Protocol; the Yale Environmental Performance Index), we find that in countries with stronger environmental policy/outcomes, urbanization has a more beneficial (or, a less negative) impact on emissions. Specifically, elasticity values are -1.1 (0.21) for higher-income (lower-income) countries with strong environmental policy, versus 0.65 (1.3) for higher-income (lower-income) countries with weak environmental policies. Our finding that the urbanization–emissions elasticity may depend on the strength of a country’s environmental policy, not just marginal increases in income, is in contrast to the idea of universal urban scaling laws that can ignore local context. Most global population growth in the coming decades is expected to occur in urban areas of lower-income countries, which underscores the importance of these findings.



■ INTRODUCTION

This article evaluates environmental implications of global urbanization. Urbanization has increased dramatically, from ~30% in 1950 to more than 50% today, with ~60% projected by 2030.^{1,2} The urban developing-country population grew by ~3 million people per week during 1990–2010, equivalent to one new developing-country megacity per month, and is projected to more than double from 2.3 billion in 2005 to 5.3 billion in 2050. By 2050, Asia and Africa are expected to be home to about two-thirds of the world’s urban population (3.3 and 1.2 billion people, respectively). UN-HABITAT predicts that the developing world will be home to 95% of the world’s urban population growth during the next four decades.²

Urbanization is a complex phenomenon, with myriad impacts.^{2,3} Under favorable conditions, urbanization increases productivity, provides economic opportunities, generates wealth, and leads to a flourishing of new ideas in the arts, sciences, politics, and other fields.^{4–6} Under other conditions, urbanization quickens the spread of disease and exacerbates ills such as crime, poverty, exclusion, and environmental degradation.⁴ The United Nations estimates that more than 1 billion people lived in areas classified as slums in 2005.⁷ On the global average, within a country, health is generally better in urban

than in rural areas, owing to improved sanitation and nutrition, and easier access to contraception and health care.^{8,9}

To evaluate environmental impacts of urbanization, we explore here the following hypotheses related to per capita CO₂ emissions. Our unit of analysis is nations, because available global CO₂ estimates and international regulations styled on the Kyoto Protocol generally track and report emissions by country. Empirical evidence from North America and Europe emphasizes the possible energy efficiencies of urban areas, especially of denser urban areas,^{8,9} suggesting the following hypothesis:

Hypothesis 1a: in higher-income countries, the urbanization–emission elasticity is negative (urbanization reduces emissions).

Investigations of urbanization and CO₂ emissions in lower-income countries are limited. Potential differences between higher- and lower-income countries include how cities generate, spend, and distribute income. Higher-income service economies in the West have comparatively low levels of urban-scale income inequality and have resources to invest in urban form and infrastructure.^{2,10–12} In contrast, cities in lower-income

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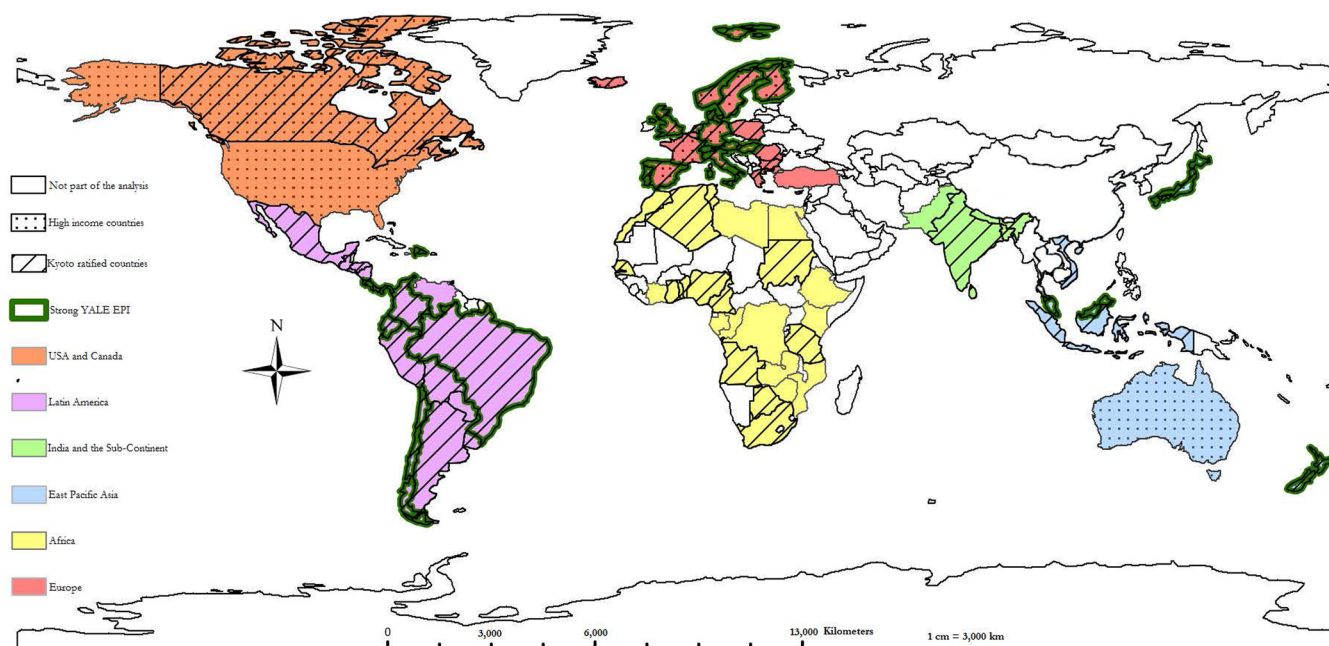


Figure 1. Countries and subgroups included in the analysis.

countries are experiencing rising incomes, but also rising pollution and income inequality.^{2,10–12} Our expectation for lower-income countries is that urbanization increases wealth (a socially beneficial outcome) and that in lower-income countries (unlike in higher-income countries), wealth effects outweigh urban energy efficiency.

Hypothesis 1b: in lower-income countries, the urbanization–emission elasticity is positive (urbanization increases emissions).

Recent analyses of urban areas emphasize universal urban scaling laws,^{13,14} and imply little or no impact of local context (e.g., culture, politics) on aspects of cities such as the provision of material infrastructure (e.g., road surface, gasoline stations, length of electrical cables), patterns of social activity (e.g., crime rates, patent creation, private R&D employment), and individual human needs (e.g., household electrical and water consumption).¹³ Thus, we anticipate that energy consumption and CO₂ emissions depend on income and urbanization rates, not local context (e.g., environmental regulations).

Hypothesis 2a: in higher-income countries, presence or absence of strong pro-environment policy does not change the urbanization–emission elasticity.

Hypothesis 2b: in lower-income countries, presence or absence of strong pro-environment policy does not change the urbanization–emission elasticity.

A novel aspect of our work is exploring the importance of national environmental policies. We employ panel rather than cross-sectional data, and present results for fixed- and random-effects models.

METHODS

We tested the hypotheses using panel data on 80 countries for the period 1983–2005. From the original (109-country) data set, we dropped 9 countries because of the paucity of data. We additionally omitted five countries (China, Singapore, Ireland, Trinidad and Tobago, and Thailand) as statistical outliers, and 15 Middle Eastern countries because of colinearity and paucity of data (see the Supporting Information).^{15,16} We stratified the

data by region (Africa, Latin America, North America, Europe, India and the Sub-Continent, East Asia), higher- versus lower-income (annual Gross National Income per person is more/less than US\$11,456, based on the World Bank’s year-2009 income classifications),¹⁷ and environmental policy. Income group is binary (higher; lower) because analyses using four income groups (low, lower-middle, upper-middle, and high) yielded similar results for the first three bins. “Higher-income” here equates to the “high income” label by the World Bank; “lower-income” here would equate to “low, lower-middle, and upper-middle income” using World Bank labels.¹⁷ Income groups are created based on final-year income. For example, Cyprus (considered here to be higher income) changed from upper-middle to high income between 1983 and 2005. Variables were added via forward stepwise regression, controlling for variables described in the literature as the most robust determinants for emissions. Age structure has been used in the literature as an estimator; we do not include it here, as its validation and correct specification have so far remained inconclusive.^{18,19}

We separately employed two indicators of the strength of national environmental policy: (1) ratification status for the Kyoto Protocol (ratified/nonratified), and (2) the Yale Environmental Performance Index (EPI), a country-specific comprehensive evaluation of environmental quality.²⁰ The EPI ranks countries on 25 performance measures, including ecosystem vitality, environmental health, agricultural water intensity, and air pollution and its effect on ecosystems and human health. Strictly, EPI is a measure of national environmental outcomes and performance. However, we argue here that it provides a reasonable gauge at the national scale of how close countries are to established environmental policy goals; with few globally available alternative metrics to choose from, we use EPI here as an (imperfect) proxy for the strength of national environmental policies.²⁰ Based on EPI, we grouped countries into two bins (stronger/weaker environmental policy), with the top-ranked 22 countries with available data regarded as having stronger environmental policy (Figure 1). Our models interact

Table 1. Descriptive Statistics

group ^a	income (US\$ GDP person ⁻¹ year ⁻¹)	urbanization (% of population living in urban settlements)	CO ₂ emissions (tCO ₂ person ⁻¹ year ⁻¹)
	mean (std)	mean (std)	mean (std)
all countries	\$7,000 (\$9,400)	55% (22%)	2.3 (3.2)
EPI countries	\$14,000 (\$11,000)	69% (11%)	3.6 (1.8)
non-EPI countries	\$4,400 (\$1,200)	50% (23%)	1.8 (2.5)
Kyoto countries	\$7,800 (\$9,700)	57% (21%)	2.5 (2.5)
non-Kyoto countries	\$4,100 (\$7,600)	47% (25%)	1.6 (2.4)

^aGroup comparisons were performed via analysis of variance (ANOVA). All entries in the bottom four rows are statistically significantly different than the first row ($p < 0.01$). "EPI" refers to the 22 high-EPI countries (EPI = environmental performance indicator).

urbanization with income and environmental policy to evaluate these connections.

