The Asymmetrical Effects of Economic Development on Consumption-based and Production-based Carbon Dioxide Emissions, 1990 to 2014

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Abstract
The authors examine the potentially asymmetrical relationship between economic development and consumption-based and production-based CO₂ emissions. They decompose economic development into economic expansions and contractions, measured separately as increases and decreases in gross domestic product per capita, and examine their unique effects on emissions. Analyzing cross-national data from 1990 to 2014, the authors find no statistical evidence of asymmetry for the overall sample. However, for a sample restricted to nations with populations larger than 10 million, the authors observe a contraction-leaning asymmetry whereby the effects of economic contraction on both emissions outcomes are larger in magnitude than the effects of economic expansion. This difference in magnitude is more pronounced for consumption-based emissions than for production-based emissions. The authors provide tentative explanations for the variations in results across the different samples and emissions measures and underscore the need for more nuanced research and deeper theorization on potential asymmetry in the relationship between economic development and anthropogenic emissions.

Keywords
environmental sociology, climate change, asymmetry, economic development, CO₂ emissions

Asymmetry refers to a type of irreversible causal process in which “an outcome generated by a given cause cannot be reversed by simply eliminating the cause or turning back the cause to its earlier condition” (Lieberson 1985:175; York and Light 2017). Recent studies in environmental sociology and environmental economics assess the asymmetry in the relationship between nations’ economic development and carbon dioxide emissions, finding that the effect of economic contraction on per capita production-based (i.e., territorial) carbon dioxide emissions is different from a reversal of the effect of economic expansions (Shahiduzzaman and Layton 2015; Sheldon 2017; York 2012). These findings suggest that projections of future greenhouse gas emissions based on symmetric models could be inaccurate to some extent (Sheldon 2017).

However, to the best of our knowledge, prior research has not investigated if an asymmetry exists in the relationship between consumption-based carbon dioxide emissions and economic development. Related longitudinal studies on development and emissions, which focus explicitly on research questions other than asymmetry, have found differences in the relationship between development and production-based and consumption-based emissions (e.g., Knight and Schor 2014).

Other recent research has revealed nontrivial differences in the changing effect of population size on emissions for nations in different structural and geographical contexts (Jorgenson and Clark 2013). Therefore, it is possible that asymmetry in development and emissions relationships could be sensitive to or influenced by the size of nations’ populations.

In this study, we aim to advance the research on socioenvironmental asymmetry by empirically evaluating the following research questions. First, is the relationship between nations’ economic development and consumption-based carbon dioxide emissions asymmetrical? Second, does the...
potential asymmetry in the association with development differ between consumption-based emissions and production-based emissions? And third, do asymmetrical relationships between development and carbon emissions differ for nations with different population sizes? To evaluate our research questions, we estimate cross-national time-series regression models for multiple samples of nations for the period from 1990 to 2014.

**Literature Review**

**Economic Development and Carbon Dioxide Emissions**

Economic development is identified as a primary driver of anthropogenic greenhouse gas emissions (e.g., Jorgenson 2014; Rosa and Dietz 2012; Rosa, York, and Dietz 2004). This is largely because economic output stems from activities that consume materials and energy, and generate waste. Given that fossil fuel is the dominant form of energy in the world, economic development is expected to be positively associated with carbon dioxide emissions from fossil fuel combustion, which is confirmed by longitudinal research. For example, in a study of the majority of the world’s nations, Jorgenson and Clark (2012) found positive associations between production-based carbon dioxide emissions and gross domestic product (GDP) in terms of scale (total emissions), intensity (per capita emissions), and ecoefficiency (emissions per unit of economic output) and found important differences in the changing magnitude through time of the associations between economic development and emissions for nations in different structural contexts (see also Longhofer and Jorgenson 2017; Thombs forthcoming). Lamb et al. (2014) found that economic development is positively associated with consumption-based carbon dioxide emissions, and Knight and Schor (2014) found that for a sample of wealthy nations, the association between development and consumption-based emissions was stronger than the association between development and production-based emissions.

