DISCUSSION PAPER SERIES

IZA DP No. 10380

Population Growth and Carbon Emissions

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November 2016

Forschungsinstitut
zur Zukunft der Arbeit
Institute for the Study
of Labor

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November 2016

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IZA Discussion Paper No. 10380
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ABSTRACT

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We provide evidence that lower fertility can simultaneously increase income per capita and lower carbon emissions, eliminating a trade-off central to most policies aimed at slowing global climate change. We estimate the effect of lower fertility on carbon emissions accounting for the fact that changes in fertility patterns affect carbon emissions through three channels: total population, the age structure of the population, and economic output. Our analysis proceeds in two steps. First, we estimate a version of the STIRPAT equation on an unbalanced yearly panel of cross-country data from 1950-2010. We demonstrate that the coefficient on population is nearly seven times larger than the coefficient on income per capita and that this difference is statistically significant. Thus, regression results imply that 1% slower population growth could be accompanied by an increase in income per capita of nearly 7% while still lowering carbon emissions. In the second part of our analysis, we use a recently constructed economic-demographic model of Nigeria to estimate the effect of lower fertility on carbon emissions accounting for the impacts of fertility on population growth, population age structure, and income per capita. The model was constructed to estimate the effect of lower fertility on economic growth, making it well-suited for this application. We find that by 2100 C.E., moving from the medium to the low variant of the UN fertility projection leads to 35% lower yearly emissions and 15% higher income per capita. These results strongly suggest that population policies should be a part of the approach to combating global climate change.

JEL Classification: J11, O40, Q50

Keywords: climate change, economics, demography

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* We thank Lint Barrage and Matthew Turner for helpful comments and Quamrul Ashraf for sharing the economic-demographic model with us.

1 Introduction

Population growth is a major driver of carbon emissions, both historically and in projections of future emissions [1, 2]. Yet, relatively little attention has been devoted to investigating the potential for population policies to influence global climate change [3]. Motivated by this fact, this paper examines the effect of lower fertility on carbon emissions, taking into account three crucial channels: total population, the age structure of the population, and output per capita. We provide evidence that lower fertility can simultaneously increase income per capita and lower carbon emissions, even without taking into account economic damages from climate change. This result is in stark contrast to other environmental policies, such as carbon taxes and cap-and-trade policies, which must balance environmental benefits against lost output [4]. Thus, our results strongly suggest that population policies can serve as an effective tool to combat global climate change.

Our analysis proceeds in two steps. First, we estimate a version of the STIRPAT equation to find the partial elasticities of carbon emissions with respect to population, output per person, and the age structure of the population [5, 6]. Consistent with existing literature, we find that the partial elasticity of emissions with respect to population is larger than the elasticity with respect to output per person [7], and we are the first to provide formal statistical evidence for this fact. The partial elasticity of emissions with respect to population is nearly 7 times greater than the elasticity with respect to income per capita. This implies that 1% slower population growth could be accompanied by an increase in income per capita of nearly 7% while still decreasing carbon emissions, eliminating a trade-off central to other environmental policies.

By themselves, STIRPAT regressions cannot tell us about the impacts of changes in population on emissions, because population growth will affect carbon emissions both directly and through the other explanatory variables [3, 8]. To overcome this problem, the second step of our analysis employs a recently developed economic-demographic model of Nigeria to estimate the effect of lower fertility on both carbon emissions and income per capita [9]. The model was developed to estimate the effect of fertility on income per capita, and we use our regression results to estimate the impact of lower fertility on emissions. We find that by 2100 C.E. moving from the medium to the low variant of the UN fertility projection leads to 35% lower yearly emissions and 15% higher income per capita.

These results have important implications for climate change policy. It is widely accepted, and enshrined in international agreements, that the burden of mitigating global climate change needs to vary between rich and poor countries in order to ensure that developing countries can continue to experience economic growth and poverty reduction [10, 11]. At the same time, the projected economic and population growth in the developing world indicates that these poorer countries will be substantial contributors to climate change [12]. Thus, there is a desperate need to find policy options that will lessen emissions from developing countries without impeding economic development. Our analysis suggests that population policies can achieve this difficult goal. Moreover, if population policies eliminate the trade-off between environmental and economic priorities, then they will not suffer from the free-rider problems that pose a central challenge in current approaches to mitigating global climate change [13, 14].

To the best of our knowledge, we are the first to demonstrate how population policies can simultaneously increase income per capita and lower carbon emissions, eliminating a trade-off central to existing policy proposals. Our paper, however, is closely related to two existing literatures. The first is the literature estimating the STIRPAT equation [15, 7]. Our key contribution to this literature is to examine how the STIRPAT equation provides evidence for the ability of reductions in population to achieve both economic and environmental priorities. From a statistical perspective, we build on the existing STIRPAT literature by formally testing the difference in coefficients between population and income per capita and by using an updated dataset for output per person. Second, our work is related to applications of the population-energy-technology (PET) model that estimate the effect of exogenous changes in population and urbanization on carbon emissions [16, 3, 2]. We build on this literature by expressly examining economic outcomes and by considering a broader range of channels through which changes in fertility affects these economic outcomes.

2 The STIRPAT equation

2.1 Methods

The first step of our analysis is to estimate the elasticity of carbon emissions with respect to income per capita and population. To do so, we estimate the STIRPAT equation:

$$I_{i,t} = P_{i,t}^{a} A_{i,t}^{b} T_{i,t}^{\tilde{c}} e_{i,t}, \tag{1}$$

where $I_{i,t}$ is environmental impact in country i at time t, P is population, A is affluence (income per capita), T is technology, and e is the residual error term. A substantial literature analyzes STIRPAT regressions to examine the determinants of many measures of the environmental impact of human activity [7]. We focus on total carbon emissions.

The STIRPAT equation is derived from the IPAT accounting identity [17, 18], and most applications of STIRPAT are focused on decomposing environmental impacts between explanatory variables. This decomposition can be aimed at explaining past emissions or predicting future emissions. Our goal is slightly different. We want to understand the effect of changes in fertility on both environmental and economic outcomes, accounting for the effect of fertility on population levels, population structure, and income per capita. Thus, we use the partial elasticities from the regression equation to parameterize our economic-demographic model (see section 3).

Given our goal, the difference between the coefficients on population (a) and affluence (b) is of primary importance. Thus, in all regressions, we test the null hypothesis of $a = b$. While the literature provides a wide range of estimates for both coefficients – depending on the dependent variable under consideration and the choice of regression specification – we are the first to test for a difference in coefficients between population and affluence [7]. If a is significantly larger than b, then decreases in population can lower carbon emission even while substantially increasing income per capita, overcoming the trade-off central to most environmental policies.

