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Carbon dioxide emissions in the short run: The rate and sources of economic growth matter

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Keywords

Economic growth, emissions, pollution, business cycle, asymmetry, sector

JEL Classification

Q56, O44, E32

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Carbon dioxide emissions in the short run: The rate and sources of economic growth matter

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Abstract
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1. Introduction

There has been recent discussion on the effects of the business cycle on carbon dioxide (CO_2) emissions and specifically on whether the elasticity of emissions with respect to income (the "emissions-income elasticity" – the percentage change in emissions for a 1% increase in income) differs at times of economic growth and contraction (Bowen and Stern, 2010; Peters et al., 2012; Jotzo et al., 2012; York, 2012; Heutel, 2012; Doda 2013, 2014; Sheldon, 2015). But the impact of economic growth on emissions in a given country may vary not only depending on where in the business cycle the country is, but also on the source of economic growth and the characteristics of the country. In this paper, we explore how CO_2 emissions from the combustion of fossil fuels and the manufacture of cement are influenced by the rate and sources of economic growth a country is experiencing, with a focus on short-run dynamics.

Figure 1 plots annual growth in CO_2 emissions against annual growth in gross domestic product (GDP) for our large estimation sample (189 countries, 1961–2010). We make two observations. First, a positive association exists: years of faster economic growth tend to see quicker growth in emissions (in both OECD and non-OECD countries). Second, there is substantial dispersion around the trend, especially for non-OECD countries, indicating that factors other than contemporaneous GDP growth are important in explaining annual emissions growth rates. It may also be that the effect of GDP growth on CO_2 emissions depends on the characteristics of the GDP growth, such as its sectoral composition.

Figure 2 shows the annual growth rates of global CO_2 emissions and gross world product (GWP) over our study period. Short-run fluctuations in CO_2 emissions are clearly linked to the global business cycle. The global CO_2 emissions growth rate is normally less than the GWP growth rate, reflecting reductions in the carbon intensity of GWP over time.

In this paper, we first investigate if the emissions-income elasticity is similar during economic expansions and contractions. York (2012) argued that this elasticity is likely to be lower during contractions, as reductions in the use of durable assets (e.g. factories, cars) accumulated in booms might be relatively slight in contractions.

We next test for lagged effects of economic growth on emissions growth. Lagged effects might be expected because the emissions implications of investment projects or durable assets may take time to be fully realized. For example, coal-fired power plants ordered during a boom may not noticeably add to emissions until they come on-line in a subsequent year. Similarly, a vehicle purchased in the December of a boom year (for example) would not add much to road-sector emissions until the next calendar year. Conversely, recovery from recessions might be low-emission in nature as capital is reemployed rather than built from scratch.[1] Delayed effects of GDP growth on emissions could also emerge as a result of labor employment being a "lagging indicator" of the business cycle (Schwartz, 2012). Kayser (2000) and Dargay and Hanley (2007), for instance, report that unemployment is associated with reduced car ownership and gasoline use. If employment lags GDP growth, this might contribute to emissions growth lagging GDP growth also.

We then explore whether the emissions-income elasticity varies by the source of GDP growth. Because industrial activities are usually thought to be relatively energy- and emissions-intensive, we hypothesize that national CO_2 emissions are particularly sensitive to changes in industrial value-added. On the expenditure side, we then test whether growth in household consumption, investment, government consumption, exports, and imports have different emissions implications. We do not have a strong *a priori* hypothesis on the relative magnitudes of the emissions impacts of changes in consumption and investment, noting that each likely involves a mix of high- and low-emission activities. For example, consumption includes expenditure on transport and industrial products, but also some low-emission services such as haircuts; investment includes expenditure on construction – which may in some settings be energy and emissions intensive – but may also involve the adoption of some emissions-reducing technologies.

The growing importance of emissions embodied in international trade has attracted attention (e.g. Peters et al., 2011; Kander et al., in press). Because exports are skewed towards industrial goods,[2] shocks to an economy that are transmitted from the economies of its export partners may have relatively large implications for domestic emissions. To test for this, we

[1] A countervailing force could be faster adoption of emissions-reducing technology during periods of faster economic growth, which would exert some downward pressure on emissions growth during and perhaps after booms (vis-à-vis recessions). Our estimations do not provide specific evidence in favor of this possibility.
[2] 55% of global exports of goods and services in 2010 were manufactured goods. Another 15% were fuels, ores, and metals (World Bank, 2014).

estimate a model in which changes in the GDP growth rates of a country's export partners affect GDP, which in turn affects emissions.

Finally, we test whether the short-run emissions-income elasticity is affected by a country's per-capita GDP level or its fossil fuel endowments, and whether the elasticity has changed over time. Identifying causes of heterogeneity in the effects of economic growth will allow us to better understand how any particular country's emissions are likely to evolve as its economy grows. We also decompose the short-run effects of economic growth on CO_2 emissions into separate effects on energy use and the carbon intensity of energy.

Because climate change is a function of the stock of greenhouse gases in the atmosphere rather than the flow, knowledge of the short-run drivers of CO_2 emissions might be thought to be of second-order importance from an environmental point of view. But we must move through the short run to reach the long run, and as we will show, recessions or booms can have implications for a country's emissions growth rates for some years. Short-run relationships are also important for policy. Our estimates can serve as inputs, for example, in (a) assessing the implications of various economic growth scenarios for a country's ability to meet an emissions target; (b) estimating how permit prices in an emissions trading scheme (ETS) might be affected by an uptick in economic growth (or a recession); or (c) calculating how government revenue from an emissions price is likely to be affected by changing economic circumstances. Our estimates should also be of use in informing parameter choices in models of economy-emissions links, as well as in calibrating emissions intensity targets against absolute emissions targets (as the strength of an emissions intensity target depends on how emissions should be expected to evolve as GDP expands; Jotzo and Pezzey, 2007).

Existing evidence on how the emissions-income elasticity varies with the business cycle is not conclusive. York (2012) reports that the emissions-income elasticity is higher during individual years of economic expansion than during individual years of economic contraction, but both Doda (2013) and Sheldon (2015) challenge York's (2012) findings. Doda finds extreme heterogeneity across countries and Sheldon finds that the elasticity is in fact greater in recessions than in booms for the United States and the majority of other large emitters, although estimating single-country time-series models with small samples can result in biased and implausible estimates. Our results show that asymmetry in the emissions-income elasticity is not statistically robust unless changes over several years are considered.

Other studies have examined various aspects of the short-run emissions-income relationship. Jakob et al. (2012) estimate five-year differenced regressions, reporting that the emissions-income elasticity is lower in Organization for Economic Co-operation and Development (OECD) countries, a finding also not supported by our data (which cover a more comprehensive sample). Peters et al. (2012) argue that, with the exception of the recent global financial crisis (GFC), global economic slowdowns typically result in permanent reductions in CO_2 emissions so that global emissions recommence growth after the recession on a new lower trend line. Heutel (2012) reports that the short-run emissions-income elasticity is less than unity in the United States, and Doda (2014) uses data for 122 countries to show that emissions are generally pro-cyclical. Narayan and Narayan (2010) estimate error-correction models for 43 developing countries, finding considerable variation in the average short-run CO_2 emissions-income elasticity across regions: 0.6 for Middle Eastern countries, 0.9 for South Asia, 0.7 for Latin America, 0.7 for East Asia, and 0.0 for Africa. Jaunky (2011) extended the analysis to 36 high-income countries, reporting an average short-run emissions-income elasticity of 0.7 and substantial variation across countries. There are many studies using Granger causality tests for individual countries, with, for example, Zhang and Cheng (2009) finding Granger causality from GDP to energy use and from energy use to CO_2 emissions in China. But this literature does not assess whether there are systematic differences in the emissions implications of different sources of economic growth or in countries with different characteristics. To our knowledge, ours is the most comprehensive study to date in terms of both country coverage and our focus on various dimensions of the short-run emissions-income relationship.

The current paper also relates to the large body of work on the long-run relationship between GDP and national CO_2 emissions. Emissions are a byproduct of economic activity, and this prior work suggests that increasing GDP is generally associated with increasing CO_2 emissions. While some high-income countries have achieved reductions in CO_2 emissions for reasons such as shifts to nuclear and renewable energy (Burke, 2012a; Liao and Cao, 2013), there is no evidence of a common per capita GDP level after which per capita CO_2 emissions decline (Dijkgraaf and Vollebergh 2005; Wagner, 2008; Galeotti et al., 2009; Vollebergh et al., 2009; Stern, 2010; Steinberger et al., 2013; Anjum et al., 2014). Our estimates provide evidence in favor of declining emissions growth rates as per capita GDP increases, but reveal that emissions continue to be influenced by the short-run business cycle.

The paper proceeds as follows. Section 2 presents our method and discusses the data. Section 3 documents our results. The final section discusses our findings.

2. Methods

2.1. Basic specification

We are interested in measuring the average effect of growth in GDP (Y) on growth in CO_2 emissions (C). Our basic estimation equation is:

$$\Delta lnC_{i,t} = \alpha \Delta lnY_{i,t} + \beta_i + \beta_t + \varepsilon_{i,t} \qquad (1)$$

where Δ is the first difference operator, the βs are country (i) and year (t) fixed effects, and ε is an error term. It is important to include country fixed effects as there may be time-invariant factors such as geography, endowments, and initial institutions that influence the trajectories of both emissions and GDP. Year fixed effects remove the influence of common global variables such as world energy prices. Subtracting $\Delta \ln Y_{i,t}$ from both sides of Eq. (1) shows that the same-year effect of a 1% increase in GDP on the carbon intensity of GDP is given by (α-1)%.

Eq. (1) assumes that log CO_2 emissions follow a unit root process, so that shocks have a permanent effect on CO_2 emissions levels. This follows recent work by Barros et al. (in press) who find that CO_2 emissions data are indeed highly persistent.