We used the following analyses and tests to investigate our hypotheses. Group comparisons were evaluated using one-way analysis of variance (ANOVA). We tested for heteroskedasticity (White's test) and autocorrelation (Wooldridge's test) and corrected for autocorrelated errors (1st term autoregressive: AR1) and heteroskedasticity using generalized least-squares (GLS) regressions with both fixed and random effects. We employed the Hausman test to evaluate how parameter estimates differ between both approaches: the null of the test is that the coefficients estimated by the random effects estimator (more efficient) are the same as the ones estimated by the fixed effects estimator (more consistent). If the difference is statistically significant ($p < 0.05$), then analyses should use fixed effects estimators. Here we provide both fixed and random effects results, as we do not find sufficient evidence to fully reject the null of random effects (see the Supporting Information, Tables S1 and S2). The random effects model assumes that the time and individual components are not fixed over time, and that all countries in the panel have time-variant effects. Stated differently, the random effects model allows for estimating the urbanization coefficient taking into account heterogeneity across nations, with the time and individual error components being estimated individually from each other. An important drawback of the random effects approach, however, is the bias that partial pooling introduces in coefficient estimates, especially in situations where omitted variable bias may occur, which is likely to be the case here. The fixed effects estimation, in contrast, avoids that bias, because confounding from an omitted variable is removed via the separate unit effects.²¹ Fixed effects models respect the orthogonality assumption and are better suited as an estimator for a nonrandomly selected sample of countries. Our fixed effects estimator also allows us to correct for endogeneity between emissions and energy variables. We do not consider the endogeneity to be evidence of true causality because emissions and energy-use could be driven by a common third process with different lags. Our fixed effects specification corrects for endogeneity albeit with a large standard error. From a theoretical standpoint, we also expect high energy-consumption (in a fossil fuel based economy) to lead to more CO₂ emissions and not the other way round; therefore, we do not find issues with reverse causality and misspecification in the model.

The net outcome of our models is estimates of the impact of urbanization on national CO₂ emissions per capita, controlling for variables such as per capita income,²² percentage of land dedicated to agriculture,²² and energy use.²² In our analyses, CO₂ per capita refers to the natural log of metric tons of petroleum consumption per capita (dependent variable).

Agriculture intensity is the natural log of the proportion of land dedicated to agriculture adjusted for population. Total energy use is log-transformed (units: natural log of kg of oil-equivalent per capita). Income is the natural log of GDP per capita (2005 dollars).²³ The natural logarithm allows us to correct for some of the skewness of the distribution, making the data sets closer to a normal distribution, and allows for the coefficients to be interpreted as elasticities.

Urbanization is defined here as the percentage of the total population that lives in urban areas, as defined by the United Nations (UN) Section on Population Division, Estimates, and Projects.²⁴ This definition follows country-by-country definitions of "urban"; it thus avoids using uniform criteria to distinguish between urban and rural areas because of the variety of situations in which urbanization arises around the world, instead relying on national statistical offices to establish and characterize the most appropriate criteria for their urban areas.²⁴ Establishing a rigid criterion that would define an urban area as one where, for example, population exceeds a certain amount could be inappropriate for countries like India, where rural areas with none of the characteristics of urban areas frequently can have a large number of inhabitants.²⁴ The data on urban areas and urban populations employed here are based on definitions by national statistical offices, and are reported by the UN.²⁴ Those definitions could include administrative boundaries, population size and density, economic, and other criteria related to the functional nature of urban areas (e.g., availability of water-supply, sewerage, or electric lighting).

As a sensitivity analysis, we separately developed models allowing for nonlinearities, including interactions between income, urbanization, and strength of environmental policy; results are in the Supporting Information. Results below are statistically significant for one and two-sided tests unless stated otherwise.

RESULTS AND DISCUSSION

Descriptive statistics are in Tables 1 and S1 (Supporting Information). Correlations among the variables are in Table 2. For the period 1983–2005, economic growth rates were slightly higher for high-EPI than for low-EPI countries

Table 2. Correlations Among Variables

	CO ₂	agricultural intensity	energy use	GDP/capita	urbanization
CO ₂	1				
agricultural intensity	0.12	1			
energy use	0.88	0.053	1		
GDP/capita	0.93	0.081	0.89	1	
urbanization	0.76	0.051	0.68	0.79	1

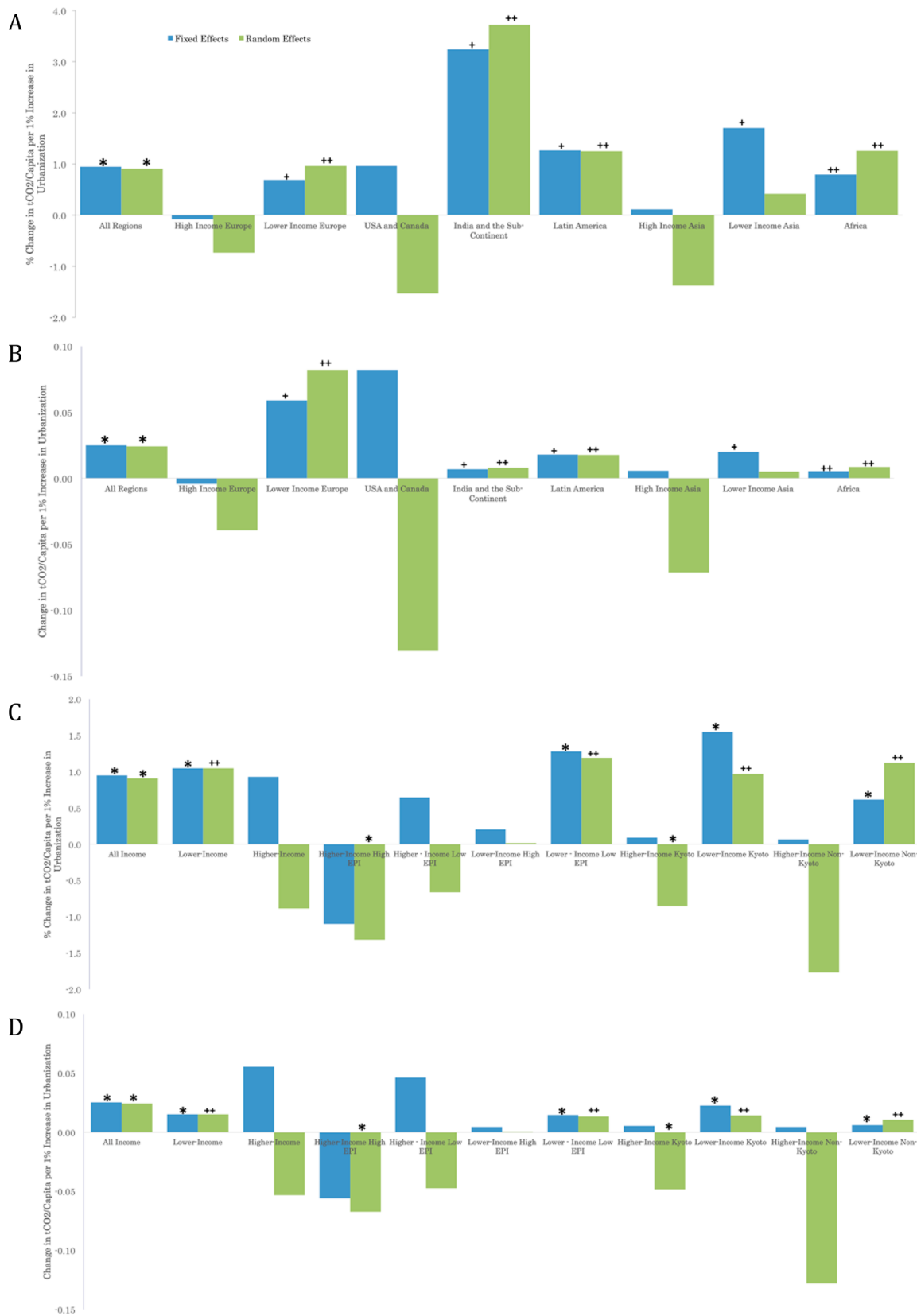


Figure 2. Elasticity values by geographic region (subplots A and B) and by policy framework (C, D), based on percent changes (A, C) and absolute-value changes (B, D). For example, for all regions, a 1% increase in urbanization is associated with a 0.95% (0.021 tCO₂) increase in emissions per person per year. “Higher-income” versus “lower-income” categorization is based on the year-2009 GPD per capita being above or below US\$11,456. ++ Statistically significant at the 1% level for *one and two-sided* significance tests. + Statistically significant at the 10% level for *one and two-sided* significance tests. * Statistically significant at the 10% level for *one-sided* significance tests (H_0 for higher-income countries: coef ≥ 0 ; H_0 for lower-income countries: coef ≤ 0).

(average annual GDP growth: 2.6% versus 2.3%, respectively, $p < 0.05$). Among higher-income countries, per capita GDP is similar between high versus low EPI countries (means: \$23,500 vs \$22,300; $p < 0.06$). In contrast, for lower-income countries, mean income differs between high-EPI (\$4,400) versus low-EPI (\$2,100) nations ($p < 0.01$). Average annual growth in per capita CO₂ is greater in higher-income than in lower-income countries if one considers absolute emission-increases (annual change in emission rate, units: [kgCO₂ person⁻¹ y⁻¹] y⁻¹: 66 vs 17, $p < 0.01$), but the reverse holds if one considers relative emission-increases (0.63% y⁻¹ [higher-income] vs 0.88% y⁻¹ [lower-income], $p < 0.01$). Between 1983 and 2005, average annual growth in urbanization rates was six times higher for lower-income countries than for higher-income countries (0.89% y⁻¹ vs 0.15% y⁻¹).