**Asymmetry in the GDP and Emissions Relationship**

Economic development is not a smooth or gradual process but instead often entails cyclical expansion and contraction periods and occasional large-scale recessions. Economic contraction and its contributing factors are not simply the reversal of economic expansion and its contributors. Thus, it may not be justified to assume, for example, that the effect of per unit increase in GDP per capita on carbon dioxide emissions is symmetric (i.e., equal in magnitude but opposite in direction) to the effect of per unit decrease in GDP per capita.

In an asymmetric relationship, the outcome is determined by not only the current condition of the predictor but also the history of changes leading to this condition. As York and Light (2017) illustrated, assuming symmetry when the actual relationship is asymmetrical could mask the effect of the history of changes of predictor variables. Failure to account for asymmetry when it actually exists for a predictor and an outcome could also lead to inaccurate estimates for other predictor variables in the same models, regardless of whether their relationships with the outcome are asymmetric or not (Gately and Huntington 2002).

In an analysis that includes most of the world’s nations, York (2012) found that the relationship between changes in GDP per capita and changes in production-based carbon dioxide emissions is asymmetrical: the estimated effect of per unit increase of GDP per capita on increasing emissions per capita during economic expansion is greater than the estimated effect of per unit decrease of GDP on decreasing emissions during economic contraction. We refer to this type of asymmetry as expansion-leaning asymmetry. York suggested that the asymmetry observed in his study may be due partly to a type of “infrastructural momentum” in which the more carbon-intensive infrastructure and durable goods (e.g., power plants, factories, automobiles, transportation system) constructed and produced during economic expansions continue to be in service and generate carbon dioxide emissions during subsequent periods of economic contraction (see also York 2008).

Focusing on just the United States, Shahiduzzaman and Layton (2015) and Sheldon (2017) found an opposite form of asymmetry: the estimated effect of per unit decrease of GDP on decreasing production-based emissions during economic contraction is greater than the estimated effect of per unit increase of GDP on increasing production-based emissions during economic expansion. We refer to this type of asymmetry as contraction-leaning asymmetry. Sheldon also found contraction-leaning asymmetry between aggregate GDP and energy consumption in the U.S. industrial sector and, to a lesser degree, in the commercial and residential sectors. The contraction-leaning asymmetry observed in the United States may be explained by behavioral shifts of individuals and operational changes by companies to adopt more energy-efficient behaviors and practices (e.g., reduce miles driven, discard production equipment with lower energy efficiency) during periods of economic contraction, and retain such practices in subsequent periods of economic expansion (Shahiduzzaman and Layton 2015; Sheldon 2017).

The existence of asymmetry, on the basis of tests of statistical significance, may indicate missing independent variables (Clark, Gilligan, and Golder 2006; York and Light 2017). One such scenario is what Lieberson (1985:75–76) called “ceteris paribus error,” where changes in the independent variable cause changes not only in the outcome of interest but also in other unobserved variables, and these additional changes create a condition that hinders the reversal of the outcome of interest even if the independent variable is reversed to its initial status. In this sense, the infrastructural momentum can be conceptualized as a set of...
unobserved variables on the energy intensity of nations’ infrastructure, while the behavioral-operational shift (Shahiduzzaman and Layton 2015; Sheldon 2017) can be seen as a set of unobserved variables on the energy intensity of consumer expenditure and business operations.

Sheldon (2017) suggested that the difference in their results relative to York’s (2012) findings could be due at least partly to the contraction-leaning asymmetry observed in the United States being outweighed in cross-national contexts by expansion-leaning asymmetry in other countries. York (2012) observed expansion-leaning asymmetry for both higher income and lower income nations but reported that the estimated coefficients for higher income nations change if nations with small populations are included in the sample. As noted in the introduction, recent longitudinal research has revealed nontrivial differences in the changing effect of population size on carbon emissions for nations in different contexts (Jorgenson and Clark 2013). Additionally, a recent study (Clement and York 2017) revealed an asymmetrical relationship between natural population change (i.e., fertility and mortality) and county-level land development in the United States, whereby the rate at which human births increase built-up land area is significantly greater than the rate at which human deaths curtail this process. Overall, this mixture of findings suggest that potential asymmetry in the relationship between nations’ economic development and carbon emissions could be sensitive to population size in general (Jorgenson and Clark 2013), especially by the inclusion of nations with relatively small populations in analyzed samples in particular (York 2012).