We do not control for industry or energy-sector variables as the effect of GDP growth on CO_2 emissions growth may partly operate *through* such variables. For instance, GDP growth may affect the size of the manufacturing sector or the demand for coal, which in turn would have implications for emissions. It would be inappropriate to control for the size of the manufacturing sector or the use of coal as we would be attenuating the coefficient for GDP growth. Results tables will show standard errors that are robust to heteroskedasticity and clustered by country to allow for possible country-by-country patterns of autocorrelation.

2.2. Additional specifications

The first of our additional specifications is a check for asymmetric effects of positive and negative GDP growth, as reported by York (2012). We estimate:

$$\Delta lnC_{i,t} = \alpha_0 \Delta lnY^{+}_{i,t} + \alpha_1 \Delta lnY^{-}_{i,t} + \beta_i + \beta_t + \varepsilon_{i,t} \qquad (2)$$

where the "+" variable equals GDP growth when GDP growth exceeds zero, and zero otherwise. The "–" variable equals GDP growth when GDP growth is less than zero, and zero otherwise. We also estimate Eq. (2) for two-, three-, four-, and five-yearly panels to investigate potential asymmetric effects over longer periods.

To investigate the effect of GDP growth on emissions in subsequent years, we add lags of GDP growth to Eq. (1) as follows:

$$\Delta lnC_{i,t} = \alpha_j \sum_{j=0}^{5} \Delta lnY_{i,t-j} + \beta_i + \beta_t + \varepsilon_{i,t} \qquad (3)$$

Summing *T* of the α coefficients from estimates of Eq. (3) provides an estimate of the *T*-year emissions-income elasticity (for example, the two-year elasticity is approximately $\alpha_0 + \alpha_1$). In addition, we estimate specifications with year-*t*-1 "boom" and "recession" dummies, where the boom dummy equals 1 if the first difference of log GDP exceeds +0.05 (0 otherwise) and the recession dummy equals 1 if annual GDP contracts (0 otherwise). We obtain similar results using an alternative cut-off for the boom dummy (e.g. +0.03 or +0.07).

To explore the channels through which the short-run emissions-income relationship operates, we separately estimate GDP growth effects on the (a) energy use growth rate and (b) growth rate of the carbon intensity of energy. In a further step we also explore the short-run effect of GDP growth on different sub-categories of energy use (e.g. energy used by industry; by road transport; and by households).

To test whether the sectoral composition of economic growth is of consequence for national CO_2 emissions, we divide total value added (*V*) into four constant-price components: real value added in agriculture (*A*), manufacturing (*F*), other industry (*D*), and services (*S*):

$$V = A + F + D + S \qquad (4)$$

Differentiating Eq. (4) with respect to time (*t*), dividing by *V*, and denoting d*x*/d*t* by a dot over variable *x*, we have:

$$\frac{\dot{V}}{V} = \frac{A}{V}\frac{\dot{A}}{A} + \frac{F}{V}\frac{\dot{F}}{F} + \frac{D}{V}\frac{\dot{D}}{D} + \frac{S}{V}\frac{\dot{S}}{S} \qquad (5)$$

Eq. (5) states that the growth rate of total value added equals the weighted average of the sectoral value-added growth rates. We use $\dot{x}/x \cong \Delta lnx$ and then estimate a form of Eq. (1) in which $\Delta\, lnY$ has been replaced by the right-hand side of Eq. (5), noting that ΔlnV and ΔlnY are generally similar, as GDP is value added "plus any product taxes and minus any subsidies not included in the value of products" (World Bank, 2014). Because the right-hand-side terms in Eq. (5) are additive, each represents an equivalent increment to value added growth, meaning that the regression coefficients for each of the terms can be directly compared. The weights we use are the share of each sector in national real value-added in year *t*-1, although we obtain similar results using time-invariant sectoral weights for each country.

We also carry out a similar exercise along the expenditure (*E*) dimension to examine whether emissions growth is affected differently by real growth in household consumption (*C*), investment (*I*), government consumption (*G*), exports (*X*), and imports (*M*). The national accounting identity is:

$$E = C + I + G + X - M \tag{6}$$

Differentiating Eq. (6) with respect to *t* and dividing by *E*, we have:

$$\frac{\dot{E}}{E} = \frac{C}{E}\frac{\dot{C}}{C} + \frac{I}{E}\frac{\dot{I}}{I} + \frac{G}{E}\frac{\dot{G}}{G} + \frac{X}{E}\frac{\dot{X}}{X} - \frac{M}{E}\frac{\dot{M}}{M} \tag{7}$$

Eq. (7) shows that the expenditure growth rate equals the weighted average of the growth rates of each of the expenditure items of the national accounting identity. We estimate a version of Eq. (1) in which $\Delta\, lnY$ is replaced with the right-hand side of Eq. (7), weighting each growth term with the share of that expenditure item in total constant-price expenditure in year *t*-1. Because the right-hand side terms are again additive, their regression coefficients can be directly compared.

The emissions implications of external economic shocks may differ from the emissions implications of domestically-caused GDP fluctuations. This is a broader exercise to the analysis of the emissions implications of exports, as external shocks may affect other expenditure categories (e.g. investment) in addition to affecting exports. To explore this possibility we constructed an export-partner GDP growth variable similar to that used by Burke (2012b), employing year-1995 export-partner weights (based on exports of goods). We interact this variable with the year-1995 share of all exports in GDP to allow the effect of external shocks to GDP to be larger for more open economies. This interacted term is then used as an instrumental variable (IV) for each country's GDP growth rate.[3] Our IV approach allows for a consistent local-average-treatment-effect estimate of the impact of external economic shocks to a country's GDP on that country's CO_2 emissions. As far as we are aware, these estimates provide the first evidence on the emissions implications of plausibly exogenous external shocks to GDP.

One line of inquiry that we do not pursue, but that may warrant consideration, is the separate identification of the emissions implications of permanent and transitory shocks to GDP (e.g. Narayan et al., 2011; Sbrana, 2013).

2.3. Data

Our main estimates use data on CO_2 emissions and GDP from the World Bank (2014). The emissions data, collated by the Carbon Dioxide Information Analysis Center (CDIAC), cover CO_2 emissions from fossil fuel combustion and cement production. They exclude other emissions such as from land use change and forestry, and follow production- rather than consumption-based emissions accounting. The GDP data are in constant 2005 US dollars.[4] We also use data on energy use and energy-sector CO_2 emissions from the International Energy Agency (IEA, 2014a, 2014b). Other data sources include Norman (2009) and the International Monetary Fund (IMF, 2009). A full list of variable definitions and sources is in Appendix A.

Our main estimation sample covers 6,956 country-year observations from 189 countries over the 50 years 1961–2010. The panel is unbalanced, with each country appearing for an average of 37 years and only 79 countries appearing for the full 50 years. The 189 countries accounted for 98% of the global population in 2010. The most populous countries not in our

[3] The method of instrumental variables, widely used in econometrics, can compactly test the effect of an exogenous explanatory variable on the dependent variable through its effects on one of the explanatory variables included in the regression. The method can be interpreted as a two-stage regression. In the first stage we use the (interacted) export-partner GDP growth variable to predict each country's GDP growth and in the second stage – the reported results – we examine the implications of this predicted GDP growth for emissions. In practice, the IV method combines these two stages in a single formula.

[4] We use the World Bank's market exchange rate GDP series. The World Bank also provides a purchasing power parity (PPP)-adjusted GDP series, but only for 1990 onwards. The two series are both constructed using the growth rates of real GDP from each country's national accounts, meaning that they provide identical year-to-year variation in our differenced log regression model.

sample are Myanmar (52 million people in 2010) and the Democratic Republic of Korea (25 million), both due to missing GDP data. Estimates using IEA emissions/energy data cover a smaller sample of countries (134) but extend to year 2012. 2010 is the most recent year for which the CDIAC CO_2 emissions data are currently available. Missing observations for some additional variables (e.g. real value-added by sector) reduce some of our samples.

While there are uncertainties in both the emissions data and the GDP data, we obtain similar estimates of the same-year emissions-income elasticity using either the World Bank or the IEA emissions data and an identical estimate (to two decimal places) using GDP data from the Penn World Table (Feenstra et al., 2013). We also obtain a similar same-year emissions-income elasticity using GDP data in PPP terms from the Conference Board (2014) for the sub-sample of country-years covered by those data.

3. Results

3.1. Basic elasticity and testing for asymmetry

Table 1 presents our initial estimates of Eqs. (1) and (2), with Columns 1–2 using yearly data. The estimate in Column 1 suggests a same-year emissions-income elasticity of 0.5. The estimate is quite precise, and significantly different from both 0 and 1 at the 1% level. This means that the same-year emissions-income response is inelastic, and that a 1% increase in GDP is on average associated with a same-year decline in the carbon intensity of GDP of 0.5% (=0.5-1). Column 2 splits GDP growth into separate positive and negative terms (Eq. 2). Similar coefficients are obtained for each (0.5, to one decimal place) and a t-test cannot reject the null that the effects are the same.[5] This result differs from York's (2012) evidence that the same-year emissions-income elasticity is higher during years of economic expansion. Appendix B provides a reconciliation, showing that obtaining significantly-different coefficients for the two growth terms relies on both (a) using standard errors that are not robust to heteroskedasticity, *and* (b) excluding small countries from the estimation sample.[6]

[5] An alternative approach is to split GDP growth in each country into separate terms for when (a) GDP growth exceeds the t-5 to t-1 average rate for that country and (b) GDP growth is less than or equal to the t-5 to t-1 average rate for that country. Using this approach we also obtain similar coefficients for periods of high and low GDP growth (0.55***, 0.53***), again providing no evidence of same-year asymmetry.

[6] Our specifications also differ from York's main estimates in that we (a) include country and year fixed effects; (b) use aggregate rather than per-capita CO_2 and GDP; and (c) use ordinary least-squares rather than generalized least-squares. Appendix B shows, however, that either the use of

Columns 3–10 of Table 1 use differenced-log specifications based on two-, three-, four-, and five-yearly samples to test whether asymmetry is any stronger over longer intervals. We obtain slightly larger (0.6–0.7) same-period emissions-income elasticities, as expected (as longer time intervals allow more time to response). Tests of the equality of the coefficients provide statistically significant evidence that the emissions-income elasticity in periods of expansion differs from the emissions-income elasticity during recessions only in the four- and five-yearly differenced estimations (Columns 8 and 10). Column 10 suggests that the elasticity is 0.7 in (five-yearly) periods of expansion and 0.4 in (five-yearly) periods of contraction.