Our regression models estimate CO₂ emissions (dependent variable) as a function of urbanization, percentage of land dedicated to agriculture, income, and energy use. We find little evidence to support a nonlinear relationship between environmental impacts and urbanization. (We also do not find evidence in the data to support an environmental Kuznets curve for CO₂ emissions.) Here we highlight results from our monotonic (log-linear) model (Supporting Information, Tables S2 and S3 model A), which is parsimonious, yet it explains 82% of the variance in CO₂ emissions.^{25,26} In general, regression models isolate the impact of each independent variable on the dependent variable, accounting for variations in other independent variables. Some countries in the panel have a significant proportion of nonfossil energy, including the Scandinavian countries (~45% large renewables), France (~80% nuclear), Belgium (~54% nuclear), Switzerland (~40% nuclear), Brazil (~90% hydro), and Germany (25% renewables). Other countries have an energy mix that is diverse and changing. On average, increases in income, energy use, and the percentage of land dedicated to agriculture each lead to higher emissions levels. Agriculture is energy-intensive and may play an important role in national CO₂ emissions.²⁷

The all-country emissions elasticity for urbanization is statistically significant, with a value of 0.95 (95% CI: 0.27–1.7); i.e., a 10% increase in urbanization is on average associated with a 9.5% increase in emissions per capita, all else being equal. An elasticity between 0 and 1 (“inelastic”) indicates that the percentage change in emissions is smaller than the percentage change in urbanization. An elasticity greater than 1 (“elastic”) means that a percentage change in urbanization leads to a more than proportionate change in CO₂ emissions. A negative elasticity means that urbanization reduces per capita emissions. Elasticity values from random and fixed effects models are statistically significant for lower-income Europe (0.96; 95% CI: 0.33–1.6), India and the Sub-Continent (3.2, 95% CI: 0.18–6.3), Latin America (1.3; 95% CI: 0.64–1.9), and Africa (1.3; 95% CI: 0.72–1.8). Elasticity values for lower-income Asia are statistically significant for fixed effects models but not random effects models.

Figure 2 presents relative and absolute changes in emissions per change in urbanization. Coefficient estimates and confidence intervals are presented in Tables S3–S6 (Supporting Information). The lower-income group shows a positive and statistically significant elasticity with random and fixed effects estimators (1.1; 95% CI: 0.35–1.7); overall, elasticity values for the higher-income group are not statistically significant.

Elasticity values for countries with strong environmental outcomes and policy (high scoring EPI) suggest that, all else

equal, strong environmental policy reduces the urbanization emission elasticity (makes it less positive or more negative). That is, urbanization has a more beneficial impact (or, a less negative impact) in countries with strong environmental policy than in other countries. Elasticity values are statistically significant for both random and fixed effects models for lower-income countries with low EPI, Kyoto ratified, or Kyoto nonratified. In addition, for random effects models, elasticity values are statistically significant for higher-income countries with strong environmental outcomes and policy (high EPA and Kyoto ratified). Urbanization is correlated with reduced CO₂ emissions in lower-income countries with strong environmental performance (0.21; 95% CI: -1.1 – +1.6) than in lower-income countries with weaker environmental policies (1.3; 95% CI: 0.51–2.1).

A negative elasticity (coefficient < 0) suggests that urbanization reduces average per capita emissions. A negative “elastic” elasticity (coefficient < -1; see higher-income, high-EPI, random effects model) implies not only that urbanization reduces emissions, but also a multiplier effect whereby an individual moving from a rural to an urban area impacts his/her own emissions plus emissions from other people in a community.²⁸ (The rationale that elasticity < -1 necessarily uncovers a “multiplier” effect follows from the observation that any individual, including one moving to an urban area, can at most reduce her own emissions by 100% [i.e., to zero emissions]; therefore elasticity < -1 means that each person moving to an urban area impacts [reduces] others’ emissions too.) Potential mechanisms for a multiplier effect are as follows. As urban demand for goods, services, employment, and schools increases, governments and markets may respond with improved public transportation services, roads, and other infrastructure that could reduce total emissions,²⁹ all potential aspects of energy-efficient urban form.¹⁰ Under the right circumstances, urbanization can also trigger two other important greenhouse gas (GHG) offsetting forces: it can slow national population growth through changing fertility patterns (as women have more employment opportunities, they might marry later and delay having their first child), and it can provide incentives for smaller household sizes (urban land is more expensive than rural land; health care is more readily available in urban areas, which reduces child mortality and thereby makes smaller family size more likely), which potentially reduces a household’s energy demand.^{29,30}

Most (~95%) of the global population growth in coming decades is expected to occur in urban areas of lower-income countries.³¹ Our results suggest that for lower-income countries, the elasticity is positive, elastic, and statistically significant (i.e., growth in urban population increases per capita emissions). Urbanization correlates with increasing economic activity, which can increase energy consumption and CO₂ emissions.^{29,31,32}

We generated several alternative models to explore the robustness of our findings; see the Supporting Information. The additional models generally yielded consistent results. For example, if we allow an urbanization–income² interaction term in the model, the urbanization–emissions elasticity remains positive and small for lower levels of income with strong environmental policy (0.37; 95% CI: -0.96 – +1.7) and remains negative but not statistically significant for higher-income countries with strong environmental policy (-0.95; 95% CI: -4.3 – +2.4). Our policy–income²–urbanization² interaction terms were equally consistent with the results described above (Supporting Information, Tables S4–S7).

Table 3. Urbanization and CO₂ Emissions in the Literature

author(s)	stratification	methodology ^{a,b,c}	control variables	data	urbanization elasticity
Martinez-Zarzo and Maroutti, 2011	income	STIRPAT (LC)	population, GDP/capita, urbanization (%), age structure, energy efficiency, industry (%), GDP	88 developing countries: low, lower-middle, and upper-middle income, 1975–2003, yearly data	all countries (0.51–1.3) low/low-middle income (0.80) low-middle/upper-middle income (0.45)
Poumanyong and Kaneko, 2011	income	IPAT (FD)	population, GDP/capita, energy intensity, industry (%), GDP, services (%), GDP, urbanization, total energy use	99 countries: low, middle, and high income countries, 1975–2005, yearly data	all countries (0.45) low income (0.43) middle-income (0.51) high-income (0.36)
Shi, 2003	income	STIRPAT (GLS)	population, GDP/capita, manufacturing (%), GDP, services (%), GDP, nontradable (%), GDP, working population stratified by age (%)	93 countries: low, lower-middle, upper-middle, high income countries, 1975–1996, yearly data	population not urbanization. all countries (1.42) low-income (1.58) lower-middle (1.97) upper-middle (1.42) high income (0.83)
Liddle and Lung, 2010	age structure	STIRPAT (OLS)	population, GDP/capita, population structure, urbanization (%), non fossil fuels (%), residential electricity consumption (%), total, rail (%), total road network, industrial energy consumption (%) total	17 developed countries: 1960–2005 and include observations at 5-year intervals	developed countries (0.48)
Fan et al., 2010	income	STIRPAT (PLS)	population, GDP/capita, urbanization, population structure, energy intensity	208 countries: low, lower-middle, upper-middle, and high income countries 1970–2005, yearly data	all countries (0.24) low-income (0.33) lower-middle (0.23) lower-middle (0.23) high (0.57)
Cole and Neumayer, 2004	no stratification	STIRPAT (FD)	population, urbanization rate, age structure, GDP/capita, energy intensity, manufacturing (%), GDP	86 countries, 1975–1998, yearly data	all countries (0.70)
York et al., 2003	no stratification	STIRPAT (RLS)	population, GDP/capita, industrial (%), GDP, urbanization (%)	146 countries, 1996	all countries (0.62)
Present article	income, region, and environmental policy	population adjusted (GLS)	GDP/capita, urbanization (%), agricultural land (%), energy use (kg oil equivalent per capita)—all variables include population adjustments	80 countries, 1983–2005; income (low, lower-middle, upper-middle, and high income countries); region (Europe, Latin America, North America, Africa, Sub-Continent, Pacific East Asia); policy (Kyoto Ratification, Yale University's Environmental Performance Index)	all countries (0.91) low income—high EPI (0.02) low income—low EPI (1.19) high income—high EPI (–1.32) high income—low EPI (–0.67)

^aAll dependent variables are country level CO₂ emissions. ^bSTIRPAT is the stochastic environmental impacts by regression on population, affluence, and technology model. IPAT refers to impact = population × affluence × technology. ^cStatistical methods listed here include latent class (LC) models, first differences (FD), generalized least-squares (GLS), partial least-squares (PLS), and restricted least-squares (RLS).

As income increases, environmental impacts may shift from immediate and localized issues, to more delayed issues such as air and chemical pollutants and later to sustainability.^{12,44–46} With increasing urbanization and wealth, developing nations have been shown to pollute faster, and at lower income levels, than did developed countries.⁴⁸ Although recent research has reported a negative urbanization–emissions elasticity for higher-income countries, and some work has investigated regional impacts, no prior research has investigated the income, regional and policy interactions of this relationship.^{48–51} Importantly, our investigation did not find evidence that urbanization reduces emissions similarly across all incomes and environmental policy groups; instead, we found evidence of a negative elasticity only in some cases (higher-income countries with high EPI or with Kyoto ratification).

Our results corroborate earlier findings that urbanization is an increasingly important determinant of GHG emissions in the developed and developing world.^{57–64} We bridge a gap in the literature by considering the urbanization–emissions relationship by region, national income, and strength of environmental policy (Table 3). STIRPAT (stochastic environmental impacts by regression on population, affluence, and technology)-based approaches have reported that urbanization's impact on CO₂ emissions is smaller in higher-income countries than in other countries but with a positive elasticity for all income levels.^{49–51} In contrast, we find the urbanization–emissions elasticity to be negative and statistically significant only in specific cases (countries with higher-income and strong environmental policy). Our findings indicate that the relationship between urbanization and higher-income is not in itself sufficient to foster a negative elasticity with carbon emissions; rather, strong environmental policy and its implementation are essential to reduce the environmental footprint of urbanization. That finding, highlighting the importance of environmental policy, is a core contribution of this article to the literature.

A strength of the analyses presented here is that they employ panel data, thereby allowing us to explore changes over time in many locations. A limitation of our analyses is that we are unable to identify specific policies that might impact the elasticity in different regions and levels of urbanization and development. That type of research is an important next step. Variables not explicitly examined here include urban density, the proportion of specific energy end points (e.g., transportation, heating, electricity-generation) met using nonfossil sources, and weather. We leave those evaluations for future research. Our data rely on self-reported values from participant countries; we were unable to verify raw-data estimates. In addition, our data cover direct emissions only, not life cycle emissions; others have found that life cycle approaches shed important and useful light on understanding the environmental impacts of urbanization.^{53–56}

As with many empirical analyses, causation is unclear: policy differences may cause the observed differences in elasticity values, may be caused by the differences in elasticity, or may merely correlate with other unobserved differences. Although not explored here, as different regions and countries develop and populations grow, they face vastly different challenges related to urbanization (and, potentially, different urbanization–emission elasticity values); policy solutions may differ by region, country, or within-country area. Our statistical analyses in some cases grouped low, lower-middle, and upper-middle income categories, because certain models given here yielded similar results for the three groups; however, the policy challenges and potential solutions they face may differ. Evaluating how population density

and how national and inter-regional urban area characteristics shape the urbanization–emissions elasticity – within national and regional scenarios – is a natural next step in future work.