**Consumption-based and Production-based Carbon Dioxide Emissions**

To the best of our knowledge, previous research on potential asymmetry in the development and emissions relationship has focused on production-based (also known as territorial-based) carbon dioxide emissions, which only reflect emissions that occur from the direct burning of fossil fuels and cement manufacturing within a country. However, measures of consumption-based emissions, which include emissions from domestic activities but also adjust for emissions transfers via international trade (i.e., adding in emissions embodied in imports and subtracting emissions embodied in exports), are important to consider because production and consumption activities are increasingly spatially separated in the global economy (e.g., Bunker and Ciccantell 2005; Chase-Dunn and Jorgenson 2007; Chase-Dunn, Kawano, and Brewer 2000; Le Quéré et al. 2015; Peters et al. 2011).

We suggest that analyses of both consumption-based emissions and production-based emissions could provide a more comprehensive understanding of potential asymmetry in economy-emissions relationships. As argued by Rosa and Dietz (2012), ultimately, most releases of greenhouse gases are driven by consumption of goods and services by individuals, households and organizations, and the manufacturing, transport and waste disposal that underpins that consumption. (p. 2)

Moreover, prior longitudinal research, which focuses on research questions and empirical relationships other than asymmetry, has analyzed both types of emissions (e.g., Franzen and Mader 2018; Knight and Schor 2014; Lamb et al. 2014; Liddle 2018). Therefore, in this study we assess if the relationships between GDP per capita and both consumption-based and production-based carbon emissions per capita are asymmetric, and for both emissions outcomes, we tentatively assess if the results vary across groups of countries with different population sizes.

**Methods**

**Sample**

The overall sample consists of 2,784 country-year observations for 118 nations from 1990 to 2014. These are the nations and yearly observations that are currently available for consumption-based carbon dioxide emissions. Although cross-national data are more widely available for production-based emissions, we include only the same nations and country-year observations for these data as well, which allows tentative comparisons across the models that we estimate for the two emissions outcomes.

**Dependent Variables**

The two dependent variables are per capita consumption-based carbon dioxide emissions and per capita production-based carbon dioxide emissions, both of which are measured in metric tons. We obtained these data from Global Carbon Atlas (http://www.globalcarbonatlas.org), which compiles emissions data from multiple sources. Global Carbon Atlas gathers production-based emissions data from Boden, Andres, and Marland (2016), the United Nations Framework Convention on Climate Change (2016), and BP (2016) and obtains consumption-based emissions data from Peters et al. (2011) and Peters, Davis, and Andrew (2012), with additional updates for more recent years. Population statistics used to calculate per capita emissions are gathered from the United Nations (2015) Population Division.

**Independent Variables**

The key independent variable is GDP per capita in constant 2010 U.S. dollars. Consistent with much prior research on anthropogenic emissions, we also estimate models with the following additional independent variables: exports as a percentage of total GDP, imports as a percentage of total GDP, manufacturing value added as a percentage of total GDP,
urban population as a percentage of total population, and age dependency ratio. We obtain the data for all independent variables from the World Bank’s (2017) online World Development Indicators.

**Modeling Techniques**

We use the modeling approach advocated by York and Light (2017) and York (2012) to analyze asymmetry. We transform all variables with natural logarithm and calculate the first-differenced values of the logged variables (i.e., logged and differenced). The log transformation corrects for skewness and allows us to estimate elasticity models. We estimate panel regression models of the logged and differenced variables that also include both country-specific and year-specific fixed effects. First differencing and country-specific fixed-effects together in the same models control for unobserved heterogeneity that is unique to each nation and is either invariant or changing over time at constant rates. Year-specific fixed effects (i.e., period effects) control for unobserved heterogeneity that is unique to each year and consistent for all countries. We estimate robust standard errors, clustered by nation.

We constructed two “slope dummy” variables (Hamilton 1992) to account for, separately, the increases and decreases in GDP per capita. The first slope dummy, increases in GDP per capita, takes the values of first-differenced log of GDP per capita only when the values are positive but equals zero when the values are negative. The second slope dummy, decreases in GDP per capita, takes the values of first-differenced log of GDP per capita only when the values are negative but equals to zero otherwise. We include both slope dummy variables as independent variables, whose coefficients stand for the effects of, respectively, increases and decreases of GDP per capita on emissions. Such an approach, where all possible slope dummy interactions are included in the model, is also referred to as a “contextual effects model”, and used in prior sociological studies that pursue other research questions (e.g., Burns, Kick, and Davis 2003; Jorgenson 2004; Rice 2007).