To estimate equation (1), it is necessary to assume a specification for technology (T). We make the following assumption:

$$lnT_{i,t} = \tilde{f}_i + \tilde{g}_t + hlnS_{i,t} + x'_{i,t}\tilde{\delta}, \tag{2}$$

where f_i is a fixed effect capturing time-invariant differences between countries, g_t is a fixed effect capturing differences in global technology over time that affect all countries, $S_{i,t}$ is a measure of the age structure of the population, and $x_{i,t}$ is a set of control variables including urbanization and trade. All three of the time-varying explanatory variables have been found to affect carbon emissions in the existing literature [19, 2, 15]. The inclusion of age structure, $S_{i,t}$, is important for our results since changes in fertility patterns mechanically alter the age structure of the population, implying that we need to capture this effect in the economic-demographic model. We assume that trade and urbanization, however, are not directly affected by fertility or income per capita. Thus, we include them in the regressions to avoid omitted variable bias, but do not employ them in our simulation model. In the appendix, we also include income per capita squared to capture the environmental Kuznets curve (EKC), but the term is insignificant in our main specification.

Recent advances in the STIRPAT literature have demonstrated the importance of correcting for potentially non-stationary variables [20, 15]. Thus, our main specification estimates a log-linearized version of (1) in first differences. Thus, our estimating equation becomes:

$$\begin{gathered} lnI_{i,t} - lnI_{i,t-1} = a(lnP_{i,t} - lnP_{i,t-1}) + b(lnA_{i,t} - lnA_{i,t-1}) + \\ c(lnS_{i,t} - lnS_{i,t-1}) + (x_{i,t} - x_{i,t-1})'\delta + (g_t - g_{t-1}) + (lne_{i,t} - lne_{i,t-1}), \end{gathered} \tag{3}$$

where $c = \tilde{c}h$, $\delta = \tilde{\delta}h$, and $g_t = h\tilde{g_t}\ \forall t$. It is crucial to note that the coefficients on population and affluence are still the same as in equation (1).

Our equation is estimated on an unbalanced yearly panel of countries. We use standard sources for all data. Our dependent variable is carbon emissions from production, which are from Oak Ridge National Laboratory [21]. Our measures of population and income per capita come from the Penn World Tables (PWT) version 8 [22]. We employ the newly created output-side measure of income per capita, which is the best match for our emissions measure. Age structure, urbanization and trade data are all from the

World Bank's World Development Indicators database. To capture age structure, we use the fraction of population of between the ages of 15-64, which we denote as 'working age.' In the appendix, we show that all our results are robust to alternate measures of income, alternate samples, and alternate estimation strategies.

2.2 Results

Table 1 presents the results of the STIRPAT regression using equation (3). In column 1, we present a simple regression with only population and income per capita as explanatory variables. This specification highlights the potential for lower population to decrease emissions and increase income per capita simultaneously. Specifically, the coefficient on income per capita is .207, while the coefficient on population size is 1.364, a 6.7-fold difference. The difference is statistically significant at the .1% level. The difference in coefficients implies that a decrease in population can both decrease emissions and raise income per capita as long as the elasticity of income per capita with respect to population is less than 6.7. Thus, decreases in population can achieve both environmental and economic policy priorities. To ensure that this result is not driven by outliers, figure 1 presents the residual scatter plot from the regression in column 1.

Column 2 adds the share of the working age population, the other key variable to be affected by a change in fertility. While significant, the inclusion of the working age population has little effect on the population and income per capita coefficients. To ensure that our results are not driven by omitted variables, the final two columns add controls for urbanization and trade. Again, the key results are unchanged. In all cases, the equality of coefficients can be rejected at the .1% level. Importantly, the regression coefficients are not substantially altered by the inclusion of urbanization or trade, which provides support for our assumption that changes in population do not affect carbon emissions through these channels. If urbanization was an important channel through which population led to increases in emissions, the coefficient on population would decrease substantially once urbanization was included as a control variable in the regression. Our preferred specification is column 4, which includes controls for the major confounding variables identified in the literature. Thus, we use this specification to parameterize the economic-demographic model in the second phase of our analysis.

In the appendix, we show that our key qualitative result – the large difference in coefficients between population and income per capita – holds in a number of other settings. To ensure that the results are not driven by attenuation bias, which can be exacerbated by differencing, we demonstrate that the results hold when estimating the equation in levels. In this case, the squared term on income per capita becomes significant. While our goal is not to provide a detailed examination of the EKC relationship, the fact that first differencing removes the squared term is consistent with existing literature [23]. We also show that the results are unaffected by moving to a balanced sample of countries, indicating that the results are not driven by the changing sample. We also re-estimate the STIRPAT equation using total income, instead of income per capita. The population coefficient is statistically significant in this specification, further supporting the idea that population matters above and beyond increasing total output. Finally, we show that the qualitative results are unchanged if we use several other measures of income per capita. We use the consumption-side and national accounts measures from the PWT, demonstrating that our results are not driven by the use of the output side measure, as well as the exchange-rate based measure from World Development Indicators, demonstrating that our results are not a byproduct of the adjustments for price differences across countries.

2.3 Discussion of regression results

The regression coefficients presented in table 1 capture the effect of the explanatory variables on carbon emissions through two key channels, the energy intensity of output and the carbon intensity of energy, in addition to their direct effects. Unfortunately, regressions of this type cannot tell us more about the specific mechanism through which population and output affect carbon emissions. Since our economic-demographic model does not explicitly model the energy intensity of output or the carbon intensity of energy, we rely on the simplified reduced-form relationship provided by the STIRPAT regression to parameterize the effects of population, age structure, and income on carbon emissions. Understanding the exact causal mechanisms underlying these regression results is an interesting and important way forward for future work in this area.

While we are the first to formally test for the difference in coefficients between population and income per capita, these results are consistent with the existing literature. Jorgensen and Clark estimate an equation similar to ours, and the results display the same qualitative pattern [19]. Specifically, they find a population elasticity of 1.43 and an income per capita elasticity of .65 in their first-differenced specification with similar results in alternate specifications. Our major differences in specification, in addition to formally testing for different coefficients, include the use of new data, differing time scales, the inclusion of age structure, and the use of time fixed-effects in all specifications. They find that the elasticities are relatively stable across time and space [19, 24]. Knight *et al* also find similar results when focusing on alternate population measures such as employed persons and hours worked [25]. For example, when also controlling for hours worked, they find a population elasticity of 2.25 and an income per capita elasticity of .59. Earlier work, which did not use panel data to mitigate omitted variable bias, finds similar coefficients for population and income per capita [5, 6]. More exhaustive reviews of elasticities found in the existing literature, as well as discussions of different estimation techniques and specifications, can be found in O'Neill *et al* (2012) and Liddle (2014, 2015) [2, 15, 7].