Overall, our results support hypothesis 1b but do not support hypotheses 2a and 2b. We find only partial support for hypothesis 1a, specifically only for higher-income nations with strong environmental policy. Our findings highlight the potential role of policy as a contributor to the elasticity magnitude; the results do not reveal location-invariant universal urban scaling laws. Our research suggests that in both developed and developing countries alike, the CO₂ impacts of urbanization are better (lower) if they come accompanied by the successful development and implementation of strong environmental policies.

■ ASSOCIATED CONTENT

⑤ Supporting Information

Additional details about our statistical methods, results with complete tables and figures for all of our models (linear, nonlinear and interactions), and further statistical analyses. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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Notes

The authors declare no competing financial interest.

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Supplemental Results

Table S1. Descriptive Statistics for Selected Groups

Group*	Income (\$US GDP person ⁻¹ year ⁻¹)	Urbanization (% of Population Living in Urban Settlements)	CO ₂ Emissions (tCO ₂ person ⁻¹ year ⁻¹)
	Mean (STD)	Mean (STD)	Mean (STD)
<i>All Countries</i>	\$7,000 (\$9,400)	55% (22%)	2.3 (3.2)
High-Income	\$23,000 (\$6,500)	77% (10%)	5.83 (1.3)
Low-Income	\$2,500 (\$2,900)	49% (21%)	1.31 (1.6)
<i>EPI Countries</i>	\$13,900 (\$11,000)	69% (11%)	3.6 (1.8)
High-Income	\$16,000 (\$10,600)	72% (12%)	4.5 (2.4)
Low-Income	\$5,600 (\$8,400)	52% (21%)	1.2 (2.5)
<i>Non-EPI Countries</i>	\$4,400 (\$1,200)	50% (23%)	1.8 (2.5)
High-Income	\$7,400 (\$9,900)	53% (23%)	2.3 (2.6)
Low-Income	\$4,400 (\$6,700)	51% (22%)	1.9 (2.4)
<i>Kyoto Countries</i>	\$7,800 (\$9,700)	57% (21%)	2.5 (2.5)
High-Income	\$8,300 (\$10,000)	58% (21%)	2.7 (2.6)
Low-Income	\$6,600 (\$9,000)	54% (22%)	2.2 (3.3)
<i>Non-Kyoto Countries</i>	\$4,100 (\$7,700)	47% (25%)	1.6 (2.4)
High-Income	\$13,000 (\$12,000)	61% (24%)	3.6 (2.9)
Low-Income	\$3,100 (\$4,900)	50% (21%)	1.5 (1.9)

* Group comparisons were performed via analysis of variance (ANOVA). All entries in the bottom four rows are statistically significantly different than the first row ($p \leq 0.01$).

Table S2. Regression Results – Fixed Effects

Variable ^{1,2}	[A]			[B]		[C]		[D]				
	GLS ³ (CI)	(95% CI)	P-Value	Income Nonlinearity (95% CI)	P-Value	Urban Nonlinearity (95% CI)	P-Value	Full Model ² (95% CI)	P-Value			
Agricultural Intensity	0.0675 (0.0141 - 0.121)	0.013	**	0.325 (0.241 - 0.408)	≤0.001	**	0.321 (0.239 - 0.402)	≤0.001	***	0.351 (0.233 - 0.398)	0.023	**
Energy Intensity	0.334 (0.251 - 0.416)	≤0.001	***	0.372 (0.273 - 0.471)	≤0.001	***	0.361 (0.263 - 0.459)	≤0.001	***	0.370 (0.271 - 0.469)	≤0.001	***
Income (Income)²	.357 (.259 - .456)	≤0.001	***	0.287 (0.177 - 0.398)	≤0.001	***	0.320 (0.217 - 0.425)	≤0.001	***	0.302 (0.192 - 0.412)	≤0.001	***
Urbanization^{4,5}	0.949 (0.271 - 1.68)	≤0.001	***	-0.0291 (-0.0614 - 0.00315)	≤0.001	***	--	--	--	-0.0189 (-0.0514 - 0.0135)	0.254	--
(% Urban)²	0.949 (0.271 - 1.68)	≤0.001	***	1.01 (0.361 - 1.66)	≤0.001	***	0.751 (0.0801 - 1.42)	≤0.001	***	0.790 (0.113 - 1.44)	0.018	***
Constant	-1.08 (-1.16 - -1.00)	≤0.001	***	--	--	--	-0.000334 (-0.000507 - -0.000172)	≤0.001	***	-0.0003245 (-0.000492 - -0.000158)	≤0.001	***
Adjusted R² Overall	0.749			0.754			0.772			0.914		
Overall Model P-Value	(0.001)			(0.001)			(0.001)			(0.001)		
Hausman Test (Prob > Chi²)⁶	0.0599			0.053			0.0248			0.0922		
Countries	80											
Years	1983-2005											

*** Indicates statistical significance (two-sided) at the 1% level, ** at the 5% level and, * at the 10% level.

[1] *CO₂ per Capita* is the natural log of metric tons of petroleum consumption per capita. *Agriculture Intensity* is the natural log of the proportion of land dedicated to agriculture adjusted for population effects. *Energy Intensity* is the natural log of kg of oil equivalent per capita. *Income* is the natural of GDP per capita in 2005 dollars. *Urbanization* is the percentage of the total population living in urban areas.

[2] A ln(dependent variable) - ln(independent variable) regression produces coefficients that can be understood as elasticities. eg., a 1% increase in agricultural intensity leads to a 0.0675% increase in CO₂ emissions per capita. When the independent variable is a percentage the coefficient has to be multiplied by 100 to obtain the elasticity (urbanization). eg., a 1% increase in urbanization leads to a 0.908% increase in CO₂ emissions per capita.

[3] GLS corrects for heteroskedasticity and autocorrelation in the error terms. A random effects regression regression allows for heterogeneity among nations and is used when there is reason to believe that differences across entities in a panel may have some influence on the dependent variable.

[4] According to the World Bank some countries define urbanization based on the size or characteristics of settlements and others base their definition on the presence of certain infrastructure and services. For most countries in the data set 'urban population' is that which is living in 'inner city, inner and outer suburban districts, and inner and outer counties'.

[5] In the regional, income, and policy framework models every binary interaction term is multiplied by the urbanization term. The regional, income, or policy urbanization-emissions elasticity is then obtained by subtracting the *urbanization* coefficient from the *urbanization*interaction* coefficient.

[6] The null of the hausman test is that the coefficients estimated by the random effects estimator (more efficient) are the same as the ones estimated by the fixed effects estimator (more consistent). If the difference is statistically significant (5% is considered appropriate) then the analysis should be used using a fixed effects estimator. Here we fail to reject the null of random effects and estimate our models using random effects.

Table S2. Regression Results – Random Effects

Variable ^{1,2}	[A]		[B]		[C]		[D]					
	GLS ³ (95% CI)	P-Value	Income Nonlinearity (95% CI)	P-Value	Urban Nonlinearity (95% CI)	P-Value	Full Model ² (95% CI)	P-Value				
Agricultural Intensity	0.0675 (0.0141 - 0.121)	0.013	**	0.0504 (0.00168 - 0.0984)	0.043	**	0.0678 (0.0179 - 0.117)	≤0.001	***	0.0542 (0.00736 - 0.101)	0.023	**
Energy Intensity	0.385 (0.299 - 0.471)	≤0.001	***	0.429 (0.345 - 0.515)	≤0.001	***	0.404 (0.321 - 0.488)	≤0.001	***	0.436 (0.352 - 0.520)	≤0.001	***
Income (Income)²	0.462 (0.387 - 0.537)	≤0.001	***	0.434 (0.361 - 0.507)	≤0.001	***	0.474 (0.401 - 0.546)	≤0.001	***	0.451 (0.379 - 0.523)	≤0.001	***
Urbanization^{4,5}	0.906 (0.541 - 1.27)	≤0.001	***	-0.0585 (-0.0797 - -0.0374)	≤0.001	***	--	--	--	-0.0438 (-0.0655 - -0.0223)	≤0.001	***
(% Urban)²	0.906 (0.541 - 1.27)	≤0.001	***	0.874 (0.524 - 1.21)	≤0.001	***	0.546 (0.178 - 0.914)	≤0.001	***	0.581 (0.226 - 0.937)	≤0.001	***
Constant	-5.87 (-6.71 - -5.04)	≤0.001	***	--	--	--	-0.000307 (-0.000404 - -0.000211)	≤0.001	***	-0.000256 (-0.000353 - -0.000159)	≤0.001	***
Adjusted R² Overall	0.886			0.905			0.904			0.914		
Overall Model P-Value	(0.001)			(0.001)			(0.001)			(0.001)		
Hausman Test (Prob > Chi²)⁶	0.0599			0.053			0.0248			0.0922		
Countries	80											
Years	1983-2005											

*** Indicates statistical significance (two-sided) at the 1% level, ** at the 5% level and, * at the 10% level.

[1] *CO₂ per Capita* is the natural log of metric tons of petroleum consumption per capita. *Agriculture Intensity* is the natural log of the proportion of land dedicated to agriculture adjusted for population effects. *Energy Intensity* is the natural log of kg of oil equivalent per capita. *Income* is the natural of GDP per capita in 2005 dollars. *Urbanization* is the percentage of the total population living in urban areas.

[2] A ln(dependent variable) - ln(independent variable) regression produces coefficients that can be understood as elasticities. eg., a 1% increase in agricultural intensity leads to a 0.0675% increase in CO₂ emissions per capita. When the independent variable is a percentage the coefficient has to be multiplied by 100 to obtain the elasticity (urbanization). eg., a 1% increase in urbanization leads to a 0.908% increase in CO₂ emissions per capita.

[3] GLS corrects for heteroskedasticity and autocorrelation in the error terms. A random effects regression regression allows for heterogeneity among nations and is used when there is reason to believe that differences across entities in a panel may have some influence on the dependent variable.

[4] According to the World Bank some countries define urbanization based on the size or characteristics of settlements and others base their definition on the presence of certain infrastructure and services. For most countries in the data set 'urban population' is that which is living in 'inner city, inner and outer suburban districts, and inner and outer counties'.