We thus conclude that while statistical support for York's conclusion of asymmetry in the same-year emissions-income elasticity is not strong, there is support for York's conclusion when longer-term average behavior is taken into account. The estimates in Columns 8 and 10 of Table 1 are similar if we control for lags of GDP growth, suggesting that lagged effects and contemporaneous asymmetry in the emissions-income relationship are different processes.

3.2. Effects with a lag

We now examine the dynamics of the short-run emissions-income relationship. Table 2 presents results for Eq. (3), i.e. with lags of the GDP growth term to year *t*-5. These provide a point estimate of the 6-year emissions-income elasticity of 0.8, with the difference between the 6-year and same-year elasticities significant at the 1% level. In unreported specifications with additional yearly lags we obtain a 10-year emissions-income elasticity of 1.0 and a 14-year elasticity of 0.8. Our results thus suggest that GDP growth affects emissions not only in the same year, but also in subsequent years, with around 40% (=0.3/0.8) of the effect of GDP growth on CO_2 emissions realized with a lag. Columns 7–9 include the boom and recession dummies for year *t*-1. Consistent with the earlier Columns, the estimates suggest that emissions growth is quicker following a boom and slower following a recession (holding current-year GDP growth fixed). The magnitudes in Column 9 suggest these effects are equal to around one percentage point of current-year emissions growth, which is reasonably large.

standard errors that are robust to heteroskedasticity *or* estimation on a full sample is enough to remove a significant difference between the effects of the two growth terms. See also Doda (2013).

Figure 3 presents the coefficients for the year effects from Column 6 of Table 2. These are large and positive for the late 1960s and early 1970s, and generally smaller subsequent to the first global oil price shock in 1973. The average year effect for the period 1971–2010 is close to zero, consonant with the average year effect for this period reported by Anjum et al. (2014). We present some further discussion of year effects in section 4, but leave a comprehensive examination of how year effects are affected by global energy prices and the global business cycle to future researchers.

3.3. Separate effects for energy and the carbon intensity of energy

To examine the channels via which the short-run effect of GDP growth on CO_2 emissions operates, Table 3 presents separate estimates for the effect of GDP growth on growth in both energy use and the carbon intensity of energy. For consistency with the source of our energy data we switch to CO_2 emissions data from the IEA (2014a). The sum of coefficients for any individual variable in regressions for the two new dependent variables will equal the corresponding coefficient in the CO_2 emissions regression.

The same-year emissions-income elasticity of 0.6 estimated using the IEA data can be separated into two parts: an energy-income elasticity of 0.4 and a carbon intensity of energy-income elasticity of 0.2. Both are significantly different from zero at the 1% level. The energy effect is straightforward to understand: economic growth is associated with increased use of energy. The (smaller) carbon intensity of energy effect emerges because many economies have adopted more carbon-intensive energy sources (coal, oil, natural gas) as their economies have grown and they climb what has been called the "national-level energy ladder" (Burke, 2010, 2013). These elasticities are illustrated in Figure 4.

Table 3's one-year lagged effects of GDP growth are also positive and significant in the energy use and CO_2/energy equations, with three-quarters (0.155/0.206) of the next-year effect of GDP growth on CO_2 emissions resulting from the next-year effect of GDP growth on energy use. The next-year effect of booms appears to operate only via energy use (rather than via the carbon intensity of energy).

What types of energy use are most sensitive to changes in GDP? Table 4 presents results that consider five energy sub-categories: energy use by industry; energy use by road transport; energy use by other forms of transport; residential energy use; and an "other" category that mainly represents energy used by the services and other sectors and energy lost in transformation processes such as electricity generation. We expected that residential energy use would be the least sensitive to GDP fluctuations, as heating, cooling, and other household energy requirements are probably relatively resilient. We expected industrial energy use to be particularly sensitive. The results in Table 4 confirm these expectations, with the mean same-year income elasticities equaling 0.1 for residential energy use and 0.7 for industrial energy use. Road transport energy use also has a relatively high same-year income elasticity.

The Table 4 results also show that delayed effects of GDP growth are particularly noticeable in the road transport sector: growth in road transport energy consumption is typically 1.4 percentage points higher in the year after a boom and 2.5 percentage points lower in the year after a recession (after accounting for the effect of current GDP growth). For industrial and residential energy use, lagged effects are smaller in magnitude and statistically insignificant.

3.4. Sectoral, expenditure-item, and external effects

Column 1 of Table 5 examines if the sectoral composition of GDP growth affects national CO_2 emissions. As discussed, our sectoral value-added growth rates have been scaled by the size of each sector in total value-added, so the regression coefficients are the effects of comparable changes in a country's economy. The point estimates of the same-year (national) emissions-income elasticity are 0.8 for the manufacturing sector and for other industry (which includes mining, construction, electricity, water, and gas), 0.5 for the services sector, and 0.2 for agriculture. That the elasticity is particularly high for manufacturing and other industry is intuitive, as these sectors are generally energy- and emissions-intensive. The services sector includes transport, which means that the elasticity for services value-added is probably not as low as it would otherwise be. The elasticity for agricultural value-added is low (0.2) and not significantly different from zero, although it is important to bear in mind that the regressions use data for CO_2 emissions from fossil fuel combustion and cement production only.

The estimates of the same-year effects of sectoral value-added on national emissions are less precise than our earlier elasticity estimates, as can be seen by the larger standard errors. We can only reject the (separate) null hypotheses that the elasticities for manufacturing, other industry, and services equal the elasticity for agriculture at significance levels of 9–13%. Nevertheless, the estimates suggest that industrialization (shifting from agriculture to industry) is typically emissions intensive, whereas a move from industry to services is a chance to reduce an economy's emissions intensity. The implied same-year emissions-income elasticity for a country in which half of the expansion in real GDP occurs in industry, half is in services, and there is no change in agricultural output is 0.65 (=[0.8+0.5]/2).

Column 2 of Table 5 examines the emissions effects of growth in each of the five terms of the national accounting identity. For some countries there are discrepancies between the expenditure data and the GDP data (World Bank, 2014).[7] We restrict our sample to observations for which the discrepancy between E and Y is less than 5% of Y. The coefficients for the household consumption, investment, and government consumption terms are similar to one another (0.4–0.5), suggestive of there being no major differences in their average emissions implications.

The coefficient for exports growth in Column 2 of Table 5 is fairly small (0.3) and is similar in absolute value to the coefficient for imports. These coefficients suggest that (a) for countries maintaining roughly constant trade deficits or surpluses, short-run changes in trade exposure ($[X+M]/Y$) do not have substantial emissions implications; and (b) a mercantilist policy of increasing exports and reducing imports would, quite naturally, place upward pressure on domestic emissions (other things equal). We do not use the relatively small coefficient for exports growth to conclude that international trade is relatively low-emission in nature, as some countries (e.g. Singapore) have sizeable entrepôt trade (import then re-export), and re-exports should have few domestic emissions implications. The estimate in Column 3 of Table 5 restricts the sample to country-years in which t-1 exports were less than 40% of GDP. As expected, we find a larger coefficient (0.6) for the exports growth term.

Columns 4–5 of Table 5 use export-partner GDP growth as an instrumental variable for the GDP growth rate. Column 4 shows that shocks from export partners have a particularly large effect on emissions, with a same-year emissions-income elasticity of 0.9. Export-partner GDP growth may not be fully exogenous for large economies such as the United States, but we obtain a similar result (0.8) in Column 5 excluding the 20 largest economies in 1995 – accounting for 85% of GWP in that year – from our sample. GDP fluctuations flowing from changes in export-partner GDP growth rates thus appear to have a large same-year effect on

[7] See "Limitations and exceptions" in the World Bank (2014) variable definitions.

emissions, although unreported statistical tests cannot confirm that this exceeds the mean overall effect. Because our IV estimates use plausibly exogenous fluctuations in GDP growth, they also confirm that economic growth has a causal effect on emissions.

The point estimates and 95% confidence intervals for the same-year emissions-income elasticity and the sectoral and external effects are illustrated in Figure 5. While the confidence intervals are overlapping, the magnitudes of the point estimates are intuitive and, as noted, we can conclude that growth in agricultural value-added has a different same-year effect on national CO_2 emissions than growth in the value-added of the other sectors if we use p-values of up to 0.13. That the point estimate of the same-year emissions-income elasticity of shocks from export partner economies is relatively large makes sense as, as noted, export partner shocks might disproportionately affect emissions-intensive parts of the economy (e.g. production of industrial goods for export).

3.5. Testing for heterogeneity

Table 6 presents specifications that explore if the same-year emissions-income relationship is affected by each country's development level or fossil fuel endowments, and if it has changed over time. Unlike our previous estimates, Columns 1–2 exclude country fixed effects to use both between and within variation in each country's GDP per capita. These suggest that higher GDP per capita (measured using market exchange rates) is associated with lower emissions growth rates (significant at 1%), but do not suggest that a country's GDP per capita significantly influences the same-year emissions-income elasticity. Similar results are obtained in Columns 3–4 with country fixed effects, although the lagged log GDP per capita terms are no longer statistically significant. Column 5 uses a dummy for country-years with above-median GDP per capita (in t-1), finding a significant and negative coefficient for the higher-income dummy but not the interaction. The estimate implies that countries with an above-median GDP per capita have annual CO_2 emissions growth rates around 2 percentage points lower (holding the current GDP growth rate and country and year effects constant). This effect is similar (1.5 percentage points, significant at the 5% level) if country fixed effects are excluded (estimate not shown).[8]

[8] In unreported specifications using GDP per capita data in PPP terms from Feenstra et al. (2013) we find a positive and statistically-significant coefficient for the interaction terms in Columns 2 and 4 of Table 6, although not for the interaction term in Column 5. The Column 4 result using the Feenstra et al. data implies that the same-year emissions-income elasticity is larger in higher-income countries

In sum, emissions trajectories tend to be flatter (and potentially downward-sloping) in higher-income countries, consistent with a degree of (long-run) decoupling of emissions from income. But we find no evidence of decoupling in the short run; the emissions of high-income countries still fluctuate pro-cyclically.