More recently, a growing literature has included 'intensity' variables, such as the energy intensity of output, in STIRPAT regressions and found more similar coefficients between population and income per capita [26, 20, 7]. This addition is an important step forward in accounting applications of STIRPAT, but is not appropriate for our purpose. Our goal is to determine whether decreases in fertility can simultaneously achieve economic and environmental policy priorities. As noted above, our economic-demographic model does not have an explicit energy sector, and therefore, the appropriate regression coefficients must include the effect of population and income on carbon emissions via the energy intensity of output and the carbon intensity of energy. Earlier results including 'intensity' variables suggest that the difference in elasticities between population and income per capita could be explained by a greater effect of population on the energy intensity of output, which is an interesting area for further study. As discussed in section 3.2, the careful modeling of fertility and omission of an explicit energy sector in the economic-demographic model represent a trade-off when compared to modeling strategies based on PET [16, 3, 2]. Section 4 discusses several ways that the current analysis could be extended in future work, including more explicit modeling of the energy sector.

3 The Impact of fertility on economic and environmental outcomes

3.1 Methods

The second step of our analysis quantifies the effect of lower fertility on economic and environmental outcomes. STIRPAT regressions, while useful for decomposition exercises, are insufficient for determining the overall environmental impact of an exogenous change in an explanatory variable [3, 8]. The regression cannot tell us about the relationship between the explanatory variables. To fully account for these interdependencies, we use the economic-demographic model developed by Ashraf, Weil, and Wilde (AWW) [9]. The model was constructed explicitly to evaluate the effect of changes in fertility on income per capita, making it well-suited for our purposes. We examine the effect of an exogenous reduction in fertility on both economic and environmental outcomes in Nigeria. As in the original analysis, our exogenous change in fertility is a movement from the medium to the low variant of the UN fertility projections, though we use the most recent projections [27].

The AWW model examines the effect of fertility on economic growth through several channels, which can be divided into three main categories. We call the first category *composition effects*. Changes in fertility alter the age structure of the population, which affects economic output through the number of people of working age (the 'dependency effect'), savings behavior (the 'life-cycle saving effect'), and labor supply differences within the working age population (the 'life-cycle labor supply effect'). We deem the second category *behavioral effects*, which encompasses changes in economic behavior for an individual as a direct result of having children. When fertility is reduced, parents have more time to work (the 'childcare effect') and can invest more resources in the education of each child (the 'child-quality effect'). The third category is *factor accumulation*. High fertility reduces the amount of physical capital per person (the 'Solow effect') and natural capital per person (the 'Malthus effect'). Moreover, the increase in labor force participation caused by lower fertility leads to greater human capital via work experience (the 'experience effect').

We use the AWW model to measure the effect of the change in fertility on the total population level, the age structure of the population, and income per capita. We then combine the model output with our regression results from column 4 in table 1 to estimate the impact on carbon emissions. Since we do not know the future values for the time fixed effects, we estimate the ratio of carbon emission between the two scenarios.

Our work in closely related to analyses that estimate the effect of exogenous changes in population and urbanization on carbon emissions using the PET model [16, 3, 2]. The key difference between the analyses is that the present paper is expressly interested in the effect of fertility on both economic and environmental outcomes. Thus, we use an economic-demographic model specifically designed to estimate the effects of fertility on economic growth, accounting for all of the channels discussed above. The earlier works focus on compositional effects and do not report economic outcomes from their analyses.

This approach involves trade-offs. The PET model captures rich details of the population composition and energy sector, but only examines some of the channels through which fertility affects economic outcomes. Another strength of the AWW model lies in the careful selection of well identified parameters taken from the existing microeconomic literature. Thus, the parameters are strongly grounded in the historical experience of Nigeria. The strict requirements for parameterizing the model, however, imply that it can only be applied in a single country, unlike the PET model. Also, the demographic model does not explicitly model the energy sector. Instead, we use the STIRPAT regressions to capture the reduced-form effects of population, age structure, and income on carbon emissions.

3.2 Results

The results of our analysis are presented in figure 2. In all cases, results are presented as the ratio of the outcome under the low fertility scenario compared to the outcome under the medium fertility scenario. Panel A presents the outcomes of the major variables in the analysis. Emissions are sharply reduced under the low fertility scenario, while income per capita increases. This is the key qualitative message of our analysis. Specifically, emissions fall by 10% by 2055 and 35% by 2100. Income per capita, meanwhile, increases by 10% in 2055 and 15% by 2100. Thus, the income gains occur sooner, while emission reductions are back-loaded.

The share of the population that is of working age increases slightly as a result of the change in fertility patterns. At its highest point, the share is 4.5% higher than it would have been without the reduction in fertility. The reduction in population follows a path very similar to that of total emissions, demonstrating how strongly changes in population levels drive emissions.

Panel B translates these effects into their impact on emissions. As suggested by panel A, emission reductions due to lower population drive the results. Increases in the working age fraction of the population and income per capita have only small positive effects on emission levels. Between the two, the change in the working age share has a bigger effect on emissions than does the increase in income per capita, though the effects become more similar over time.

The appendix includes results when using alternate specifications and measures of income per capita. In all cases, the qualitative effects are similar. The most significant difference occurs when using the balanced regression sample or estimating the regression in levels. In this case, emissions increase in the low fertility scenario briefly, due to the increase in the share of the working age population. By 2100, there is a substantial decline in emissions, leaving our key results unchanged.

4 Discussion

The trade-off between economic and environmental priorities is central to the most commonly discussed policies aimed at combating global climate change [4]. It is important to note that population policies have a positive effect on economic outcomes before considering the feedback from environmental to economic damages. This is the crucial difference with integrated assessment models – which often translate all damages in economic units – that show a positive effect of climate policies on economic outcomes [28, 29]. These feedback benefits would certainly still occur as a result of population policies, but they are not necessary to achieve positive economic outcomes.

While our primary goal is simply to demonstrate that lower population policies can simultaneously increase income per capita and lower carbon emissions, our results also have substantial implications for policy. First, implementing population-based policies in developing countries can help overcome problems of international burden sharing in the reduction of climate change [30, 10]. This is especially relevant given high predicted fertility in developing countries and evidence for a high unmet demand for contraceptives [31, 27]. Indeed, under certain burden-sharing agreements, poor African countries are not expected to substantially contribute to emission reductions over the next several decades [30, 32]. Yet, our analysis suggests that moving to a feasible fertility scenario in Nigeria can lower relative emissions by 10% in 2055 and 35% by 2100. Second, since such policies do not have inherent economic trade-offs, they do not suffer from free-rider problems, implying that it will be substantially easier to reach agreements to lower emissions through population-based policies [13, 14].

We do not argue that population policies are a panacea for solving environmental and economic problems. In particular, we have not shown that population policies are sufficient to meet reasonable emissions targets on a global scale or even that feasible reductions in fertility would bring emissions below their current level, which would require a reduction in the level of population. Instead, our results strongly suggest that population policies should be a component of the international approach to climate policy. Indeed, given the fact that many countries – especially wealthier countries, China, and Russia – contribute substantially to global carbon emissions despite having low rates of population growth, it is highly unlikely that population policies will be the primary driver of emission reductions. Still, whatever global emission reductions can be achieved via population policies can be achieved without the economic trade-off central to most other policies and will likely be easier to implement given the lack of free-rider concerns. To understand what role reduced fertility can play in the reduction of total global carbon emissions, future work would need to extend the analysis presented here to the entire world.