[5] In the regional, income, and policy framework models every binary interaction term is multiplied by the urbanization term. The regional, income, or policy urbanization-emissions elasticity is then obtained by subtracting the *urbanization* coefficient from the *urbanization*interaction* coefficient.

[6] The null of the hausman test is that the coefficients estimated by the random effects estimator (more efficient) are the same as the ones estimated by the fixed effects estimator (more consistent). If the difference is statistically significant (5% is considered appropriate) then the analysis should be used using a fixed effects estimator. Here we fail to reject the null of random effects and estimate our models using random effects.

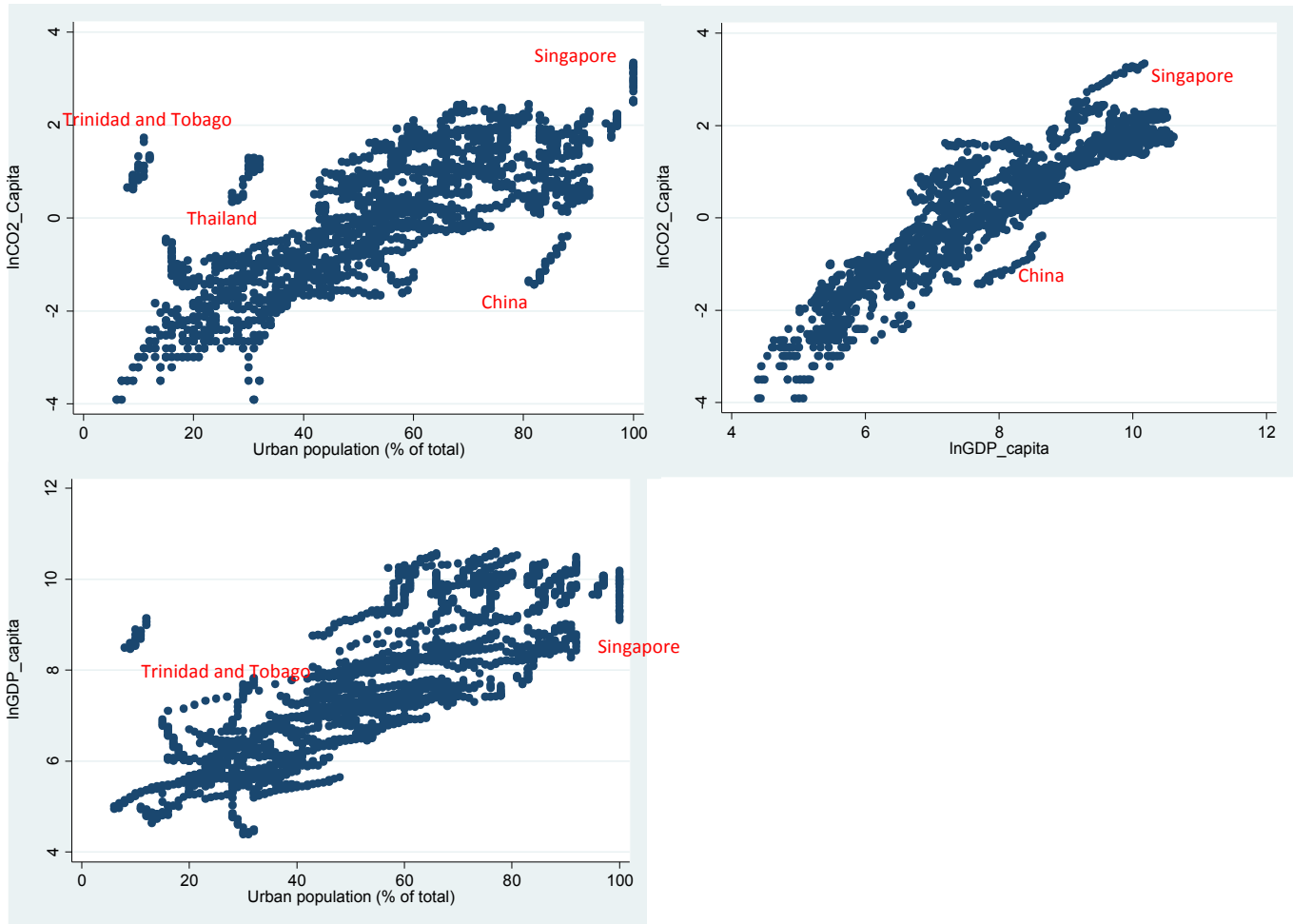


Figure S1. *Outliers: Leverage and Influence.* China, Thailand, Trinidad and Tobago, Singapore, and Ireland.

In general, high leverage observations are those with an extreme value on a predictor variable (such as Singapore with urbanization, for example), and outliers are those observations that are numerically distant from the rest of the data. Influence refers to the ability of an observation to substantially affect the estimate of regression coefficients. China, Singapore, Thailand and Trinidad and Tobago are outliers with high residuals (and influence within their regional groupings), while the case of Ireland is different as it is a case of influence. In an iterative analysis to investigate which countries had strong influence in Europe (running our regressions to see which countries markedly affected results), Ireland stood out from the rest and was removed from the sample. Other studies have shown that Ireland is an outlier in European terms regarding decoupling CO2 emissions from transport emissions from 1970-2000 as it achieved immaterialisation (which describes the decoupling of both material production and consumption from economic production and can be measured by using indicators such as energy intensity or transport intensity) of transport during this time period and was markedly above the EU15 average in dematerialization of transport (referring to the decoupling of the specified environmental harm from material production and may consist of technical development and/or shifts within the sector observed and can be measured, by changes in the carbon intensity of energy production or by changes in the carbon intensity of transport). Ireland experienced a below average freight intensity and passenger transport intensity, with a completely different economic sectorial shift focusing on high-tech industrial production rather than in service employment.

Tapio, P; *et al.* Energy and transport in comparison: Immaterialisation, dematerialisation and decarbonisation in the EU15 between 1970 and 2000. *Energy Policy*. **2007**. 35, 433-451.

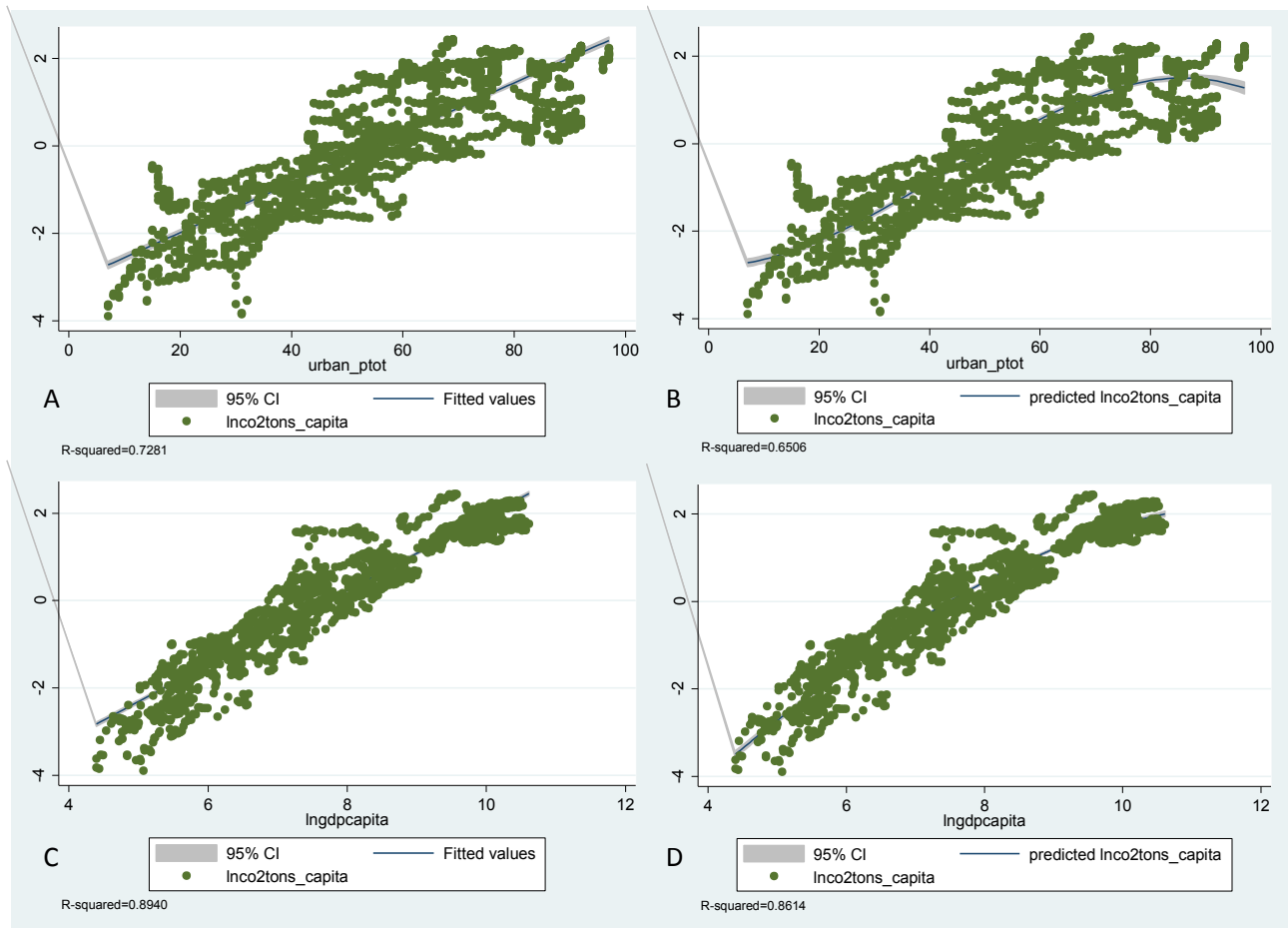


Figure S2. Scatter Plot: *tCo2 Emissions/Capita vs. %Urbanization and lnCO₂ Emissions.* (A) Linear model (emissions and urbanization), (B) Non-linear model with an urbanization² term, (C) Linear model (emissions and income), (D) Non-linear model with an income² term. The linear models are a better fit overall.