Column 6 of Table 6 interacts year-*t* GDP growth with a dummy for fossil fuel-rich countries, defined using year-1971 reserves estimates constructed by Norman (2009). Our expectation was that the same-year emissions-income elasticity is larger in countries with more abundant fossil fuel reserves, as prior work has shown that the longer-run economic growth trajectories of these countries tend to be more emissions-intensive (Neumayer 2002; Burke, 2012a, 2013; Stern, 2012; Anjum et al., 2014). The estimate confirms this: the average same-year emissions-income elasticity is only 0.3 for countries with below-median fossil fuel reserves, and 0.6 for countries with above-median reserves. Column 7 interacts GDP growth with a time trend. The insignificant coefficient suggests that the same-year emissions-income elasticity has not displayed significant linear change over time.

For further evidence on potential heterogeneity, Table 7 splits our sample into OECD members and non-OECD members. The Table also estimates effects for energy use and the carbon intensity of energy (using the IEA data). The results in Columns 1–2 indicate that the same-year emissions-income elasticity is similar in OECD (0.65) and non-OECD (0.57) countries. Column 3 reveals that in OECD countries, 91% of this elasticity (=0.59/0.65) results from increased energy use. Just 9% is from moving to more carbon-intensive energy (Column 5). Outside the OECD, on average only 70% of the same-year emissions-income elasticity operates via energy use (=0.40/0.57), and 30% is due to increases in the carbon intensity of energy. This higher share is explained by lower-income countries generally being in a phase of development that involves relatively rapid adoption of fossil fuels (Burke, 2013).

Obtaining similar emissions-income elasticities for the OECD and non-OECD sub-samples suggests that our results are not driven by outliers. We also obtain a similar same-year emissions-income elasticity for a sample that excludes country-years in which the *t*-1

(0.47*** in countries at the 25th percentile of *t*-1 GDP per capita; 0.62*** in countries at the 75th percentile). Table 6 uses World Bank data for consistency with our other estimates.

population was less than 0.5 million people, which reduces Table 1's estimation sample by 16%. 0.5 million people is the sample-selection criterion used by York (2012). We obtain near-identical estimates of the same-year emissions-income elasticity controlling for (a) separate sets of year dummies for each of the seven regions defined by the World Bank (2014); (b) country-by-country time trends; or (c) changes in the urban share of the population and in each country's age dependency ratio. These are variables that are not likely to be important same-year causal channels between income growth and emissions growth, and so are variables that it might be desirable to control for.

4. Discussion

We have presented a large amount of new evidence on the short-run implications of GDP growth for national CO_2 emissions from fossil fuel combustion and cement production. The average short-run emissions-income elasticity is less than unity, with a same-year elasticity of around 0.5 and an elasticity allowing a five-year response of 0.8. We found no significant difference in the same-year emissions-income elasticity during years of economic expansion or contraction, but a lower elasticity is detectable over longer contractions (four or five years). Delayed effects are particularly noticeable in the road transport sector and mean that economic growth increases CO_2 emissions not only this year but also in subsequent years. Most of the effect of GDP growth on CO_2 emissions operates via energy demand, particularly in OECD countries. Fluctuations in industrial value-added and flowing from export partner economies have relatively large implications for national emissions. Fluctuations in consumption and investment have similar effects. The short-run emissions-income elasticity does not appear to fall as per capita incomes increase, and is typically higher in fossil-fuel rich countries. We do not find that this elasticity has increased or decreased in a linear way over time.

Our estimates reveal that a recession has two effects on emissions. First, emissions are likely to be lower that year than they would otherwise be. Second, emissions grow more slowly in *subsequent* years. This, of course, does not mean that a recession is a desirable way to reduce emissions (Bowen and Stern, 2010).

Our short-run emissions-income elasticity estimates are similar to Jaunky's (2011) estimates for a 36-country sample and Heutel's (2012) estimates of 0.5–0.9 for the US. Our five-year elasticity of 0.8 using distributed lags of GDP growth (Table 2) is similar to Liao and Cao's

(2013) estimates of 0.8–1.1 (for all but the highest-income countries) using levels data; Anjum et al.'s (2014) estimate of 0.8 using average growth rates over a forty-year period; and Liddle's (2015) estimate of 0.8 using levels data. The estimate is, however, lower than Stern's (2010) between estimate of the long-run emissions-income elasticity of 1.5. An advantage of our approach is that time-invariant factors such as each country's historical average temperature are controlled for by the use of differencing and country fixed effects. Our estimated two-year energy-income elasticity of 0.5 is consistent with cross-sectional levels regressions that indicate that the long-run energy-income elasticity is around 0.7 (Csereklyei et al., in press).

Our estimates of the emissions-income elasticity could help to parameterize the aggregate demand for emissions and thus be used in estimates of revenue collections under an ETS or an emissions tax. For instance, our finding that the same-year emissions-income elasticity does not vary significantly over the business cycle implies that the same-year effects of recessions and booms on ETS permit prices are fairly symmetric.

Previous research (Peters et al., 2012; Doda, 2014) noted that year-to-year variations in CO_2 emissions are on average larger than year-to-year variations in GDP, as observable in Figures 1 and 2.[9] Because the emissions-income elasticity is less than unity, our results indicate that the higher variability of CO_2 emissions is caused by factors other than GDP fluctuations. Emissions (particularly of small countries) can be noticeably affected by a single emissions-intensive project, such as the opening or closing of a coal-fired electricity plant. Other factors contributing to emissions volatility likely include energy price fluctuations and fossil fuel resource discoveries.

Peters et al. (2012) and Jotzo et al. (2012) report that global CO_2 emissions grew at a rapid pace – faster than GDP – in 2010 following the global recession of 2009. Using the data employed in this paper, GWP and global CO_2 emissions increased by 4.1% and 4.9% in 2010, after falls of 2.1% and 0.5% in 2009. We have found that emissions typically grow more slowly after recessions, which may add to surprise about the 2010 global emissions surge. The relatively large emissions effects of export-partner GDP growth and industrial value-added might be part of the explanation, as 2010 saw a resurgence in international trade

[9] The standard deviation of the annual CO_2 emissions growth rate in our sample is 0.18 (versus a mean of 0.04) whereas the standard deviation of the GDP growth rate is 0.06 (mean = 0.04).

flows and industrial production.[10] Like Peters et al. and Jotzo et al. we also note that fossil fuel prices were relatively low in 2009–2010 and that other factors (e.g. rapid economic growth in emissions-intensive China) also contributed to 2010's emissions rebound. The unusual nature of 2010 is confirmed in Figure 3, which shows that it had the largest positive year effect since the 1980s.

More generally, the implications of global economic growth for global emissions may differ from the average effect of country-level economic growth on country-level emissions. There are several issues to consider. One is aggregation: if GDP growth is particularly rapid in emissions-intensive economies, global emissions should be expected to grow more quickly. Another is effects on fossil fuel extraction: GWP growth is likely to encourage additional fossil fuel extraction – and therefore increased emissions from extraction activities – whereas GDP growth in an individual country often does not have the same effect within that country (e.g. as of 2010, Luxembourg did not have an extraction sector). Finally, global booms place upward pressure on global fossil fuel prices, which would curtail emissions growth. Care is required when extrapolating our country-level results to the global level.

[10] Global exports and industrial production expanded at real rates of 14% and 7% in 2010 (World Bank, 2014).

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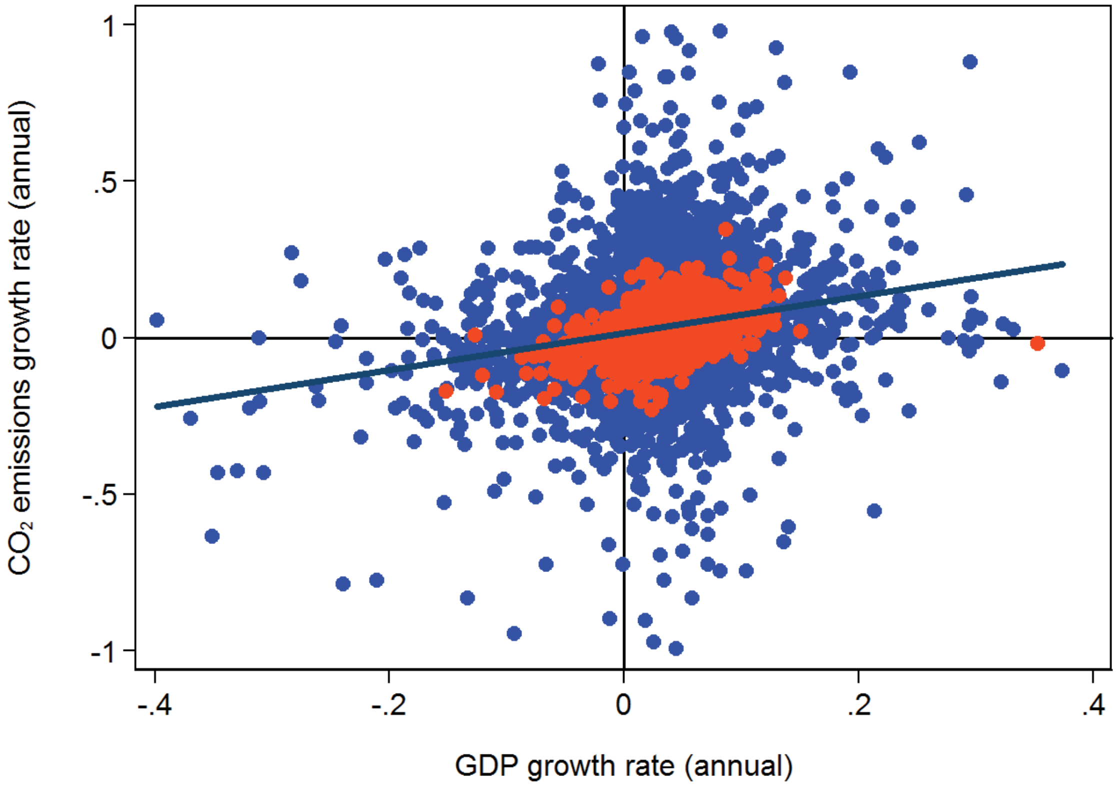

Figure 1. CO_2 emissions growth rate vs GDP growth rate. Orange (light shade): OECD (34 current members). Blue (dark shade): Non-OECD. Covers 6,904 country-year observations in 189 countries during 1961–2010 (excluding 52 observations that fall outside the shown ranges). Growth rates are calculated using differenced logs; 0.05 ≅ 5%. CO_2 emissions are those from fossil fuel combustion and cement production. Source: World Bank (2014).