Our analysis has examined the effects of an exogenously lower path of fertility given by the UN, rather than the outcome of a specific policy or set of policies. There are many policies that may lead to lower fertility, the most obvious of which is the provision of contraceptives. There are a number of other policies, however, which would also alter fertility in developing countries. As with all decisions, parents have limited resources to allocate to raising children and, as a result, many economic policies will influence fertility rates. In particular, parents must decide how to allocate resources between having more children and investing in the future of each child [33, 34]. There is considerable evidence for this 'quantity-quality trade-off' in the economics literature [35, 36]. Thus, policies that increase incentives for investment in education, for example, can also lead to lower fertility levels. Any policy that affects fertility will likely affect the evolution of population, age structure, and income per capita through other avenues, such as the effects of increased taxes or changes in government budgets. Examining the effects of particular policies represents an important area for future research to build on the analysis presented here.

While this analysis has demonstrated the potential for reductions in fertility to simultaneously achieve environmental and economic policy priorities, many opportunities remain to extend the analysis, as noted above. First, the model employed here does not include a detailed representation of the energy sector. Understanding how population, age structure, and income per capita differentially affect the energy intensity of output and carbon intensity of energy is an important step towards understanding why lowering fertility can have such positive outcomes and how to design targeted policies that can overcome trade-offs central to most efforts at combating global climate change. Including such mechanisms in the modeling stage of an analysis like ours could also sharpen the quantitative estimates. Second, expanding the geographic scope of the analysis is necessary to more fully understand the role that population policies can play in mitigating global climate change. Finally, evaluation of any particular policy necessitates extending the analysis to include specific reasons for the decline in fertility, rather than taking such a change as exogenous.

5 Conclusion

We have demonstrated that lower fertility can simultaneously achieve environmental and economic policy priorities. This stands in stark contrast to most policy options aimed at mitigating global climate change, which involve significant trade-offs between wealth and environmental protection, at least before considering the economic damages caused by reduced environmental quality. Thus, our research suggests that population policies should be considered as part of the global policy response to climate change. Indeed, such policies will likely receive increased political support because they do not suffer from free-rider problems. We hope that our analysis will spur further research regarding the ability of population polices to combat climate change.

6 Supplemental Information

6.1 Data

Our emissions data comes from Oak Ridge National Laboratories and is standard in the literature [21]. The dependent variable is *Total CO_2 Emissions from Fossil Fuels*, which is measured in thousands of metric tons of Carbon. The estimates of carbon emissions are constructed using fossil fuel inputs in production [21, 37].

We take output and population data from version 8.0 of the Penn World Tables [22, 38]. The Penn World Tables measure real GDP, which accounts for differences in prices across countries. A major innovation of version 8 is that there are now several measures of real GDP. For our analysis, we use output side real GDP, *rgdpo*, which measures the level of production, as opposed to consumption, in the economy. This is best choice because our measure of CO_2 is calculated based on fossil fuel production, rather than consumption. GDP is measured in 2005 USD. We also take population values, *pop*, from the Penn World Tables. Output per capita is just the ratio of the two variables from the PWT. The data cover 1950-2010. We use alternate measures of income in robustness exercises.

We take data on the the population age structure, urbanization rates, and trade from the World Bank's World Development Indicators (WDI) database. Trade is measured as: $(exports + imports)/GDP$. We also use the exchange-rate adjusted measure of income per capita in robustness exercises.

We drop any country from the analysis that has GDP per capita greater than 100,000 in any year. We take these high GDP numbers to indicate that true production levels are not well measured by the PWT approach. This eliminates Bermuda, Brunei, Kuwait, Qatar, and Saudi Arabia. There are also two country-year observations with negative emissions, Senegal in 1968 and Yemen in 1990, which we drop from the analysis. Our qualitative findings are unchanged if we include all of these observations. We also remove Israel, Cyprus, and Malta, which are clear outliers that bias the results in favor of finding much larger coefficients on population.

6.2 Regression Analysis

Regressions were performed in *Stata* statistical software. *Within R-squared* is calculated using the user-created module *ivreg2* [39].

6.3 Demographic Simulation

Ashraf *et al.* (2014) construct an economic-demographic simulation model that uses standard economic modeling to predict the aggregate effects of an exogenous reduction in fertility [9]. They study Nigeria from 2005-2100 under the medium and low fertility projections from the United Nations [40]. The output of the model is future paths of population, age distribution, and output per capita under different fertility scenarios and parameters estimates. We employ the results from their main exercise, which has zero technology growth and the authors' preferred estimates for each of the key parameters. We update the analysis to use the newest version of the UN projections [27]. We then combine the model's projections for output per capita and population with our econometric estimates to construct predictions for relative carbon emissions under the two scenarios using the following equation:

$$
\begin{aligned}
\frac{emissions_{j,t}}{emissions_{k,t}} = exp\bigg(& 0.226 * \big(ln(gdppc_{j,t}) - ln(gdppc_{k,t})\big) \\
& + 1.439 * \big(ln(pop_{j,t}) - ln(pop_{k,t})\big), \\
& + 0.016 * \big(ln(WA_{j,t}) - ln(WA_{k,t})\big)\bigg),
\end{aligned} \tag{4}
$$

where j denotes outcomes under the low fertility scenario, k denotes outcomes under the medium fertility scenario, and WA is the percent of the population between ages 15-65.

We make a few modifications to the starting values in the model. The original model does not impose the actual levels of GDP for Nigeria and, instead, is only concerned with the ratio between the two scenarios. We impose the level of GDP and physical capital in 2005 using the data from PWT version 8.0 for Nigeria in 2005. Consistent with the regression data, we use output side real GDP, *rgdpo*, which is 220,303.3 million 2005 USD. For the capital stock, we use *rkna*, which is 'Capital Stock at Constant National Prices', yielding 339,150.3 million 2005 USD. Unfortunately, the capital stock is not available as an output side measure. We then normalize the 'Fixed Stock of Land' to 1. When combined with the 2005 stock of human capital, which is already calculated in the original model, this yields a level of technology of $A = 4.46$.

Our adjustments have a very slight effect on the ratio of output per capita that comes from the the model. Specifically, in 2100, the original formulation leads output per capita that is 15.80% higher than in the low fertility scenario. With our adjustments, the output per capita ratio in 2100 is 15.86% higher in the low fertility scenario. The ratio of population and the fraction of the population of working age are exogenous and unaffected by imposing the initial level of GDP.