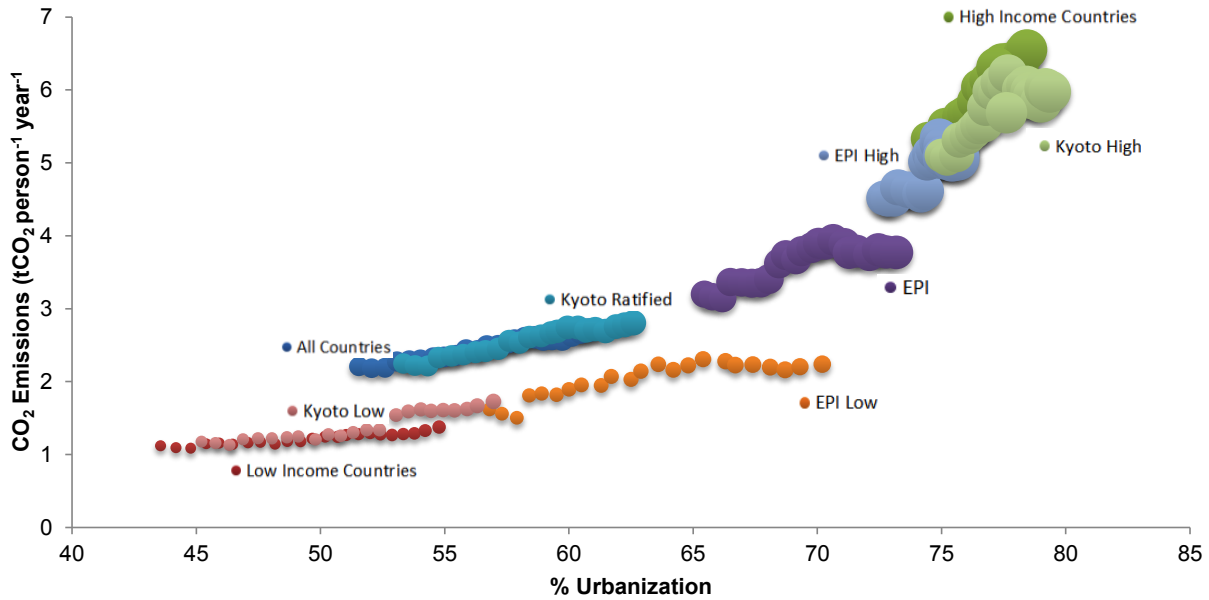


Figure S3. *tCo2 Emissions/Capita vs. %Urbanization.* Each group includes countries such as: *EPI high-income:* Austria, Japan, Norway and Switzerland, *EPI low-income:* Chile, Hungary, Malaysia and Panama, *Kyoto high-income:* Sweden, France, United Kingdom, and Canada, and *Kyoto low-income:* Algeria, Angola, Cameroon, and El Salvador.

* Data for each group is from 1983-2005.

** Bubble size represents per capita income, thus different bubble sizes represent income differences across groups.

Table S4. Regional Results – Fixed Effects

Region ^{1,2}	[A]				[B]				[C]				[D]			
	GLS Linear Model ¹ (95% CI)	Two-Sided P-Value	One-Sided P-Value	Hausman χ^2 (P-Value)	GLS Income ² (95% CI)	Two-Sided P- Value	One-Sided P-Value	Hausman χ^2 (P-Value)	GLS Urbanization ² (95% CI)	Two-Sided P-Value	One-Sided P-Value	Hausman χ^2 (P-Value)	Full Model ¹ (95% CI)	Two-Sided P-Value	One-Sided P-Value	Hausman χ^2 (P-Value)
High Income Europe	-0.0828 (-2.31-2.15)	0.942	0.471	10.50 (0.0623)	0.176 (-2.00 - 2.35)	0.874	0.437	9.82 (0.1324)	-0.196 (-4.13 - 3.74)	0.922	0.461	15.51 (0.030)	0.00296 (-3.84 - 3.84)	0.999	0.500	13.70 (0.090)
Lower Income Europe	0.6877 (-0.236 - 1.60)	0.144	0.072	23.72 (<0.001)	0.744 (-0.164 - 1.65)	0.108	0.054	25.30 (<0.001)	0.759 (0.0515 - 1.46)	0.036	0.018	26.46 (<0.001)	0.796 (0.100 - 1.49)	0.028	0.014	23.08 (0.0015)
USA and Canada	0.959 (-4.14 - 6.06)	0.713	0.357	7.13 (0.2112)	1.31 (-3.71 - 6.33)	0.608	0.304	10.84 (0.0935)	10.48 (-5.91 - 80.11)	0.768	0.384	9.12 (0.2445)	8.50 (-61.1 - 78.2)	0.811	0.406	9.23 (0.3232)
India and the Sub-Continent	3.23 (0.184 - 6.29)	0.038	0.019	16.67 (0.0052)	3.22 (0.221 - 6.23)	0.035	0.018	15.34 (0.0178)	14.5 (-28.3 - 34.2)	0.038	0.019	34.69 (<0.001)	14.7 (-28.2 - 25.8)	0.033	0.017	41.09 (<0.001)
Latin America	1.26 (0.116 - 2.42)	0.031	0.016	14.91 (0.0107)	1.49 (0.394 - 1.83)	0.008	0.004	23.70 (<0.001)	1.58 (0.485 - 2.69)	0.005	0.003	82.64 (<0.001)	1.74 (0.671 - 2.81)	0.001	0.001	78.20 (<0.001)
High Income Asia	0.109 (-5.21 - 5.44)	0.968	0.484	7.67 (0.1754)	0.338 (-4.93 - 5.61)	0.900	0.450	10.43 (0.1079)	-1.09 (-11.9 - 9.81)	0.844	0.422	19.75 (0.0061)	-0.982* (-11.8 - 9.81)	0.859	0.430	15.29 (0.0537)
Lower Income Asia	1.70 (-0.200 - 3.61)	0.080	0.040	12.02 (0.0346)	1.67 (-0.127 - 3.49)	0.068	0.034	15.09 (0.0196)	1.44 (-0.499 - 3.39)	0.192	0.096	22.56 (0.0020)	1.44 (-0.448 - 3.34)	0.381	0.191	15.87 (0.0443)
Africa	0.795 (-0.226 - 1.81)	0.127	0.064	24.72 (<0.001)	0.712 (-0.256 - 1.69)	0.149	0.075	20.55 (0.0022)	0.218 (-1.33 - 0.901)	0.702	0.351	30.14 (<0.001)	0.224 (-1.31 - 0.864)	0.686	0.343	20.94 (<0.001)

[1] A ln(dependent variable) - ln(independent variable) regression produces coefficients that can be understood as elasticities. eg, a 1% increase in agricultural intensity leads to a 0.0675% increase in CO₂ emissions per capita. When the independent variable is a percentage the coefficient has to be multiplied by 100 to obtain the elasticity (urbanization).eg., a 1% increase in urbanization leads to a 0.908% increase in CO₂ emissions per capita.
 [2] According to the World Bank some countries define urbanization based on the size or characteristics of settlements and others base their definition on the presence of certain infrastructure and services. For most countries in the data set 'urban population' is that which is living in 'inner city, inner and outer suburban districts, and inner and outer counties'.
 [3] GLS corrects for heteroskedasticity and autocorrelation in the error terms. A random effects regression regression allows for heterogeneity among nations and is used when there is reason to believe that differences across entities in a panel may have some influence on the dependent variable.
 [4] One sided-tests of statistical significance. H₀ for High Income Countries: coef >= 0. H₀ for Low Income Countries: coef <= 0.
 [5] The full model takes the general model into account in addition to an income nonlinearity (income²) and an urbanization nonlinearity (urbanization²).
 [6] The Hausman test evaluates how parameter estimates differ between a fixed and a random effects approach: the null of the test is that the coefficients estimated by the random effects estimator (more efficient) are the same as the ones estimated by the fixed effects estimator (more consistent). If the difference is statistically significant (p<0.05) then the analysis should be using a fixed effects estimator.

Table S5. Income and Environmental Policy Results – Fixed Effects

Region ^{1,2}	[A]				[B]				[C]				[D]			
	GLS Linear Model ¹ (95% CI)	Two-Sided P-Value	One-Sided P-Value	Hausman χ^2 (P-Value)	GLS Income ² (95% CI)	Two-Sided P- Value	One-Sided P-Value	Hausman χ^2 (P-Value)	GLS Urbanization ² (95% CI)	Two-Sided P-Value	One-Sided P-Value	Hausman χ^2 (P-Value)	Full Model ¹ (95% CI)	Two-Sided P-Value	One-Sided P-Value	Hausman χ^2 (P-Value)
Low, Lower-Middle and Upper-Middle Income	1.05 (0.353 - 1.74)	0.003	0.002	13.84 (0.0167)	1.07 (0.400 - 1.75)	0.002	0.001	7.17 (0.3055)	0.653 (-0.0638 - 1.37)	0.074	0.037	8.25 (0.4288)	0.681 (-0.019 - 1.38)	0.057	0.0285	20.16 (0.0097)
High Income	0.09279 (-1.81 - 1.99)	0.924	0.462	13.84 (0.0167)	0.346 (-1.53 - 2.23)	0.719	0.3595	7.17 (0.3055)	-0.377 (-4.04 - 3.27)	0.839	0.4195	21.32 (0.0033)	-0.192 (-3.77 - 3.39)	0.916	0.458	13.64 (0.0917)
High-Income & High EPI	-1.09 (-4.44 - 2.21)	0.515	0.258	11.00 (0.0514)	-0.949 (-4.25 - 2.35)	0.573	0.2865	8.44 (0.2075)	-0.136 (-7.24 - 6.97)	0.997	0.4985	16.82 (0.0186)	-0.0397 (-7.18 - 7.102)	0.991	0.4955	10.76 (0.2158)
High - Income & Low EPI	0.648 (-1.69 - 2.99)	0.588	0.294	7.44 (0.1902)	0.939 (-1.33 - 3.21)	0.417	0.2085	12.47 (0.0523)	-0.466 (-4.74 - 3.81)	0.831	0.4155	11.94 (0.1026)	-0.248 (-4.36 - 3.87)	0.906	0.453	14.48 (0.0701)
Low-Income & High EPI	0.206 (-1.118 - 1.60)	0.772	0.386	11.87 (0.0365)	0.373 (-0.962 - 1.70)	0.584	0.292	12.50 (0.0517)	0.228 (-1.51 - 1.96)	0.397	0.3985	13.10 (0.0698)	0.337 (-1.35 - 2.02)	0.694	0.347	12.44 (0.1327)
Low - Income & Low EPI	1.29 (0.506 - 2.07)	0.001	0.001	12.78 (0.0256)	1.28 (0.529 - 2.04)	0.001	0.0005	6.25 (0.3957)	0.589 (-0.261 - 1.44)	0.174	0.087	17.00 (0.0174)	0.599 (-0.232 - 1.43)	0.157	0.0785	9.94 (0.2693)
Higher-Income Kyoto	0.0921 (-1.96 - 2.14)	0.930	0.465	11.59 (0.0409)	0.351 (-1.67 - 2.37)	0.733	0.3665	8.24 (0.2209)	-0.457 (-4.18 - 3.26)	0.81	0.405	18.40 (0.0103)	-0.254 (-3.90 - 3.38)	0.887	0.4435	15.18 (0.0558)
Lower-Income Kyoto	1.54 (0.794 - 2.30)	0.001	0.001	150.98 (<0.001)	1.57 (0.852 - 2.29)	0.001	0.0005	261.87 (<0.001)	1.18 (0.411 - 1.94)	0.003	0.0015	22.35 (0.0022)	1.20 (0.451 - 1.94)	0.002	0.001	29.20 (0.0003)
Higher-Income Non-Kyoto	0.0632 (-5.03 - 5.16)	0.981	0.491	56.97 (<0.001)	0.323 (-4.70 - 5.35)	0.900	0.45	19.24 (<0.001)	3.96 (-2.55 - 33.4)	0.792	0.396	9.63 (0.2108)	3.76 (-2.54 - 3.29)	0.801	0.4005	9.94 (0.2695)
Lower-Income Non-Kyoto	-0.619 (-1.95 - 0.716)	0.364	0.182	16.27 (0.0061)	1.57 (0.852 - 2.29)	0.000	0	34.64 (<0.001)	1.18 (0.411 - 1.94)	0.003	0.0015	22.35 (0.0022)	1.02 (0.451 - 1.95)	0.002	0.001	29.20 (0.0003)