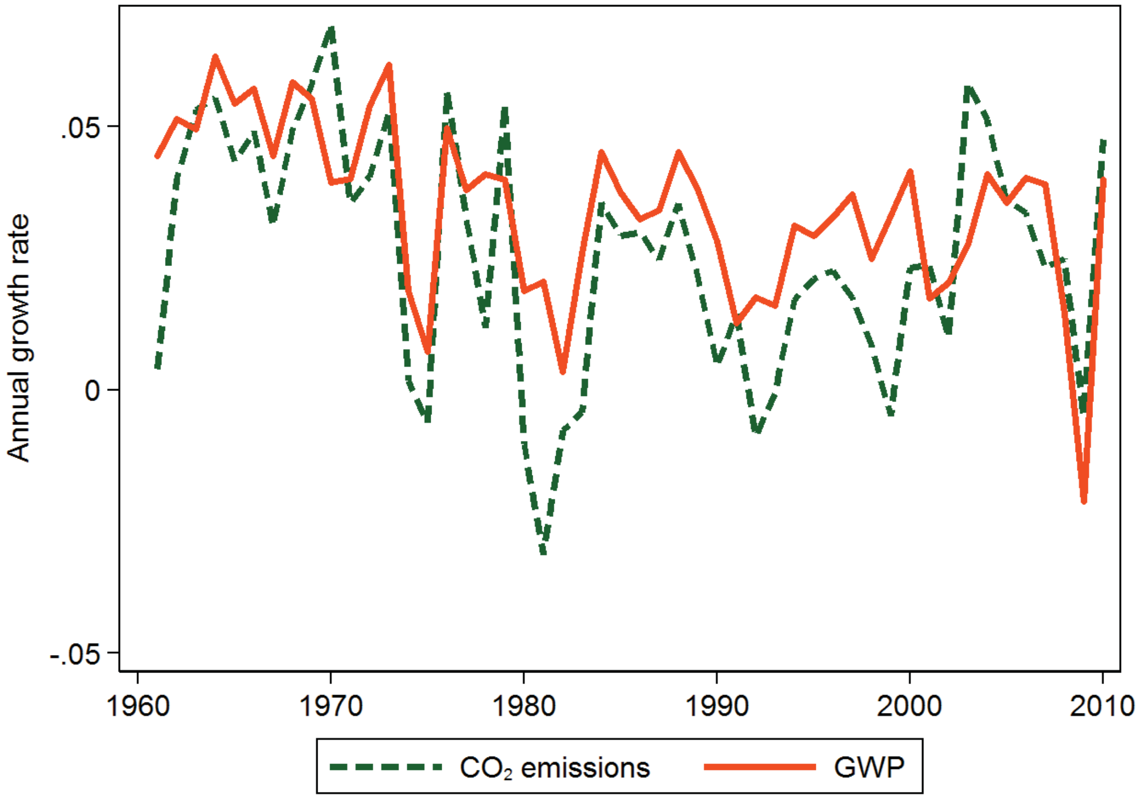

Figure 2. Growth rates of annual global CO_2 emissions and gross world product (GWP), 1961–2010. Rates are calculated using differenced logs; 0.05 ≅ 5%. CO_2 emissions are those from fossil fuel combustion and cement production. Source: World Bank (2014).

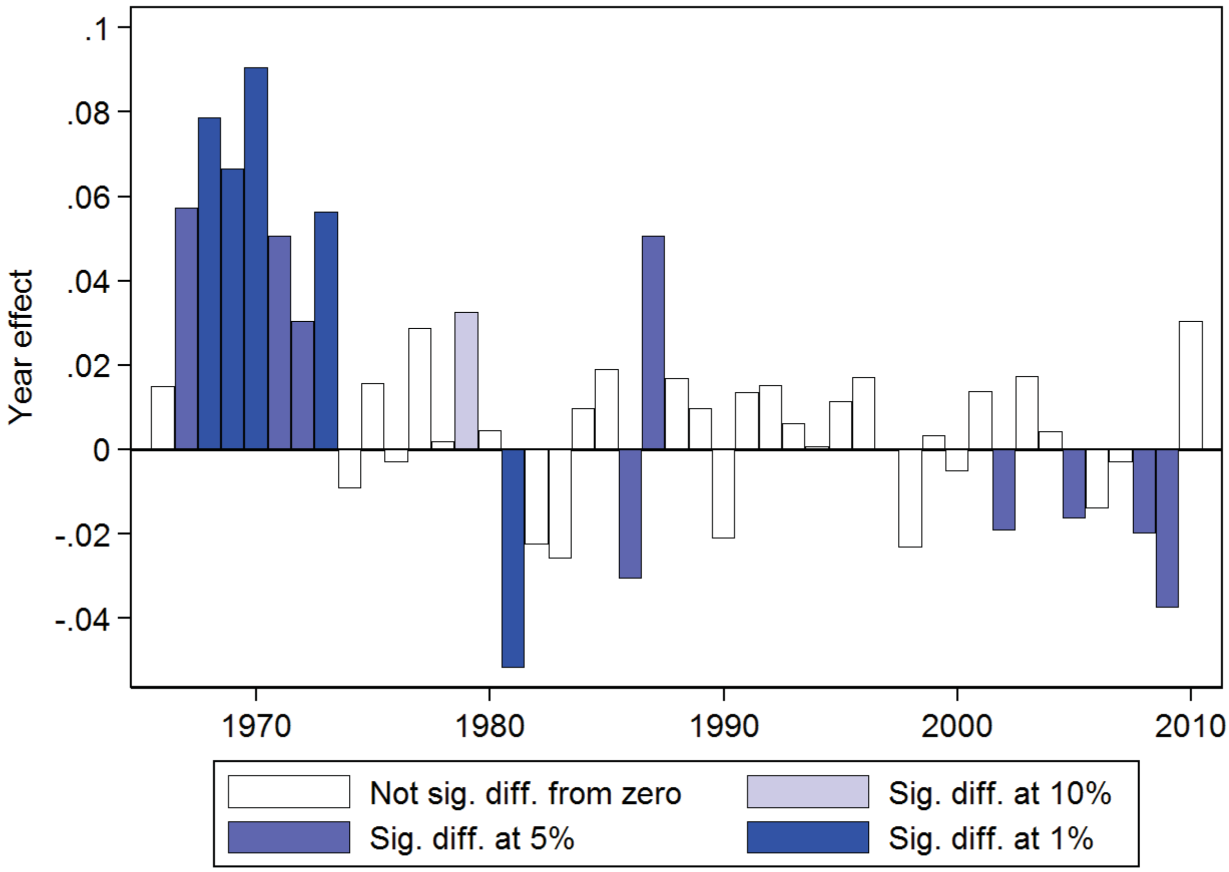

Figure 3. Year effects for CO_2 emissions from Column 6 of Table 2, an estimate that also includes the GDP growth terms to *t*-5 and country fixed effects. Each year effect in the Figure equals the coefficient for that year's year dummy plus the regression constant. The regression constant is the average country fixed effect. "Sig. diff" is significantly different from zero. The *y*-axis unit is differenced logs. The use of lagged GDP growth terms reduces the sample period to 1966–2010.

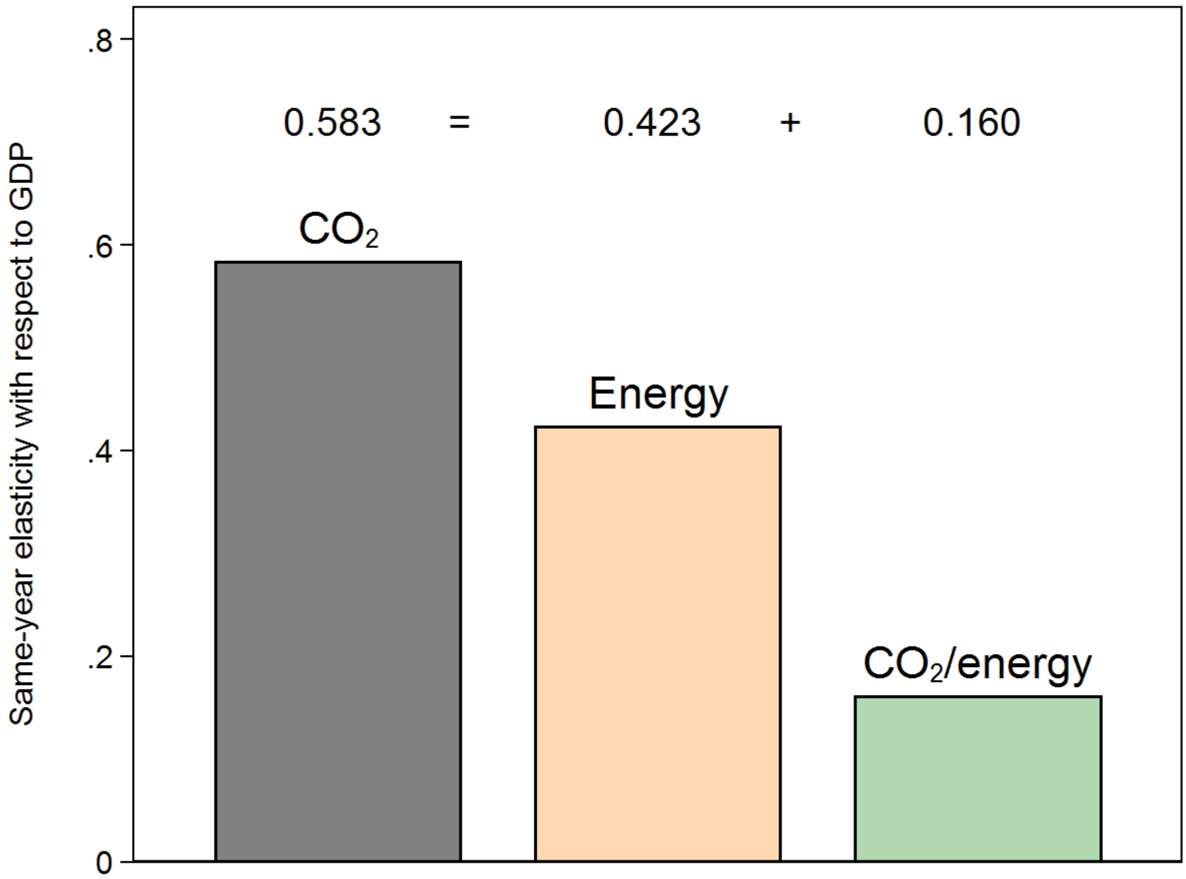

Figure 4. Elasticities from Columns 1, 4, and 7 of Table 3. The second and third sum to the first. IEA data used for the dependent variables.