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7 Tables and Figures

Table 1: Determinants of Carbon Emissions: GDP per capita and Population

	(1)	(2)	(3)	(4)
Ln pop. (a)	1.364***	1.469***	1.406***	1.439***
	(0.172)	(0.176)	(0.175)	(0.203)
Ln gdppc (b)	0.203***	0.207***	0.206***	0.226***
	(0.042)	(0.044)	(0.044)	(0.052)
% Age 15-64		0.016**	0.016**	0.016**
		(0.007)	(0.007)	(0.007)
% Urban			0.008*	0.014***
			(0.004)	(0.005)
Trade (% of GDP)				0.0002
				(0.0002)
Year FE	Yes	Yes	Yes	Yes
Observations	7133	6426	6426	5679
Countries	156	153	153	147
R-Squared	0.05	0.05	0.05	0.05
Within R-Squared	0.017	0.020	0.020	0.023
P-value: a = b	0.000	0.000	0.000	0.000
P-value: a = 1	0.036	0.009	0.022	0.032

Notes: $*p < 0.1, **p < 0.05, ***p < 0.01$. Robust standard errors clustered at country level in parentheses. Equation estimated in first differences. In all specifications, the dependent variable is the natural log of total CO_2 emissions. The sample covers 1950-2010. *Within R-squared* is the percentage of variation in the dependent variable explained by the independent variables after removing variation due to time and year fixed effects.

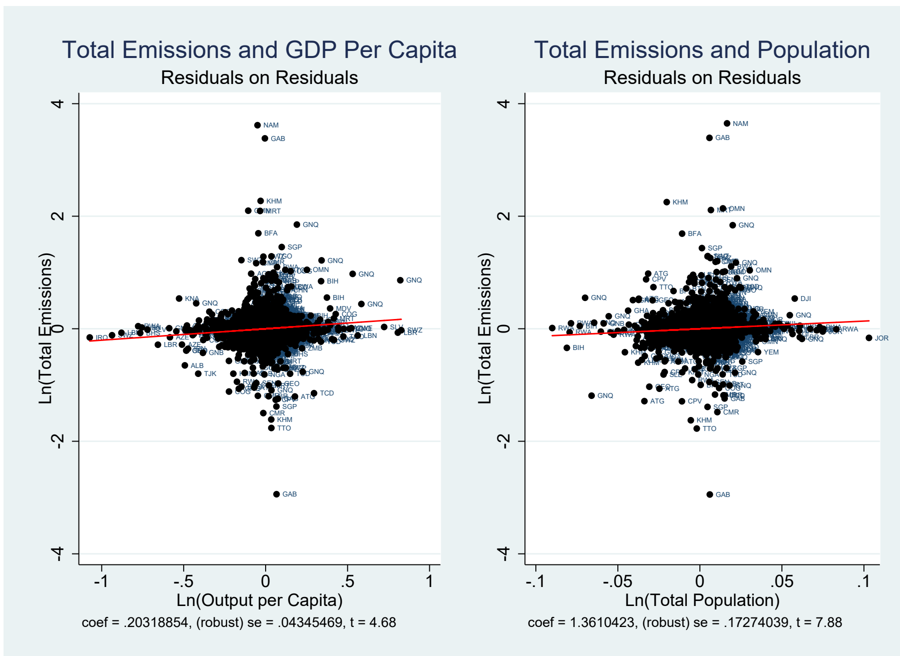

Figure 1: Partial residual plot from column 1 in table 1. Note that the x-axis is different in the two panels of the figure. This obscures the difference in slopes, which are listed below each scatter plot. The coefficient on population is significantly larger. The difference in scales is necessary for visual inspection of the role of outliers.

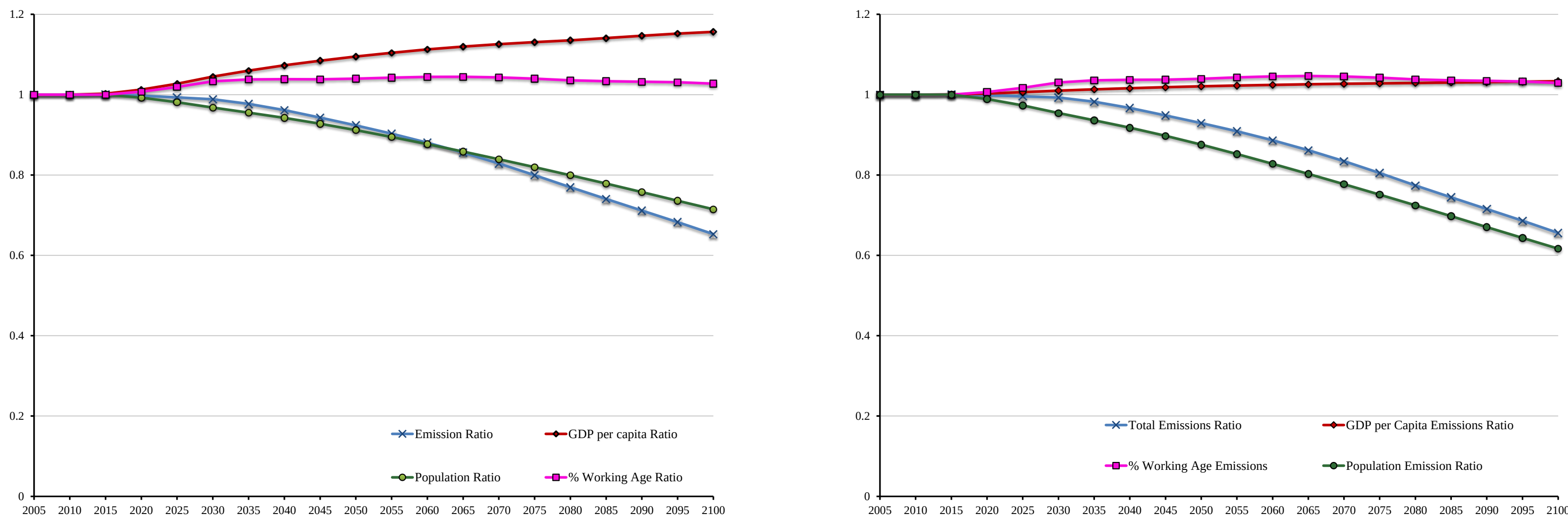

Figure 2: Results from the economic-demographic model. All variables are the ratio of the outcome of the low fertility scenario over the medium fertility scenario. *Panel A* (left) plots the main outcome variables. *Panel B* (right) decomposes the difference in emissions between sources.