For each estimated model, we also conduct Wald tests for the null hypothesis that the coefficients for increases in GDP per capita and decreases in GDP per capita are equal. If the null hypothesis is rejected, it suggests that the relationship between GDP per capita and carbon emissions per capita is asymmetric. For comparison, we also estimate models that assume a symmetric relationship by using the first-differenced log of GDP per capita as the only independent variable for GDP. We decided not to introduce a temporary lag between changes in GDP and changes in emissions because prior research indicates that fossil-fuel consumption usually responds quickly to changes in GDP per capita (Gately and Huntington 2002).

To tentatively assess if asymmetry might be sensitive to population size, we estimate models of both emissions outcomes for the full sample as well as for two reduced samples of nations with populations larger than 5 million and nations with populations larger than 10 million. Table A1 in the Appendix lists the nations included in the analyses. Table A2 in the Appendix provides descriptive statistics for both outcomes and the independent variables of interest for each of the three samples.

**Results**

Table 1 presents the estimates of baseline asymmetric and symmetric models for both consumption-based and production-based emissions. For each asymmetric model we also report the results of the Wald tests for whether the asymmetry exists.

Turning first to consumption-based emissions, in models C1a (the full sample) and C2a (the sample of country-years with populations > 5 million), the coefficients for increases in GDP per capita have smaller values than the coefficient for decreases in GDP per capita, but on the basis of the Wald test, the differences are not statistically significant. This suggests a symmetric relationship between GDP per capita and consumption-based carbon emissions per capita. In model C3a, in which the sample is restricted to country-years with populations larger than 10 million, the coefficient for increases in GDP is significantly smaller than the coefficient for decreases in GDP (Wald test \( p < .01 \)), suggesting a contraction-leaning asymmetric relationship. In per capita terms, a 1 percent increase in GDP is associated with a 0.305 percent increase in consumption-based emissions, while a 1 percent decrease in GDP is associated with a 1 percent decrease in consumption-based emissions.

Next, we turn to production-based carbon emissions. In both models P1a and P2a, the coefficients for increases in GDP per capita have different values from the coefficients for decreases in GDP per capita, but the difference is not statistically significant in either model according to the Wald test. In model P3a, which is for country-years with populations larger than 10 million, the coefficient for increases in GDP is significantly smaller than the coefficient for decreases in GDP (Wald test \( p < .05 \)), suggesting a contraction-leaning asymmetric relationship. In per capita terms, a 1 percent increase in GDP is associated with a 0.265 percent increase in production-based emissions, while a 1 percent decrease in GDP is associated with a 0.558 percent decrease in production-based emissions.

When we compare models for the two emissions outcomes, it appears that the coefficients for decreases in GDP per capita in models C1a to C3a are larger than

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1 Age dependency ratio is measured as ratio of the sum of the population aged 0 to 14 years and the population aged 65 years and older to the population aged 15 to 64 years.
Table 1. Asymmetrical and Symmetrical Models for Consumption-based and Production-based Carbon Dioxide Emissions per Capita, 1990 to 2014.