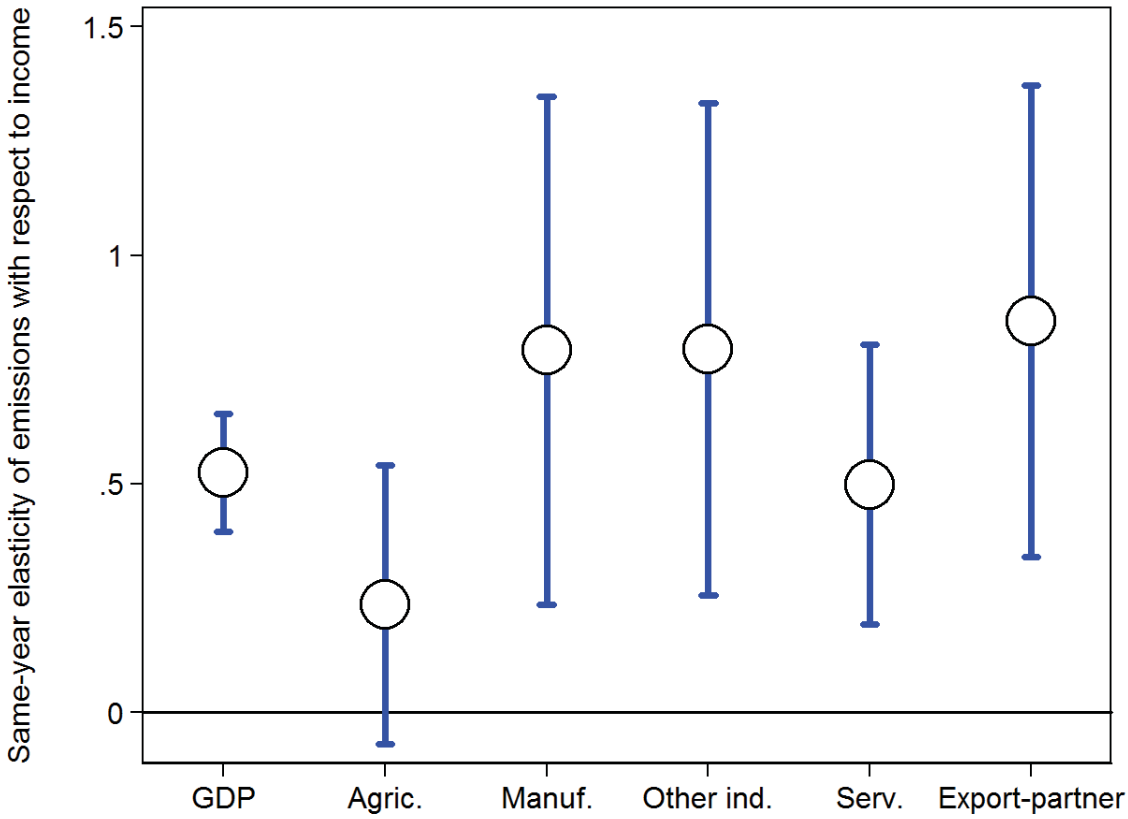

Figure 5. Same-year CO_2 emissions-income elasticities and 95% confidence intervals for GDP, for value-added in each of the four sectors, and for external shocks from the economies of export partners. Coefficients are from Column 1 of Table 1 and Columns 1 and 4 of Table 5. Elasticities are for national (not sectoral) emissions. Sectoral value-added has been scaled so that a percentage-point increase in each represents the same increase in national value-added. Agric. = Agriculture; Manuf. = Manufacturing; Other ind. = Other industry; Serv. = Services (including transport); Export-partner = IV estimate.

Table 1. Same-period elasticity and testing for asymmetry.

Dependent variable: Δ Ln CO_2 emissions$_{i,t}$

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Specification	Yearly		Two-yearly		Three-yearly		Four-yearly		Five-yearly	
Δ Ln GDP$_{i,t}$	0.52***		0.65***		0.71***		0.68***		0.65***	
	(0.07)		(0.08)		(0.09)		(0.10)		(0.08)	
	[0.00]		[0.00]		[0.00]		[0.00]		[0.00]	
Positive Δ Ln GDP$_{i,t}$		0.54***		0.68***		0.68***		0.79***		0.70***
		(0.09)		(0.10)		(0.10)		(0.12)		(0.08)
Negative Δ Ln GDP$_{i,t}$		0.51***		0.57***		0.76***		0.32***		0.44***
		(0.11)		(0.13)		(0.18)		(0.11)		(0.13)
		[0.84]		[0.52]		[0.71]		[0.02]		[0.09]
Country and time fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
% of observations with negative Δ Ln GDP$_{i,t}$	16	16	13	13	12	12	10	10	8	8
R^2 (within)	0.06	0.06	0.12	0.12	0.19	0.19	0.18	0.18	0.22	0.22
Observations	6,956	6,956	3,459	3,459	2,233	2,233	1,660	1,660	1,354	1,354
Countries	189	189	189	189	189	189	188	188	187	187

Notes: ***, **, and * indicate statistical significance at 1, 5, and 10%. Standard errors, shown in parentheses, are robust to heteroskedasticity and clustered by country. Odd-numbered Columns: Figures in square brackets are *p*-values for tests of equality to 1. Even-numbered Columns: Figures in square brackets are *p*-values for tests that the positive and negative terms have equal coefficients. The R^2s reflect the power of the explanatory variables and year dummies. Coefficients on country and time fixed effects not reported.

Table 2. Lagged effects.

Dependent variable: Δ Ln CO_2 emissions$_{i,t}$

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Δ Ln GDP$_{i,t}$	0.52***	0.47***	0.48***	0.49***	0.49***	0.50***	0.50***	0.50***	0.50***
	(0.07)	(0.07)	(0.08)	(0.08)	(0.08)	(0.09)	(0.07)	(0.07)	(0.07)
Δ Ln GDP$_{i,t-1}$		0.17***	0.14**	0.11*	0.09	0.09			
		(0.05)	(0.06)	(0.06)	(0.06)	(0.07)			
Δ Ln GDP$_{i,t-2}$			0.06	0.05	0.05	0.05			
			(0.05)	(0.06)	(0.06)	(0.06)			
Δ Ln GDP$_{i,t-3}$				0.07	0.00	0.01			
				(0.07)	(0.07)	(0.07)			
Δ Ln GDP$_{i,t-4}$					0.19***	0.19***			
					(0.06)	(0.06)			
Δ Ln GDP$_{i,t-5}$						-0.02			
						(0.05)			
Recession dummy$_{i,t-1}$							-0.016**		-0.012*
							(0.007)		(0.007)
Boom dummy$_{i,t-1}$								0.012**	0.009*
								(0.005)	(0.005)
Country and year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
∑ Coefficients of Δ Ln GDP terms	0.52***	0.64***	0.68***	0.71***	0.82***	0.81***	-	-	-
p-value for test that ∑ (Coefficients of Δ Ln GDP terms) = 1	0.00	0.00	0.00	0.00	0.13	0.16	-	-	-
∑ Coefficients of t-1 and earlier Δ Ln GDP terms	-	0.17***	0.20***	0.22***	0.33***	0.31***			
R^2 (within)	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Observations	6,956	6,805	6,654	6,493	6,328	6,159	6,805	6,805	6,805
Countries	189	189	189	189	189	189	189	189	189

Notes: ***, **, and * indicate statistical significance at 1, 5, and 10%. Standard errors, shown in parentheses, are robust to heteroskedasticity and clustered by country. The R^2s reflect the power of the explanatory variables and year dummies. Coefficients on country and year fixed effects not reported. All regressions use yearly data. Columns 7–9: 16% of observations had a recession and 38% of observations had a boom in year t-1. For OECD observations, these shares are 10% and 28%. The estimate in Column 1 is the same as Column 1 of Table 1.