[1] A ln(dependent variable) - ln(independent variable) regression produces coefficients that can be understood as elasticities. eg, a 1% increase in agricultural intensity leads to a 0.0675% increase in CO₂ emissions per capita. When the independent variable is a percentage the coefficient has to be multiplied by 100 to obtain the elasticity (urbanization).eg., a 1% increase in urbanization leads to a 0.908% increase in CO₂ emissions per capita.
 [2] According to the World Bank some countries define urbanization based on the size or characteristics of settlements and others base their definition on the presence of certain infrastructure and services. For most countries in the data set 'urban population' is that which is living in 'inner city, inner and outer suburban districts, and inner and outer counties'.
 [3] GLS corrects for heteroskedasticity and autocorrelation in the error terms. A random effects regression regression allows for heterogeneity among nations and is used when there is reason to believe that differences across entities in a panel may have some influence on the dependent variable.
 [4] One sided-tests of statistical significance. H₀ for High Income Countries: coef >= 0. H₀ for Low Income Countries: coef <= 0.
 [5] The full model takes the general model into account in addition to an income nonlinearity (income²) and an urbanization nonlinearity (urbanization²).
 [6] The Hausman test evaluates how parameter estimates differ between a fixed and a random effects approach: the null of the test is that the coefficients estimated by the random effects estimator (more efficient) are the same as the ones estimated by the fixed effects estimator (more consistent). If the difference is statistically significant (p<0.05) then the analysis should be using a fixed effects estimator.

Table S6. Regional Results – Random Effects

Region ^{1,2}	[A]			[B]			[C]			[D]		
	GLS Linear Model ¹ (95% CI)	Two-Sided P-Value	One-Sided P-Value	GLS Income ² (95% CI)	Two-Sided P-Value	One-Sided P-Value	GLS Urbanization ² (95% CI)	Two-Sided P-Value	One-Sided P-Value	Full Model ¹ (95% CI)	Two-Sided P-Value	One-Sided P-Value
All Regions	0.908 (0.514 - 1.27)	≤0.001	≤0.001	0.874 (0.529 - 1.21)	≤0.001	≤0.001	0.546 (0.179 - 0.913)	≤0.001	≤0.001	0.581 (0.226 - 0.937)	≤0.001	≤0.001
High Income Europe	-0.738 (-2.11 - 0.641)	0.294	0.147	-0.202 (-1.54 - 1.13)	0.767	0.384	-1.52 (-5.91 - -0.352)	0.441	0.221	-1.51 (-4.83 - 2.72)	0.584	0.292
Lower Income Europe	0.961 (0.329 - 1.59)	≤0.001	≤0.001	0.967 (0.351 - 1.58)	≤0.001	≤0.001	0.632 (0.211 - 1.05)	≤0.001	≤0.001	0.661 (0.251 - 1.07)	≤0.001	≤0.001
USA and Canada	-1.53 (-5.91 - 2.83)	0.245	0.123	-0.279 (-4.61 - 4.04)	0.249	0.125	-0.206 (-3.99 - 0.2485)	0.447	0.224	-0.7092 (-4.67 - 3.26)	0.247	0.124
India and the Sub-Continent	3.72 (1.48 - 5.92)	≤0.001	≤0.001	2.86 (0.693 - 5.01)	≤0.001	≤0.001	1.04 (-0.456 - 3.59)	0.087	0.043	0.977 (-0.444 - 2.39)	0.089	0.045
Latin America	1.25 (0.638 - 1.87)	≤0.001	≤0.001	1.26 (0.681 - 1.83)	≤0.001	≤0.001	0.819 (0.412 - 1.22)	≤0.001	≤0.001	0.821 (0.429 - 1.21)	≤0.001	≤0.001
High Income Asia	-1.38 (-4.67 - 1.91)	0.206	0.103	-1.21 (-4.27 - 1.87)	0.217	0.108	-3.62 (-5.32 - 0.916)	0.274	0.137	-3.243 (-5.94 - -0.543)	0.106	0.053
Lower Income Asia	0.418 (-0.618 - 1.45)	0.215	0.107	0.993 (0.0347 - 1.94)	0.021	0.011	0.327 (-0.00427 - 0.898)	0.192	0.096	0.108 (-0.589 - 0.807)	0.381	0.191
Africa	1.26 (0.723 - 1.79)	≤0.001	≤0.001	1.05 (0.538 - 1.57)	≤0.001	≤0.001	0.252 (-0.214 - 719)	0.145	0.073	0.275 (-0.173 - 0.724)	0.115	0.058

[1] A ln(dependent variable) - ln(independent variable) regression produces coefficients that can be understood as elasticities. eg., a 1% increase in agricultural intensity leads to a 0.0675% increase in CO₂ emissions per capita. When the independent variable is a percentage the coefficient has to be multiplied by 100 to obtain the elasticity (urbanization) eg., a 1% increase in urbanization leads to a 0.908% increase in CO₂ emissions per capita.

[2] According to the World Bank some countries define urbanization based on the size or characteristics of settlements and others base their definition on the presence of certain infrastructure and services. For most countries in the data set 'urban population' is that which is living in 'inner city, inner and outer suburban districts, and inner and outer counties'.

[3] GLS corrects for heteroskedasticity and autocorrelation in the error terms. A random effects regression regression allows for heterogeneity among nations and is used when there is reason to believe that differences across entities in a panel may have some influence on the dependent variable.

[4] One sided-tests of statistical significance. H₀ for High Income Countries: coef ≥ 0. H₀ for Low Income Countries: coef ≤ 0.

[5] The full model takes the general model into account in addition to an income nonlinearity (income²) and an urbanization nonlinearity (urbanization²).

Table S7. Income and Environmental Policy Results – Random Effects

Region ^{1,2}	[A]			[B]			[C]			[D]		
	GLS Linear Model ¹ (95% CI)	Two-Sided P-Value	One-Sided P-Value	GLS Income ² (95% CI)	Two-Sided P-Value	One-Sided P-Value	GLS Urbanization ² (95% CI)	Two-Sided P-Value	One-Sided P-Value	Full Model ¹ (95% CI)	Two-Sided P-Value	One-Sided P-Value
All Regions	0.908 (0.514 - 1.27)	≤0.001	≤0.001	0.874 (0.529 - 1.21)	≤0.001	≤0.001	0.546 (0.179 - 0.913)	≤0.001	≤0.001	0.581 (0.226 - 0.937)	≤0.001	≤0.001
Low, Lower-Middle and Upper-Middle Income	1.05 (0.682 - 1.42)	≤0.001	≤0.001	0.971 (0.612 - 1.33)	≤0.001	≤0.001	0.539 (0.147 - 0.931)	≤0.001	≤0.001	0.531 (0.147 - 0.916)	≤0.001	≤0.001
High Income	-0.887 (-2.09 - 0.319)	0.150	0.075	-0.311 (-1.50 - 0.882)	0.610	0.305	-0.355 (-0.295 - 0.296)	0.282	0.141	-0.711 (-1.37 - 0.0473)	0.461	0.231
High-Income & High EPI	-1.32 (-2.99 - 0.311)	0.112	0.056	-0.909 (-2.49 - 0.675)	0.260	0.130	-1.13 (-3.32 - 1.06)	0.596	0.298	-0.587 (-2.74 - 1.57)	0.782	0.391
High - Income & Low EPI	-0.666 (-2.61 - 1.28)	0.502	0.251	-0.765 (-2.47 - -0.235)	0.202	0.101	-2.67 (-6.29 - -0.371)	0.195	0.098	-1.76 (-5.31 - 0.182)	0.278	0.139
Low-Income & High EPI	0.0159 (-0.867 - 0.899)	0.972	0.486	0.0361 (-0.812 - 0.935)	0.936	0.468	0.0476 (0.937 - 0.959)	0.470	0.235	0.0738 (-0.891 - 1.79)	0.624	0.312
Low - Income & Low EPI	1.19 (0.803 - 1.58)	≤0.001	≤0.001	1.04 (0.658 - 1.41)	≤0.001	≤0.001	0.625 (0.181 - 1.07)	≤0.001	≤0.001	0.545 (0.116 - 0.974)	≤0.001	≤0.001
Higher-Income Kyoto	-0.851 (-2.12 - 0.422)	0.190	0.095	-0.315 (-1.56 - 0.929)	0.620	0.310	-2.12 (-5.56 - 1.31)	0.226	0.113	-1.57 (-4.97 - 1.82)	0.364	0.182
Lower-Income Kyoto	0.968 (0.562 - 1.37)	≤0.001	≤0.001	0.861 (0.471 - 1.25)	≤0.001	≤0.001	0.382 (-0.0645 - 0.827)	0.094	0.047	0.333 (-0.0981 - 0.765)	0.130	0.065
Higher-Income Non-Kyoto	-1.77 (-6.01 - 2.51)	0.418	0.209	-0.99 (-5.17 - 3.18)	0.640	0.320	-0.854 (-0.0645 - 0.827)	0.949	0.475	-1.01 (-0.0981 - 0.765)	0.939	0.470
Lower-Income Non-Kyoto	1.12 (0.562 - 1.37)	≤0.001	≤0.001	0.871 (0.471 - 1.25)	≤0.001	≤0.001	0.644 (-0.0645 - 0.827)	0.103	0.052	0.727 (-0.0981 - 0.765)	0.103	0.052

[1] A ln(dependent variable) - ln(independent variable) regression produces coefficients that can be understood as elasticities. eg., a 1% increase in agricultural intensity leads to a 0.0675% increase in CO₂ emissions per capita. When the independent variable is a percentage the coefficient has to be multiplied by 100 to obtain the elasticity (urbanization) eg., a 1% increase in urbanization leads to a 0.908% increase in CO₂ emissions per capita.