| Consumption-based Emissions | Production-based Emissions |
|-----------------------------|---------------------------|
|                             | All Nations | Population > 5 Million | Population > 10 Million | All Nations | Population > 5 Million | Population > 10 Million |
|                             | C1a | C1s | C2a | C2s | C3a | C3s | P1a | P1s | P2a | P2s | P3a | P3s |
| Changes in GDP per capita   | 0.419*** (0.0728) | 0.430*** (0.104) | 0.636*** (0.0829) | 0.343*** (0.0481) | 0.320*** (0.0704) | 0.404*** (0.0643) |
| Increases in GDP per capita | 0.408** (0.127) | 0.316*** (0.09) | 0.305b (0.116) | 0.395*** (0.0730) | 0.295*** (0.0651) | 0.265** (0.0933) |
| Decreases in GDP per capita | 0.427*** (0.118) | 0.534* (0.207) | 1.000*** (0.189) | 0.304*** (0.0734) | 0.343** (0.127) | 0.558*** (0.0818) |
| Asymmetry exists (Wald test rejects equality)? | No | No | Yes** | No | No | Yes* |
| n                            | 2,784 | 2,784 | 2,068 | 2,068 | 1,511 | 1,511 | 2,784 | 2,784 | 2,068 | 2,068 | 1,511 | 1,511 |
| Number of nations            | 118  | 118  | 91    | 91    | 70    | 70    | 118  | 118  | 91    | 91    | 70    | 70    |
| Observations per nation      | 14/23.6/24 | 14/23.6/24 | 3/22.7/24 | 3/22.7/24 | 2/21.6/24 | 2/21.6/24 | 14/23.6/24 | 14/23.6/24 | 3/22.7/24 | 3/22.7/24 | 2/21.6/24 | 2/21.6/24 |
| (minimum/average/maximum)    | R²   | .0628 | .0627 | .118 | .116 | .185 | .168 | .0905 | .0900 | .115 | .115 | .154 | .148 |
| BIC                          | -4.686.4 | -4.694.3 | -5.519 | -5.521.5 | -4,267.4 | -4,243.5 | -7.608.8 | -7.615.2 | -6.930.9 | -6.938.1 | -5,254.4 | -5,251.0 |
| ρ                            | .0152 | .0153 | .0352 | .0362 | .0498 | .0445 | .0464 | .0451 | .0755 | .0761 | .0837 | .0856 |

Note: In the model labels, C stands for consumption-based emissions, P stands for production-based emissions, a stands for asymmetrical models, and s stands for symmetrical models. Unstandardized coefficients are reported with robust standard errors in parentheses. All models include unreported country-specific and year-specific intercepts. BIC = Bayesian information criterion; GDP = gross domestic product.

*p < .05, **p < .01, and ***p < .001 (two-tailed tests).
corresponding coefficients in models P1a to P3a, while the coefficients for increases in GDP per capita in models C1a to C3a have values similar to the corresponding coefficients in models P1a to P3a. For both outcomes, as we restrict the sample to nations with relatively larger populations, the coefficients for increases in GDP per capita become smaller while the coefficients for decreases in GDP per capita become larger.

All symmetric models report positive and significant coefficients for changes in GDP per capita. Models C1s and C2s generate similar coefficients of 0.419 and 0.430, while model C3s generates a larger coefficient of 0.636, suggesting that the association between consumption-based emissions per capita and GDP per capita for country-years with populations larger than 10 million is greater than for the other two samples. Models P1s to P3s generate relatively similar coefficients for changes in GDP per capita, ranging from 0.320 to 0.404, which suggests that the relationship between production-based emissions per capita and GDP per capita does not vary substantially across countries with different population sizes, at least when we model the relationship as symmetric.

Tables A3 and A4 in the Appendix present the estimates for asymmetric models that include the additional independent variables. When exports (%GDP) and imports (%GDP) are included (as in Table A3), the results are substantively similar to the baseline models reported in Table 1. When all five additional independent variables are included (as in Table A4), the coefficients for increases and decreases in GDP per capita become significantly different from each other for the sample of country-years with populations larger than 5 million, for both emissions outcomes. However, including all five additional independent variables further restricts the sample size because of missing data, and goodness-of-fit measures (Bayesian information criterion) favor the baseline models. For these reasons, we prefer to focus on the results for the models reported in Table 1. In additional unreported analyses, we estimate models for samples of country-years with populations larger than 0.5 million and 1 million, all of which yield findings substantively consistent with the reported models for the full sample. We also estimate random-effects models with the same samples and parameterizations, and find that the results are substantively similar to the results of the fixed-effects models reported in Table 1. Full information for these unreported analyses are available from the authors upon request.

**Discussion and Conclusion**

The purpose of this study is to help advance the growing body of socioenvironmental research on asymmetry by pursuing three research questions: First, is the relationship between nations’ economic development and consumption-based carbon dioxide emissions asymmetrical? Second, does the potential asymmetry in the association with development differ between consumption-based emissions and production-based emissions? And, third, do asymmetric relationships between development and carbon emissions vary for nations with different population sizes?