Table 3. Separate effects for energy and the carbon intensity of energy.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Dependent variable	Δ Ln CO_2 emissions$^{IEA}{}_{i,t}$			Δ Ln Energy use$_{i,t}$			Δ Ln (CO_2 emissions^{IEA}/Energy use)$_{i,t}$		
Δ Ln GDP$_{i,t}$	0.583***	0.524***	0.545***	0.423***	0.379***	0.393***	0.160***	0.146***	0.152***
	(0.054)	(0.046)	(0.053)	(0.039)	(0.036)	(0.038)	(0.037)	(0.037)	(0.038)
Δ Ln GDP$_{i,t\text{-}1}$		0.206***			0.155***			0.051*	
		(0.043)			(0.035)			(0.030)	
Recession dummy$_{i,t\text{-}1}$			-0.012***			-0.006*			-0.006*
			(0.005)			(0.004)			(0.003)
Boom dummy$_{i,t\text{-}1}$			0.011***			0.011***			0.000
			(0.003)			(0.002)			(0.003)
Country and year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
∑ Coefficients of Δ Ln GDP terms	0.58***	0.73***	-	0.42***	0.53***	-	0.16***	0.20***	-
R^2 (within)	0.16	0.17	0.16	0.17	0.18	0.17	0.03	0.03	0.03
Observations	4,774	4,774	4,774	4,774	4,774	4,774	4,774	4,774	4,774
Countries	134	134	134	134	134	134	134	134	134

Notes: ***, **, and * indicate statistical significance at 1, 5, and 10%. Standard errors, shown in parentheses, are robust to heteroskedasticity and clustered by country. The R^2s reflect the power of the explanatory variables and year dummies. Coefficients on country and year fixed effects not reported. An identical sample is used in all Columns. All regressions use yearly data. IEA data used for all dependent variables. Each individual coefficient in regressions for Δ Ln CO_2 emissions$_t$ = sum of corresponding coefficients for the regressions for the other two dependent variables. These estimates cover 1962–2012.

Table 4. Results by sector of energy use.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Dependent variable	Δ Ln Energy use (total; primary)$_{i,t}$		Δ Ln Industrial energy (final use)$_{i,t}$		Δ Ln Road transport energy (final use)$_{i,t}$		Δ Ln Other transport energy (final use)$_{i,t}$		Δ Ln Residential energy (final use)$_{i,t}$		Δ Ln Other energy use$_{i,t}$	
Δ Ln GDP$_{i,t}$	0.38***	0.39***	0.68***	0.68***	0.53***	0.55***	0.38**	0.39**	0.11**	0.11**	0.39***	0.42***
	(0.04)	(0.04)	(0.07)	(0.07)	(0.07)	(0.07)	(0.19)	(0.16)	(0.05)	(0.05)	(0.05)	(0.06)
Δ Ln GDP$_{i,t\text{-}1}$	0.16***		0.00		0.26***		0.25		0.06		0.19***	
	(0.04)		(0.05)		(0.07)		(0.15)		(0.06)		(0.06)	
Recession dummy$_{i,t\text{-}1}$		-0.007*		-0.005		-0.025***		-0.005		-0.007		-0.006
		(0.004)		(0.008)		(0.008)		(0.019)		(0.007)		(0.006)
Boom dummy$_{i,t\text{-}1}$		0.011***		-0.004		0.014***		0.025*		0.005		0.012**
		(0.002)		(0.005)		(0.004)		(0.013)		(0.004)		(0.005)
Country and year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
∑ Coefficients of Δ Ln GDP terms	0.54***	-	0.67***	-	0.80***	-	0.62***	-	0.17**	-	0.58***	-
R^2 (within)	0.18	0.17	0.08	0.08	0.10	0.10	0.02	0.02	0.04	0.04	0.07	0.07
Observations	4,746	4,746	4,746	4,746	4,746	4,746	3,878	3,878	4,746	4,746	4,746	4,746
Countries	134	134	134	134	134	134	121	121	134	134	134	134

Notes: ***, **, and * indicate statistical significance at 1, 5, and 10%. Standard errors, shown in parentheses, are robust to heteroskedasticity and clustered by country. The R^2s reflect the power of the explanatory variables and year dummies. Coefficients on country and year fixed effects not reported. All regressions use yearly data. Industrial energy (final use) + Road transport energy (final use) + Other transport energy (final use) + Residential energy (final use) + Other energy use = Energy use (total; primary). These estimates cover 1962-2012. The sample in Columns 7–8 is reduced due to some instances of zero reported energy use by non-road transport.

Table 5. Sectoral and export-partner-predicted growth terms.

Dependent variable: Δ Ln CO_2 emissions$_{i,t}$

	(1)	(2)	(3)	(4)	(5)
Estimation	Using output-based terms	Using expenditure-based terms	Using expenditure-based terms	IV	IV
Excluded from sample if:	-	-	$(X>0.4Y)_{i,t\text{-}1}$	-	Large economy
Δ Ln Agriculture value added$^{Weighted}_{i,t}$	0.24				
	(0.15)				
Δ Ln Manufacturing value added$^{Weighted}_{i,t}$	0.79***				
	(0.28)				
	[0.11]				
Δ Ln Other industry value added$^{Weighted}_{i,t}$	0.79***				
	(0.27)				
	[0.09]				
Δ Ln Services value added$^{Weighted}_{i,t}$	0.50***				
	(0.16)				
	[0.13]				
Δ Ln Household consumption$^{Weighted}_{i,t}$		0.50***	0.45***		
		(0.12)	(0.10)		
Δ Ln Investment$^{Weighted}_{i,t}$		0.48***	0.50***		
		(0.11)	(0.11)		
Δ Ln Government consumption$^{Weighted}_{i,t}$		0.45*	0.33		
		(0.26)	(0.28)		
Δ Ln Exports$^{Weighted}_{i,t}$		0.28**	0.55***		
		(0.12)	(0.20)		
Δ Ln Imports$^{Weighted}_{i,t}$		-0.26**	-0.16		
		(0.10)	(0.14)		
Δ Ln GDP$_{i,t}$ (Instrumented)				0.86***	0.84***
				(0.26)	(0.26)
Country and year fixed effects	Yes	Yes	Yes	Yes	Yes
First-stage: *F*-statistic on instrument	-	-	-	36.47	36.24
R^2 (within)	0.05	0.08	0.11	0.05	0.05
Observations	4,399	3,106	2,156	6,653	5,726
Countries	159	135	105	174	154

Notes: ***, **, and * indicate statistical significance at 1, 5, and 10%. Standard errors, shown in parentheses, are robust to heteroskedasticity and clustered by country. Figures in square brackets in Column 1 are *p*-values for tests of equality to the coefficient for Δ Ln Agriculture value added$^{Weighted}_{i,t}$. Sectoral growth rates in Column 1 are weighted by the *t*-1 share of that sector in the constant-price value added of each country. Doing so allows a percentage-point increase in each term to reflect an equivalent increment to value added growth. Expenditure growth rates in Columns 2–3 are weighted by the *t*-1 share of that expenditure item in total expenditure. Columns 2–3 exclude observations for which the discrepancy between expenditure and GDP exceeds 5%. Columns 4–5 use the following instrument: Export-partner GDP growth rate$_{i,t}$ * Export share of GDP (%; 1995)$_i$. The Stock-Yogo 5% critical value for 10% maximal IV size is 16.38; the null of weak instruments is rejected if the first-stage *F*-statistic on the excluded instrument exceeds this value. "Large" economies are the 20 largest economies in 1995 (World Bank, 2014). The R^2s reflect the power of the explanatory variables and year dummies. Coefficients on country and year fixed effects not reported. All regressions use yearly data. IV = instrumental variable.

Table 6. Testing for heterogeneity.

Dependent variable: Δ Ln CO_2 emissions$_{i,t}$

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Δ Ln GDP$_{i,t}$	0.58***	0.61***	0.52***	0.54***	0.51***	0.32***	0.57***
	(0.07)	(0.07)	(0.07)	(0.07)	(0.08)	(0.07)	(0.16)
Ln GDP per capita (demeaned)$_{i,t\text{-}1}$	-0.005***	-0.006***	-0.002	-0.004			
	(0.001)	(0.002)	(0.010)	(0.010)			
Δ Ln GDP$_{i,t}$*Ln GDP per capita (demeaned)$_{i,t\text{-}1}$		0.04		0.03			
		(0.04)		(0.04)			
Above-median GDP per capita dummy$_{i,t\text{-}1}$					-0.02**		
					(0.01)		
Δ Ln GDP$_{i,t}$*Above-median GDP per capita dummy$_{i,t\text{-}1}$					0.02		
					(0.14)		
Δ Ln GDP$_{i,t}$*Above-median per capita fossil fuel reserves in 1971 dummy$_i$						0.31***	
						(0.11)	
Δ Ln GDP$_{i,t}$*Time trend (year 1960 = 0)$_t$							-0.002
							(0.006)
Country fixed effects	No	No	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Implied same-year elasticity for country with:							
25th-percentile GDP per capita$_{i,t\text{-}1}$	0.58***	0.56***	0.52***	0.50***	-	-	-
75th-percentile GDP per capita$_{i,t\text{-}1}$	0.58***	0.66***	0.52***	0.59***	-	-	-
Below-median per capita fossil fuel reserves in 1971	-	-	-	-	-	0.32***	-
Above-median per capita fossil fuel reserves in 1971	-	-	-	-	-	0.63***	-
R^2	0.07	0.07	0.06	0.06	0.06	0.06	0.06
Observations	6,953	6,953	6,953	6,953	6,953	6,395	6,956
Countries	189	189	189	189	189	156	189

Notes: ***, **, and * indicate statistical significance at 1, 5, and 10%. Standard errors, shown in parentheses, are robust to heteroskedasticity and clustered by country. The R^2s reflect the power of the explanatory variables and year dummies. Coefficients on country and year fixed effects not reported. All regressions use yearly data. The time trend increases by 1 each year. Demeaning the Ln GDP per capita term means that the coefficients in the first row of Columns 2 and 4 are the estimated values for countries with mean Ln GDP per capita.

Table 7. Results for OECD and non-OECD sub-samples.

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable	Δ Ln CO_2 emissions$^{IEA}{}_{i,t}$		Δ Ln Energy use$_{i,t}$		Δ Ln (CO_2 emissions^{IEA}/Energy use)$_{i,t}$	
	OECD	Non-OECD	OECD	Non-OECD	OECD	Non-OECD
Δ Ln GDP$_{i,t}$	0.65***	0.57***	0.59***	0.40***	0.06*	0.17***
	(0.06)	(0.06)	(0.05)	(0.04)	(0.03)	(0.04)
Country and year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
R^2 (within)	0.38	0.14	0.42	0.14	0.04	0.04
Observations	1,503	3,271	1,503	3,271	1,503	3,271
Countries	34	100	34	100	34	100

Notes: ***, **, and * indicate statistical significance at 1, 5, and 10%. Standard errors, shown in parentheses, are robust to heteroskedasticity and clustered by country. The R^2s reflect the power of the explanatory variables and year dummies. Coefficients on country and year fixed effects not reported. All regressions use yearly data. Coefficient in regressions for Δ Ln CO_2 emissions$_{i,t}$ = sum of corresponding coefficients for the other two dependent variables. OECD grouping is based on the 34-country year-2014 classification. IEA data used for all dependent variables. These estimates cover 1962–2012.