8 Appendix

8.1 Summary Statistics

Table A1: Summary Statistics for Unbalanced Sample 1950-2010

	mean	sd	min	max
C02 Emissions (thous. metric tons of C)	38,406	153,483	5	2,259,856
GDP per Capita (2005 USD)	8,300	9,478	163	59,640
Pop. (millions)	37.67	128.4	0.06	1,318
% Age 15-64	58.59	6.74	45.92	75.18
% Urban	48.84	24.13	2.19	100.0
Trade (% of GDP)	73.04	51.71	0.02	531.7
Observations	5679			
Countries	147			

8.2 Results with Total GDP

Table A2: Determinants of Carbon Emissions: Total GDP

	(1)	(2)	(3)	(4)
Ln pop. (a)	1.161***	1.262***	1.200***	1.213***
	(0.169)	(0.179)	(0.177)	(0.199)
Ln gdp (b)	0.203***	0.207***	0.206***	0.226***
	(0.042)	(0.044)	(0.044)	(0.052)
% Age 15-64		0.016**	0.016**	0.016**
		(0.007)	(0.007)	(0.007)
% Urban			0.008*	0.014***
			(0.004)	(0.005)
Trade (% of GDP)				0.0002
				(0.0002)
Year FE	Yes	Yes	Yes	Yes
Observations	7133	6426	6426	5679
Countries	156	153	153	147
R-Squared	0.05	0.05	0.05	0.05
Within R-Squared	0.017	0.020	0.020	0.023
P-value: a = b	0.000	0.000	0.000	0.000
P-value: a = 1	0.342	0.145	0.260	0.285

Notes: $*p < 0.1, **p < 0.05, ***p < 0.01$. Robust standard errors clustered at country level in parentheses. Equation estimated in first differences. In all specifications, the dependent variable is the natural log of total CO_2 emissions. The sample covers 1950-2010. *Within R-squared* is the percentage of variation in the dependent variable explained by the independent variables after removing variation due to time and year fixed effects.

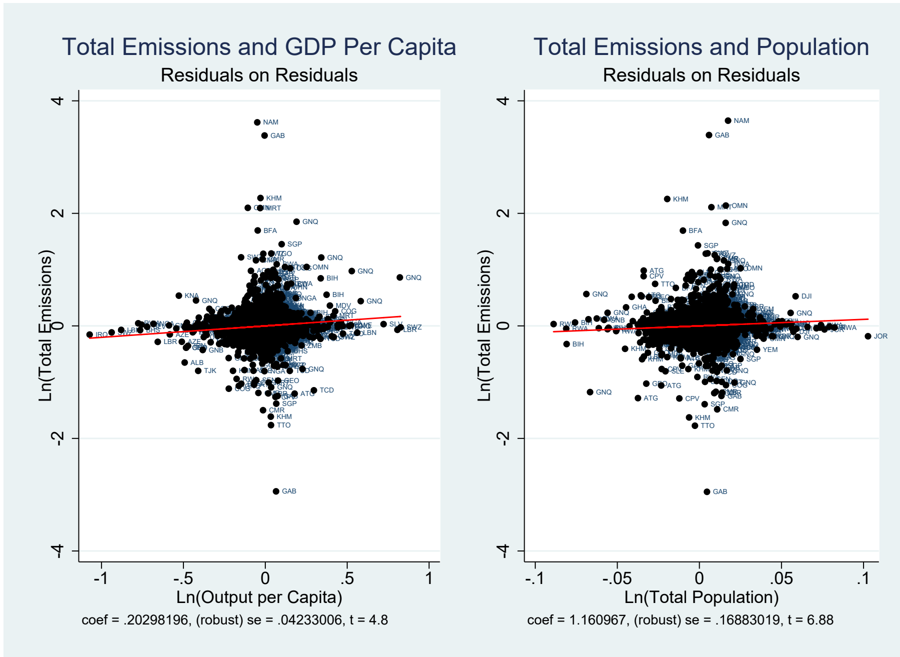

Figure 3: Partial residual plot. Note that the x-axis is different in the two panels of the figure. This obscures the difference in slopes, which are listed below each scatter plot. The coefficient on population is significantly larger. The difference in scales is necessary for visual inspection of the role of outliers.

8.3 Results from Balanced Sample

Table A3: Determinants of Carbon Emissions: Balanced Sample

	(1)	(2)	(3)	(4)
Ln pop. (a)	1.160***	1.197***	1.165***	1.127***
	(0.217)	(0.210)	(0.210)	(0.221)
Ln gdppc (b)	0.206***	0.196***	0.195***	0.214***
	(0.050)	(0.051)	(0.050)	(0.051)
% Age 15-64		0.032***	0.032***	0.035***
		(0.006)	(0.006)	(0.006)
% Urban			0.005	0.005
			(0.006)	(0.006)
Trade (% of GDP)				0.0005
				(0.0005)
Year FE	Yes	Yes	Yes	Yes
Observations	2940	2450	2450	2332
Countries	49	49	49	48
R-Squared	0.09	0.10	0.10	0.11
Within R-Squared	0.022	0.030	0.030	0.037
P-value: a = b	0.000	0.000	0.000	0.000
P-value: a = 1	0.464	0.353	0.435	0.568

Notes: $*p < 0.1, **p < 0.05, ***p < 0.01$. Robust standard errors clustered at country level in parentheses. Equation estimated in first differences. In all specifications, the dependent variable is the natural log of total CO_2 emissions. The sample covers 1950-2010. *Within R-squared* is the percentage of variation in the dependent variable explained by the independent variables after removing variation due to time and year fixed effects.

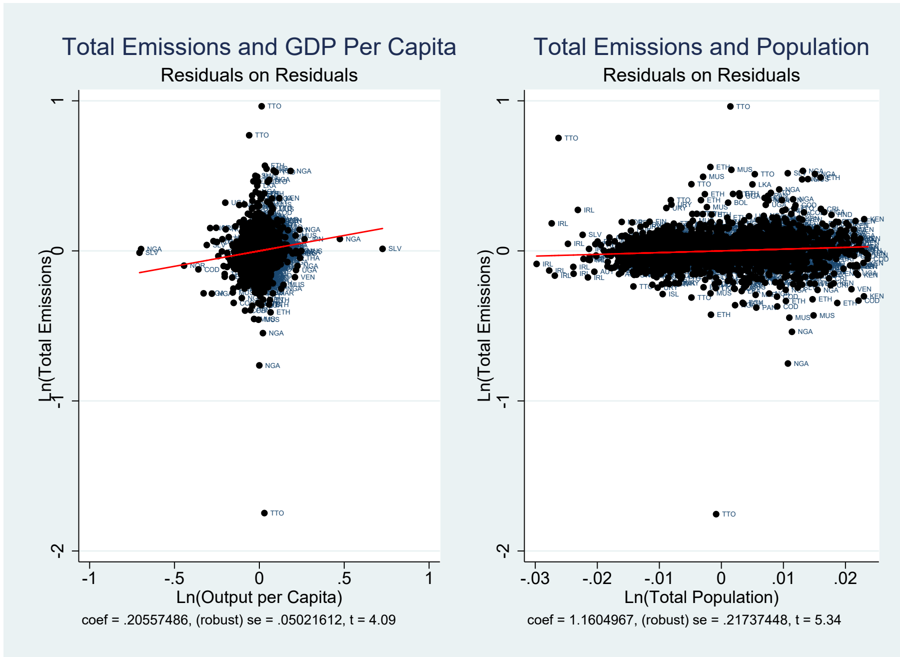

Figure 4: Partial residual plot. Note that the x-axis is different in the two panels of the figure. This obscures the difference in slopes, which are listed below each scatter plot. The coefficient on population is significantly larger. The difference in scales is necessary for visual inspection of the role of outliers.