We find no evidence of asymmetry, on the basis of tests of statistical significance, in the relationship between consumption-based carbon dioxide emissions and economic development for either the full sample of nations or the reduced sample of nations with populations larger than 5 million. However, we find contraction-leaning asymmetry for the sample of nations with populations larger than 10 million, in which the reduction rate of per capita consumption-based emissions during economic contraction is greater than its growth rate during economic expansion.

The findings for production-based emissions are similar, with a contraction-leaning asymmetry only observed for the sample of nations with populations larger than 10 million. For this group of nations, the difference in magnitude between the effects of economic expansion and contraction is larger for consumption-based emissions than for production-based emissions. This is due partly to the effect of economic contraction on consumption-based emissions being larger in magnitude than its effect on production-based emissions, while economic expansion affects both emissions outcomes at similar magnitudes.

The existence and degree of asymmetry between development and carbon dioxide emissions vary across groups of nations with different population sizes, with similar patterns of variation for both emissions outcomes. The nonexistence of asymmetry in the full sample could be resulting from the heterogeneity introduced by, among other possible factors, nations with smaller populations, which warrants deeper investigation in future research.

Prior research proposes two mechanisms to explain the opposite types of asymmetry: infrastructural momentum (York 2012; York and Light 2017) causes expansion-leaning asymmetry, while the behavioral-operational shift (Shahiduzzaman and Layton 2015; Sheldon 2017) leads to contraction-leaning asymmetry. A thorough investigation of the mechanisms underlying the asymmetry that we observe in some of our estimated models but not in others is beyond the scope of this study. Nevertheless, our findings may be partially explained by the relative strength of the two mechanisms. In countries with larger populations, the behavioral-operational shift could outweigh infrastructural momentum in affecting carbon dioxide emissions, leading to a contraction-leaning asymmetry and especially so for consumption-based emissions. In the full sample that also includes nations with smaller populations, the infrastructural momentum and the behavioral-operational shift may offset each other in cross-national contexts, which leads to an observed symmetric emissions-development relationship. And it is quite likely that processes and conditions other than infrastructural momentum and behavioral-operational shifts are relevant as well.
We do not find expansion-leaning asymmetry for either production-based emissions or consumption-based emissions, which is in contrast with York’s (2012) results. We suggest these contrasting findings could be due, at least partly, to the differences in the timespan and nations included in our study relative to York’s analysis. Our study includes data for years after 2008, when the great recession occurred, but excludes data for years prior to 1990, which constitute the majority of the timespan covered in York’s study. During economic downturns governments may provide economic stimulus and other incentives that support investment in renewable energy (Geels 2013), potentially leading to the opposite form of infrastructural momentum in which less carbon-intensive infrastructure built during economic contraction continues to curb the growth in carbon dioxide emissions during subsequent economic expansions (cf. Schor 2014). Economic downturns are also associated with changes in the impacts of international trade on carbon emissions (Huang forthcoming). Such changes likely affect the consumption-based emissions of importing nations and production-based emissions of exporting nations.

Overall, we suggest that the differences in findings across studies underscore the need for more nuanced research and deeper theorization on asymmetry in the relationship between economic development and anthropogenic emissions as well as how such model estimations are sensitive to the composition of analyzed samples and how the underlying causes of asymmetries, when observed, might change through time. We hope this study will help facilitate such future investigations.

Appendix

Table A1. Countries Included in the Analyses.