Appendix A: Variable definitions
CO_2 emissions: CO_2 emissions from the combustion of fossil fuels and the manufacture of cement (kilotonnes). Source: World Bank (2014), who obtained the series from the Carbon Dioxide Information Analysis Center.

GDP: Gross domestic product in constant 2005 US$. GDP equals gross value added plus any net taxes not included in product values. Source: World Bank (2014).

Recession dummy: 1 if GDP is lower this year than last; 0 otherwise.

Boom dummy: 1 if $\Delta\ln\text{GDP} > 0.05$; 0 otherwise.

CO_2 emissions^{IEA}: CO_2 emissions from fuel combustion (million tonnes; sectoral approach). IEA (2014a).

Energy use: Use of primary energy ("total primary energy supply"), in kilotonnes of oil equivalent. Source: IEA (2014b).

Industrial energy (final use): Total final consumption of energy by industry, in kilotonnes of oil equivalent. Industry includes: iron and steel; chemical and petrochemical; non-ferrous metals; non-metallic minerals; transport equipment; machinery; mining and quarrying; food and tobacco; paper, pulp, and print; wood and wood products; construction; textile and leather; and non-specified. Source: IEA (2014b).

Road transport energy (final use): Total final consumption of energy by the road-transport sector, in kilotonnes of oil equivalent. Includes fuels used in road vehicles as well as highway use by agricultural and industrial vehicles. Excludes military consumption; motor gasoline used in stationary engines; and diesel for use in tractors that are not for highway use. Source: IEA (2014b).

Other transport energy (final use): Total final consumption of energy by domestic transport excluding the road sector, in kilotonnes of oil equivalent. Includes domestic aviation, rail, domestic shipping, pipeline transport, and other. Source: IEA (2014b).

Residential energy (final use): Total final consumption of energy by households, excluding for transport, in kilotonnes of oil equivalent. Source: IEA (2014b).

Other energy use: Total primary energy supply minus use of final energy by industry, road transport, other transport, and residences. In kilotonnes of oil equivalent. Source: IEA (2014b).

Agriculture value added: Value added by ISIC divisions 1–5, which includes crops, livestock, forestry, hunting, and fishing. Constant 2005 US$. Source: World Bank (2014).

Manufacturing value added: Value added by ISIC divisions 15–37, which includes crops, livestock, forestry, hunting, and fishing. Constant 2005 US$. Source: World Bank (2014).

Other industry value added: Value added by ISIC divisions 10–14 and 38–45. Includes mining, construction, electricity, water, and gas. Constant 2005 US$. Source: World Bank (2014).

Services value added: Value-added in constant 2005 US$ for ISIC divisions 50–99, which includes wholesale and retail trade, transport, and government, financial, professional, and personal services (e.g. education, health care, and real estate). Constant 2005 US$. Source: World Bank (2014).

Household consumption: Household final consumption expenditure, which is the market value of all goods and services purchased by households, including durable products. This variable excludes purchases of dwellings but includes imputed rent for owner-occupied dwellings and some additional payments. Constant 2005 US$. Source: World Bank (2014).

Investment: Gross fixed capital formation, which includes land improvements (fences, ditches, drains, and so on); plant, machinery, and equipment purchases; the construction of roads, railways, schools, offices, hospitals, private residential dwellings, and commercial and industrial buildings; and net acquisitions of valuables. Covers both private and government investment. Constant 2005 US$. Source: World Bank (2014).

Government consumption: General government final consumption expenditure, which includes government current expenditures for purchases of goods and services, compensation of employees, and most expenditures on national defense and security. Excludes expenditures that are part of government capital formation. Constant 2005 US$. Source: World Bank (2014).

Exports: Value of goods and services provided to the rest of the world, including merchandise, freight, insurance, transport, travel, royalties, license fees, communication, construction, financial, information, business, personal, and government services but excluding compensation of employees, investment income, and transfer payments. Constant 2005 US$. Source: World Bank (2014).

Imports: Value of goods and services received from the rest of the world, including merchandise, freight, insurance, transport, travel, royalties, license fees, communication, construction, financial, information, business, personal, and government services but excluding compensation of employees, investment income, and transfer payments. Constant 2005 US$. Source: World Bank (2014).

Export-partner GDP growth rate: Weighted average of the GDP growth rates (in %) of export partners. Weights are based on the share of each partner in year-1995 goods exports to 179 countries. Source of GDP growth rate data: World Bank (2014). Source of export data: IMF (2009). In the case of missing partner GDP growth data for a partner in a given year, the world GDP growth rate is used for that partner in that year instead. For three countries (Belgium, Luxembourg, South Africa), year-1998 weights are used. For three other countries (Antigua and Barbuda, Kiribati, and Palau), export data from the United Nations Conference on Trade and Development (2014) were used. For the four small members of the Southern Africa Customs Union, the export partner weight is set equal to 1 for South Africa and 0 for other partners. For Bhutan and Eritrea, the export weight is set equal to 1 for the largest export market as listed by the Central Intelligence Agency (2009). See Burke (2012b).

Export share of GDP (%; 1995): Year-1995 exports of goods and services as a share of GDP. Source: World Bank (2014).

Population: Mid-year estimated number of people, based on the de facto definition of population. Source: World Bank (2014). Used in the construction of per-capita measures.

Fossil fuels reserves per capita in 1971: Value of per-capita fossil fuel reserves in 1971 in year-1971 US$. Reverse-constructed by Norman (2009). We multiplied Norman's (2009) ratio of the value of fossil fuel reserves to GDP in 1971 by GDP per capita in 1971 from the World Bank (2014).

Appendix B: Reconciling asymmetry results with York (2012)

York (2012) reported that the same-year emissions-income elasticity is lower during years of economic contraction than years of economic expansion. This Appendix reconciles our estimate in Column 2 of Table 1 with York's estimate, replicated in Panel B, Column 7, Table A1.

As can be seen in Table A1, we generally obtain coefficients for the positive and negative GDP growth terms that are not significantly different from one another. The *p*-value for a test of parameter equality in Panel A, Column 1 is 0.84, for example. The two coefficients are only significantly different from one another (Columns 5–7) when:

(1) Non-robust standard errors are used; *and*
(2) Country-years representing 0.5 million people or fewer are excluded.

The above holds using either aggregate data (Panel A) or per-capita data (Panel B). The use of both country fixed effects and year fixed effects further reduces the gap between the coefficients (e.g. Column 1).

Our use of robust standard errors is supported by modified Wald tests for groupwise heteroskedasticity in panel regressions, which strongly reject the null of homoscedasticity (*p*-value = 0.000). See Doda (2013) for a related discussion.

Table A1: Same-year asymmetry specifications.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Standard errors	Robust	Robust	Robust	Non-robust	Non-robust	Non-robust	Non-robust
Population$_{i,t}$ restriction	None	None	> 500,000	None	> 500,000	> 500,000	> 500,000
Estimator	OLS	OLS	OLS	OLS	OLS	GLS	GLS
Years	Full	Full	Full	Full	Full	Full	1961-2008
Country fixed effects	Yes	No	No	No	No	No	No
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	No
Panel A: Aggregate data							
Dependent variable: Δ Ln CO_2 emissions$_{i,t}$							
Positive Δ Ln GDP$_{i,t}$	*0.54****	0.63***	0.73***	0.63***	0.73***	0.78***	0.83***
	(0.09)	(0.09)	(0.12)	(0.05)	(0.06)	(0.05)	(0.05)
Negative Δ Ln GDP$_{i,t}$	*0.51****	0.52***	0.55***	0.52***	0.55***	0.56***	0.55***
	(0.11)	(0.11)	(0.10)	(0.07)	(0.07)	(0.07)	(0.07)
	[0.84]	[0.42]	[0.24]	[0.22]	[0.08]	[0.02]	[0.00]
R^2	*0.06*	0.07	0.07	0.07	0.07	0.09	0.07
Panel B: Per-capita data							
Dependent variable: Δ Ln CO_2 emissions per capita$_{i,t}$							
Positive Δ Ln GDP per capita$_{i,t}$	0.56***	0.61***	0.71***	0.61***	0.71***	0.76***	**0.79*** **
	(0.11)	(0.11)	(0.14)	(0.06)	(0.06)	(0.06)	**(0.06)**
Negative Δ Ln GDP per capita$_{i,t}$	0.46***	0.48***	0.50***	0.48***	0.50***	0.51***	**0.52*** **
	(0.10)	(0.10)	(0.09)	(0.06)	(0.07)	(0.06)	**(0.06)**
	[0.57]	[0.41]	[0.24]	[0.17]	[0.05]	[0.01]	**[0.00]**
R^2	0.06	0.06	0.07	0.06	0.07	0.08	**0.06**
Observations	6,956	6,956	5,885	6,956	5,885	5,564	5,564
Countries	189	189	162	189	162	161	161

Notes: ***, **, and * indicate statistical significance at 1, 5, and 10%. The figures in square brackets are *p*-values for tests of equality between the coefficients for the two growth terms. The R^2s reflect the power of the explanatory variables and year dummies (but not the country fixed effects). Coefficients on country and year fixed effects not reported. All regressions use yearly data. The "Full" sample is for 1961–2010. OLS = ordinary-least squares. GLS = generalized least-squares with the Prais-Winsten correction for first-order autocorrelation. The per-capita regressions omit 3 observations from the tallies shown. The results in *italics* are the same as Column 2 of our Table 1. "Robust" means robust to heteroskedasticity. The results in **bold** are our replication of York's (2012) estimation. The sample and coefficients in this specification are similar but not identical to York's, presumably due to data updates.