[2] According to the World Bank some countries define urbanization based on the size or characteristics of settlements and others base their definition on the presence of certain infrastructure and services. For most countries in the data set 'urban population' is that which is living in 'inner city, inner and outer suburban districts, and inner and outer counties'.

[3] GLS corrects for heteroskedasticity and autocorrelation in the error terms. A random effects regression regression allows for heterogeneity among nations and is used when there is reason to believe that differences across entities in a panel may have some influence on the dependent variable.

[4] One sided-tests of statistical significance. H₀ for High Income Countries: coef ≥ 0. H₀ for Low Income Countries: coef ≤ 0.

[5] The full model takes the general model into account in addition to an income nonlinearity (income²) and an urbanization nonlinearity (urbanization²).

Table S8. Equality of Regression Coefficients (P-Value)

	Low, Middle, Upper-Middle Income	High Income	High-Income & High EPI	High - Income & Low EPI	Low-Income & High EPI	Low - Income & Low EPI	High-Income & Kyoto	High-Income & Non Kyoto	Lower-Income & Kyoto	Lower-Income & Non Kyoto
Low, Middle, Upper-Middle Income		≤0.01	≤0.01	0.091	0.035	0.612	≤0.01	0.203	0.761	0.848
High Income	≤0.01		0.666	0.842	0.238	≤0.01	0.982	0.704	≤0.01	≤0.01
High-Income & High EPI	≤0.01	0.666		0.616	0.148	≤0.01	0.652	0.856	≤0.01	≤0.01
High - Income & Low EPI	0.091	0.842	0.616		0.534	0.066	0.881	0.652	0.108	0.088
Low-Income & High EPI	0.035	0.238	0.148	0.534		0.0168	0.261	0.422	0.0541	0.036
Low - Income & Low EPI	0.612	≤0.01	≤0.01	0.066	0.0168		≤0.01	0.196	0.234	0.856
High-Income & Kyoto	≤0.01	0.982	0.652	0.881	0.261	≤0.01		0.666	≤0.01	≤0.01
High-Income & Non Kyoto	0.203	0.704	0.856	0.652	0.422	0.196	0.666		0.214	0.192
Lower-Income & Kyoto	0.761	≤0.01	≤0.01	0.108	0.0541	0.234	≤0.01	0.214		0.681
Lower-Income & Non Kyoto	0.848	≤0.01	≤0.01	0.088	0.036	0.856	≤0.01	0.192	0.681	

Significant at the 1% level, at the 5% level, and at the 10% level.

Two sided P-Values computed from the z-statistic derived from the difference between coefficients and standard errors. The Null Hypothesis is that $B_1 = B_2$ or that $B_1 - B_2 = 0$. Then the z-statistic is $B_1 - B_2 / \sqrt{(STE_1^2 + STE_2^2)}$ and two sided P-Values are estimated from a normal z-table.

Granger Causality Tests

Null Hypothesis: CO₂ Emissions do not Granger Cause Urbanization – We Fail to Reject the Null

Testing Granger Causality of CO₂ Emissions on Urbanization

test L.lnco2tons_capita L2.lnco2tons_capita L3.lnco2tons_capita L4.lnco2tons_capita

- (1) L.lnco2tons_capita = 0
- (2) L2.lnco2tons_capita = 0
- (3) L3.lnco2tons_capita = 0
- (4) L4.lnco2tons_capita = 0

$$F(4, 1622) = 1.24$$

$$\text{Prob} > F = 0.2927$$

Null Hypothesis: CO₂ Emissions do not Granger Energy– We Reject the Null

test L.lnco2tons_capita L2.lnco2tons_capita L3.lnco2tons_capita L4.lnco2tons_capita

- (1) L.lnco2tons_capita = 0
- (2) L2.lnco2tons_capita = 0
- (3) L3.lnco2tons_capita = 0
- (4) L4.lnco2tons_capita = 0

$$F(4, 1622) = 5.24$$

$$\text{Prob} > F = 0.0003$$

List of Countries:

Country (Region; Income Level; Policy Level)

1. Algeria (Africa; Lower Income; Kyoto)
2. Angola (Africa; Lower Income; Kyoto)
3. Argentina (Latin America; Lower Income; Kyoto)
4. Australia (EP Asia; Higher Income)
5. Austria (Europe; Higher Income; EPI & Kyoto)
6. Bangladesh (India & Sub; Lower Income; Kyoto)
7. Belgium (Europe; Higher Income; Kyoto)
8. Belize (Latin America; Lower Income; Kyoto)
9. Benin (Africa; Lower Income; Kyoto)
10. Bolivia (Latin America; Lower Income; Kyoto)
11. Botswana (Africa; Lower Income; Kyoto)
12. Brazil (Latin America; Lower Income; EPI & Kyoto)
13. Bulgaria (Europe; Lower Income; Kyoto)
14. Cameroon (Africa; Lower Income; Kyoto)
15. Canada (USA and Canada; Higher Income; Kyoto)
16. Chile (Latin America; Lower Income; EPI & Kyoto)
17. Colombia (Latin America; Lower Income; EPI & Kyoto)
18. Congo (Africa; Lower Income)
19. Costa Rica (Latin America; Lower Income; EPI & Kyoto)
20. Cyprus (Europe; Higher Income; Kyoto)
21. Denmark (Europe; Higher Income; EPI & Kyoto)
22. Dominican Republic (Latin America; Lower Income; EPI & Kyoto)
23. DR Congo (Africa; Lower Income)
24. Ecuador (Latin America; Lower Income; EPI & Kyoto)
25. Egypt (Africa; Lower Income)
26. El Salvador (Latin America; Lower Income; Kyoto)
27. Ethiopia (Africa; Lower Income)
28. Finland (Europe; Higher Income; EPI & Kyoto)
29. France (Europe; Higher Income; Kyoto)
30. Gabon (Africa; Lower Income)
31. Germany (Europe; Higher Income; EPI & Kyoto)
32. Ghana (Africa; Lower Income; Kyoto)
33. Greece (Europe; Lower Income; Kyoto)
34. Guatemala (Latin America; Lower Income; Kyoto)
35. Honduras (Latin America; Lower Income; Kyoto)
36. Hungary (Europe; Lower Income; EPI & Kyoto)
37. Iceland (Europe; Higher Income; Kyoto)
38. India (India & Sub; Lower Income; Kyoto)
39. Indonesia (EP Asia; Lower Income; Kyoto)
40. Italy (Europe; Higher Income; EPI & Kyoto)
41. Ivory Coast (Africa; Lower Income)
42. Japan (EP Asia; Higher Income; EPI & Kyoto)
43. Kenya (Africa; Lower Income)
44. Libya (Africa; Lower Income)
45. Luxembourg (Europe; Higher Income; Kyoto)
46. Malaysia (EP Asia; Lower Income; EPI & Kyoto)
47. Mexico (Latin America; Lower Income; Kyoto)
48. Morocco (Africa; Lower Income; Kyoto)
49. Mozambique (Africa; Lower Income)
50. Nepal (India & Sub; Lower Income)
51. Netherlands (Europe; Higher Income; Kyoto)
52. New Zealand (EP Asia; Higher Income; EPI & Kyoto)
53. Nicaragua (Latin America; Lower Income; Kyoto)
54. Nigeria (Africa; Lower Income; Kyoto)
55. Norway (Europe; Higher Income; EPI & Kyoto)
56. Pakistan (India & Sub; Lower Income)
57. Panama (Latin America; Lower Income; EPI & Kyoto)
58. Paraguay (Latin America; Lower Income; Kyoto)
59. Peru (Latin America; Lower Income; Kyoto)
60. Poland (Europe; Lower Income; Kyoto)
61. Portugal (Europe; Lower Income; EPI & Kyoto)
62. Romania (Europe; Lower Income; Kyoto)
63. Senegal (Africa; Lower Income; Kyoto)
64. South Africa (Africa; Lower Income; Kyoto)
65. Spain (Europe; Lower Income; EPI & Kyoto)
66. Sri Lanka (India & Sub; Lower Income; Kyoto)
67. Sudan (Africa; Lower Income; Kyoto)
68. Sweden (Europe; Higher Income; EPI & Kyoto)
69. Switzerland (Europe; Higher Income; EPI & Kyoto)
70. Tanzania (Africa; Lower Income; Kyoto)
71. Togo (Africa; Lower Income; Kyoto)
72. Tunisia (Africa; Lower Income; Kyoto)
73. Turkey (Europe; Lower Income)
74. United Kingdom (Europe; Higher Income; EPI & Kyoto)
75. Uruguay (Latin America; Lower Income; Kyoto)
76. USA (USA and Canada; Higher Income)
77. Vietnam (EP Asia; Lower Income; Kyoto)
78. Venezuela (Latin America; Lower Income)
79. Zambia (Africa; Lower Income)
80. Zimbabwe (Africa; Lower Income)