| Albania | Dominican Republic<sup>a,b</sup> |
|---------|---------------------------------|
| United Arab Emirates<sup>a</sup> | Ecuador<sup>a,b</sup> |
| Argentina<sup>a,b</sup> | Egypt<sup>a</sup> |
| Armenia | Spain<sup>a</sup> |
| Australia<sup>a,b</sup> | Estonia |
| Austria<sup>a</sup> | Ethiopia<sup>a,b</sup> |
| Azerbaijan<sup>a</sup> | Finland<sup>a</sup> |
| Belgium<sup>a,b</sup> | France<sup>a,b</sup> |
| Benin<sup>a,b</sup> | United Kingdom<sup>a,b</sup> |
| Burkina Faso<sup>a,b</sup> | Georgia |
| Bangladesh<sup>a,b</sup> | Ghana<sup>a,b</sup> |
| Bulgaria<sup>a</sup> | Guinea<sup>a,b</sup> |
| Bahrain | Greece<sup>a,b</sup> |
| Belarus<sup>a,b</sup> | Guatemala<sup>a,b</sup> |
| Bolivia<sup>a,b</sup> | Hong Kong<sup>a</sup> |
| Brazil<sup>a,b</sup> | Honduras<sup>a</sup> |
| Brunei | Croatia |
| Botswana | Hungary<sup>a,b</sup> |
| Canada<sup>a,b</sup> | Indonesia<sup>a,b</sup> |
| Switzerland<sup>a</sup> | India<sup>a,b</sup> |
| Chile<sup>a,b</sup> | Ireland |
| China<sup>a,b</sup> | Iran<sup>a,b</sup> |
| Cote d’Ivoire<sup>a,b</sup> | Israel<sup>a</sup> |
| Cameroon<sup>a,b</sup> | Italy<sup>a,b</sup> |
| Colombia<sup>a,b</sup> | Jamaica |
| Costa Rica | Jordan<sup>a</sup> |
| Cyprus | Japan<sup>a</sup> |
| Czech Republic<sup>a,b</sup> | Kazakhstan<sup>a,b</sup> |
| Germany<sup>a,b</sup> | Kenya<sup>a,b</sup> |
| Denmark<sup>a</sup> | Kyrgyz Republic<sup>a</sup> |
| Cambodia<sup>a,b</sup> | South Korea<sup>a,b</sup> |
| Kuwait | Lao PDR<sup>a</sup> |
| Sri Lanka<sup>a,b</sup> | Lithuania |
| Luxembour | Latvia |
| Morocco<sup>a,b</sup> | Madagascar<sup>a,b</sup> |
| Mexico<sup>a,b</sup> | Malta |
| Mongolia | Mozambique<sup>a,b</sup> |
| Mauritius | Malawi<sup>a,b</sup> |
| Malaysia<sup>a,b</sup> | Namibia |
| Nigeria<sup>a,b</sup> | Nicaragua<sup>a</sup> |
| Netherland<sup>a,b</sup> | Norway<sup>a</sup> |
| Nepal<sup>a,b</sup> | New Zealand |
| New Zealand | Oman |
| Pakistan<sup>a,b</sup> | Panama |
| Peru<sup>a</sup> | Philippines<sup>a,b</sup> |
| Poland<sup>a,b</sup> | Portugal<sup>a,b</sup> |
| Paraguay<sup>a</sup> | Qatar |
| Romania<sup>a,b</sup> | Russian Federation<sup>a,b</sup> |
| Rwanda<sup>a,b</sup> | Saudi Arabia<sup>a,b</sup> |
| Senegal<sup>a,b</sup> | Singapore<sup>a</sup> |
| El Salvador<sup>a</sup> | Slovak Republic<sup>a</sup> |
| Slovenia | Sweden<sup>a</sup> |
| Ethiopia<sup>a,b</sup> | Togo<sup>a</sup> |
| Thailand<sup>a,b</sup> | Trinidad and Tobago |
| Tunisia<sup>a</sup> | Turkey<sup>a,b</sup> |
| Tanzania<sup>a,b</sup> | Uganda<sup>a,b</sup> |
| Ukraine<sup>a</sup> | Uruguay |
| United States<sup>a,b</sup> | United States<sup>a</sup> |
| Venezuela<sup>a</sup> | Vietnam<sup>a,b</sup> |
| Vietnam<sup>a</sup> | South Africa<sup>a,b</sup> |
| South Africa<sup>a</sup> | Zambia<sup>a</sup> |
| Zimbabwe<sup>a,b</sup> | Zimbabwe<sup>a,b</sup> |

<sup>a</sup> Countries in the reduced sample of country-years with populations larger than 5 million.
<sup>b</sup> Countries in the reduced sample of country-years with populations larger than 10 million.
Table A2. Descriptive Statistics.