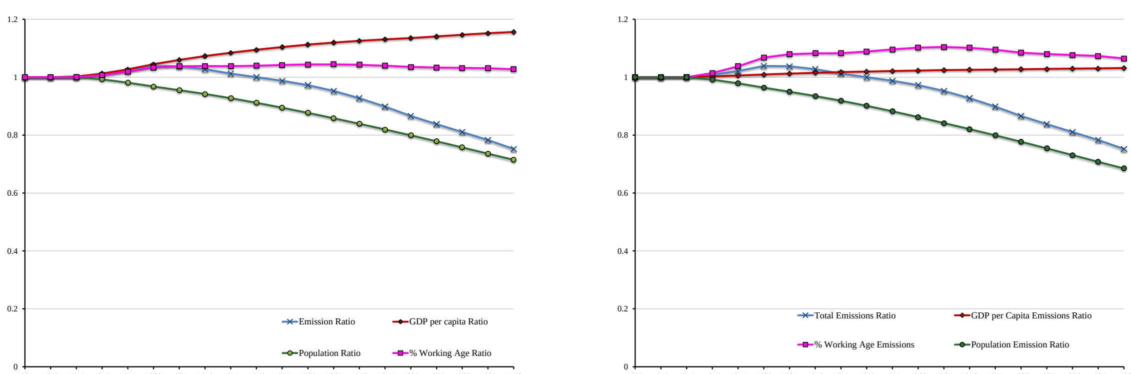

Figure 5: Results from the economic-demographic model. All variables are the the ratio of the outcome of the low fertility scenario over the medium fertility scenario. *Panel A* (left) plots the main outcome variables. *Panel B* (right) decomposes the difference in emissions between sources.

8.4 Results from Levels Regression

Table A4: Determinants of Carbon Emissions: Levels Regression

	(1)	(2)	(3)	(4)	(5)
Ln pop. (a)	1.877***	1.654***	1.781***	1.685***	1.585***
	(0.179)	(0.209)	(0.212)	(0.224)	(0.248)
Ln gdppc (b)	0.697***	0.650***	0.589***	0.576***	0.515***
	(0.098)	(0.097)	(0.111)	(0.114)	(0.121)
Ln gdppc squared (c)		-0.076**	-0.060*	-0.056*	-0.068*
		(0.033)	(0.032)	(0.032)	(0.035)
% Age 15-64			0.024**	0.023**	0.024**
			(0.009)	(0.009)	(0.009)
% Urban				0.009*	0.010**
				(0.005)	(0.005)
Trade (% of GDP)					0.0006
					(0.0006)
Country FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Observations	7291	7291	6581	6581	5840
Countries	156	156	153	153	147
R-Squared	0.98	0.98	0.98	0.98	0.98
Within R-Squared	0.328	0.339	0.336	0.342	0.361
P-value: a = b	0.000	0.000	0.000	0.000	0.000
P-value: a = 1	0.000	0.002	0.000	0.003	0.019

Notes: $*p < 0.1, **p < 0.05, ***p < 0.01$. Robust standard errors clustered at country level in parentheses. Equation estimated in first differences. In all specifications, the dependent variable is the natural log of total CO_2 emissions. The sample covers 1950-2010. *Within R-squared* is the percentage of variation in the dependent variable explained by the independent variables after removing variation due to time and year fixed effects.

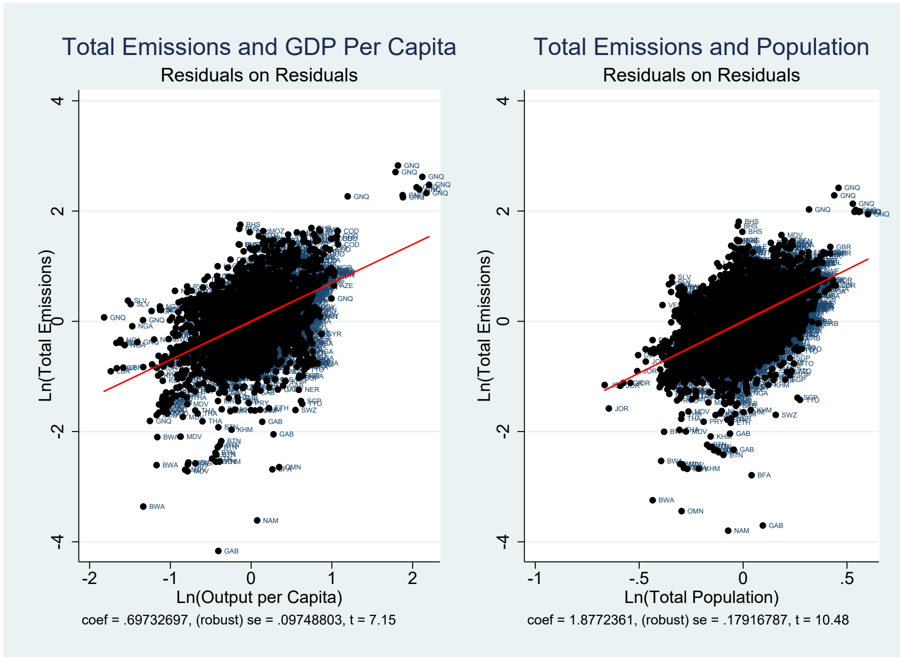

Figure 6: Partial residual plot. Note that the x-axis is different in the two panels of the figure. This obscures the difference in slopes, which are listed below each scatter plot. The coefficient on population is significantly larger. The difference in scales is necessary for visual inspection of the role of outliers.

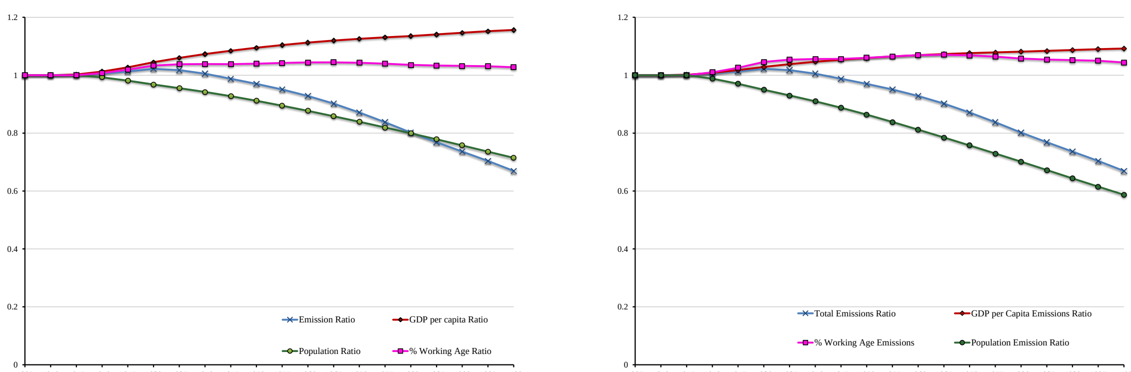

Figure 7: Results from the economic-demographic model. All variables are the the ratio of the outcome of the low fertility scenario over the medium fertility scenario. *Panel A* (left) plots the main outcome variables. *Panel B* (right) decomposes the difference in emissions between sources.