| Variable                          | n  | Mean    | SD    | Minimum | Maximum |
|-----------------------------------|----|---------|-------|---------|---------|
| Overall sample                    |    |         |       |         |         |
| Consumption-based CO₂ per capita | 2,784 | 0.0066 | 0.1050 | -0.9608 | 1.1616  |
| Production-based CO₂ per capita  | 2,784 | 0.0033 | 0.0642 | -0.5657 | 0.5919  |
| GDP per capita                    | 2,784 | 0.0209 | 0.0494 | -0.6502 | 0.3147  |
| Increases in GDP per capita      | 2,784 | 0.0295 | 0.0296 | 0        | 0.3147  |
| Decreases in GDP per capita      | 2,784 | -0.0086| 0.0325 | -0.6502 | 0       |
| Country-years with populations > 5 million |    |         |       |         |         |
| Consumption-based CO₂ per capita | 2,068 | 0.0052 | 0.0663 | -0.8806 | 0.4113  |
| Production-based CO₂ per capita  | 2,068 | 0.0031 | 0.0482 | -0.3691 | 0.3002  |
| GDP per capita                    | 2,068 | 0.0208 | 0.0449 | -0.6502 | 0.3147  |
| Increases in GDP per capita      | 2,068 | 0.0283 | 0.0286 | 0        | 0.3147  |
| Decreases in GDP per capita      | 2,068 | -0.0076| 0.0277 | -0.6502 | 0       |
| Country-years with populations > 10 million |     |         |       |         |         |
| Consumption-based CO₂ per capita | 1,511 | 0.0056 | 0.0630 | -0.8806 | 0.4113  |
| Production-based CO₂ per capita  | 1,511 | 0.0043 | 0.0460 | -0.3691 | 0.3002  |
| GDP per capita                    | 1,511 | 0.0212 | 0.0409 | -0.2555 | 0.2651  |
| Increases in GDP per capita      | 1,511 | 0.0285 | 0.0269 | 0        | 0.2651  |
| Decreases in GDP per capita      | 1,511 | -0.0072| 0.0231 | -0.2555 | 0       |

Note: All variables are transformed with natural logarithm and first-differencing. GDP = gross domestic product.

Table A3. Asymmetrical Models for Consumption-based and Production-based Carbon Dioxide Emissions per Capita, 1990 to 2014, Controlling for Exports and Imports.

|                | All Nations | Population > 5 Million | Population > 10 Million | All Nations | Population > 5 Million | Population > 10 Million |
|----------------|-------------|------------------------|--------------------------|-------------|------------------------|--------------------------|
|                | C1          | C2                     | C3                       | P1          | P2                     | P3                       |
| Increases in GDP per capita | 0.371***     | 0.278***               | 0.270*                   | 0.393***    | 0.300***               | 0.274***                 |
| Decreases in GDP per capita | 0.440***     | 0.499***               | 0.804***                 | 0.330***    | 0.365**                | 0.572***                 |
| Asymmetry exists (Wald test rejects equality)? | No          | No                     | Yes**                   | No          | No                     | Yes*                     |
| Exports (%GDP) | -0.237***    | -0.217***              | -0.198***                | -0.0114     | -0.0215†               | -0.0134                  |
| Imports (%GDP) | 0.116***     | 0.0913*                | 0.0275                   | 0.0267      | 0.0276                 | 0.000362                 |
| n              | 2,740        | 2,041                  | 1,488                    | 2,740       | 2,041                  | 1,488                    |
| Number of nations | 118         | 91                     | 70                       | 118         | 91                     | 70                       |
| Observations per nation (minimum/average/maximum) | 3/23.2/24    | 3/22.4/24              | 2/21.3/24               | 3/23.2/24   | 3/22.4/24              | 2/21.3/24               |
| R²             | .118         | .237                   | .320                     | .102        | .121                   | .160                     |
| BIC            | -4,787.0     | -5,756.9               | -4,496.0                 | -7,678.7    | -6,812.4               | -5,149.3                 |
| ρ              | .0158        | .0390                  | .0481                    | .0505       | .0739                  | .0817                    |

Note: In the model labels, C stands for consumption-based emissions, and P stands for production-based emissions. Unstandardized coefficients are reported with robust standard errors in parentheses. All models include unreported country-specific and year-specific intercepts. BIC = Bayesian information criterion; GDP = gross domestic product.†p < .10, *p < .05, **p < .01, ***p < .001 (two-tailed tests).
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