8.5 Results with National Accounts Measure of GDP

Table A5: Determinants of Carbon Emissions: National Accounts

	(1)	(2)	(3)	(4)
Ln pop. (a)	1.437***	1.517***	1.467***	1.566***
	(0.174)	(0.178)	(0.174)	(0.211)
Ln gdppc (nat'l acct.) (b)	0.500***	0.512***	0.509***	0.609***
	(0.077)	(0.084)	(0.084)	(0.095)
% Age 15-64		0.010	0.010	0.008
		(0.007)	(0.006)	(0.006)
% Urban			0.006*	0.009*
			(0.004)	(0.005)
Trade (% of GDP)				0.0002
				(0.0002)
Year FE	Yes	Yes	Yes	Yes
Observations	7133	6426	6426	5679
Countries	156	153	153	147
R-Squared	0.06	0.07	0.07	0.07
Within R-Squared	0.035	0.038	0.038	0.045
P-value: a = b	0.000	0.000	0.000	0.000
P-value: a = 1	0.013	0.004	0.008	0.008

Notes: $*p < 0.1, **p < 0.05, ***p < 0.01$. Robust standard errors clustered at country level in parentheses. Equation estimated in first differences. In all specifications, the dependent variable is the natural log of total CO_2 emissions. The sample covers 1950-2010. *Within R-squared* is the percentage of variation in the dependent variable explained by the independent variables after removing variation due to time and year fixed effects.

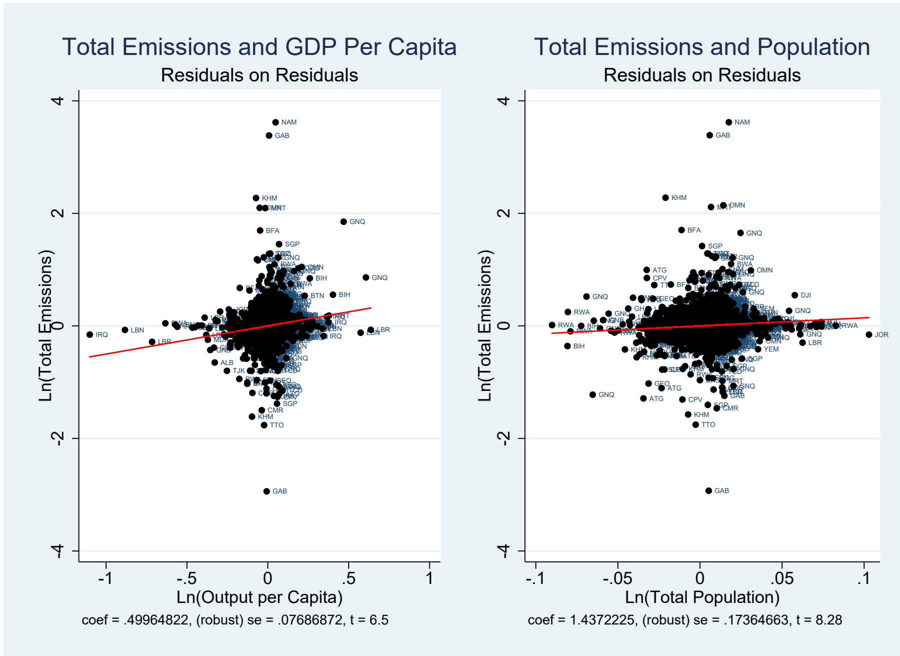

Figure 8: Partial residual plot. Note that the x-axis is different in the two panels of the figure. This obscures the difference in slopes, which are listed below each scatter plot. The coefficient on population is significantly larger. The difference in scales is necessary for visual inspection of the role of outliers.

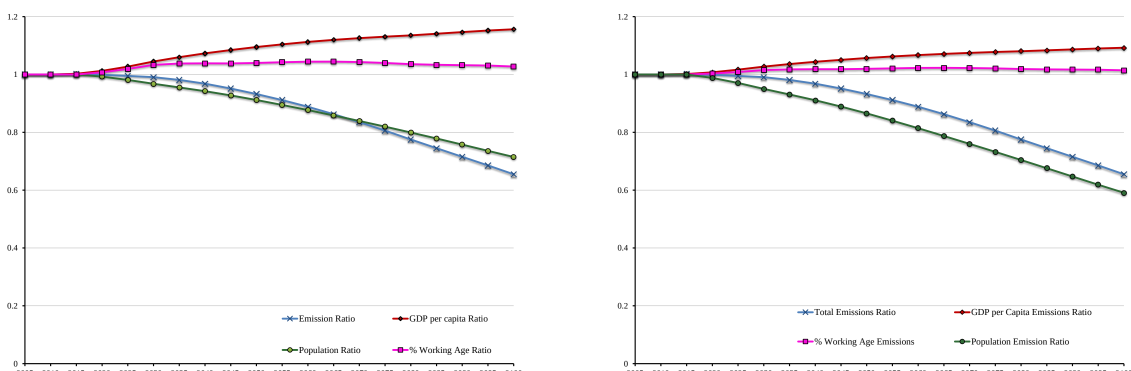

Figure 9: Results from the economic-demographic model. All variables are the outcome of the low fertility scenario over the medium fertility scenario. *Panel A* (left) plots the main outcome variables. *Panel B* (right) decomposes the difference in emissions between sources.

8.6 Results with Consumption Side Measure of GDP

Table A6: Determinants of Carbon Emissions: Consumption-side

	(1)	(2)	(3)	(4)
Ln pop. (a)	1.370***	1.459***	1.405***	1.449***
	(0.166)	(0.170)	(0.168)	(0.199)
Ln gdppc (cons. side) (b)	0.302***	0.302***	0.300***	0.324***
	(0.056)	(0.060)	(0.060)	(0.073)
% Age 15-64		0.014*	0.013*	0.013*
		(0.007)	(0.007)	(0.007)
% Urban			0.007*	0.011**
			(0.004)	(0.005)
Trade (% of GDP)				0.0003
				(0.0002)
Year FE	Yes	Yes	Yes	Yes
Observations	7133	6426	6426	5679
Countries	156	153	153	147
R-Squared	0.06	0.06	0.06	0.06
Within R-Squared	0.026	0.028	0.028	0.031
P-value: a = b	0.000	0.000	0.000	0.000
P-value: a = 1	0.027	0.008	0.018	0.025

Notes: $*p < 0.1, **p < 0.05, ***p < 0.01$. Robust standard errors clustered at country level in parentheses. Equation estimated in first differences. In all specifications, the dependent variable is the natural log of total CO_2 emissions. The sample covers 1950-2010. *Within R-squared* is the percentage of variation in the dependent variable explained by the independent variables after removing variation due to time and year fixed effects.

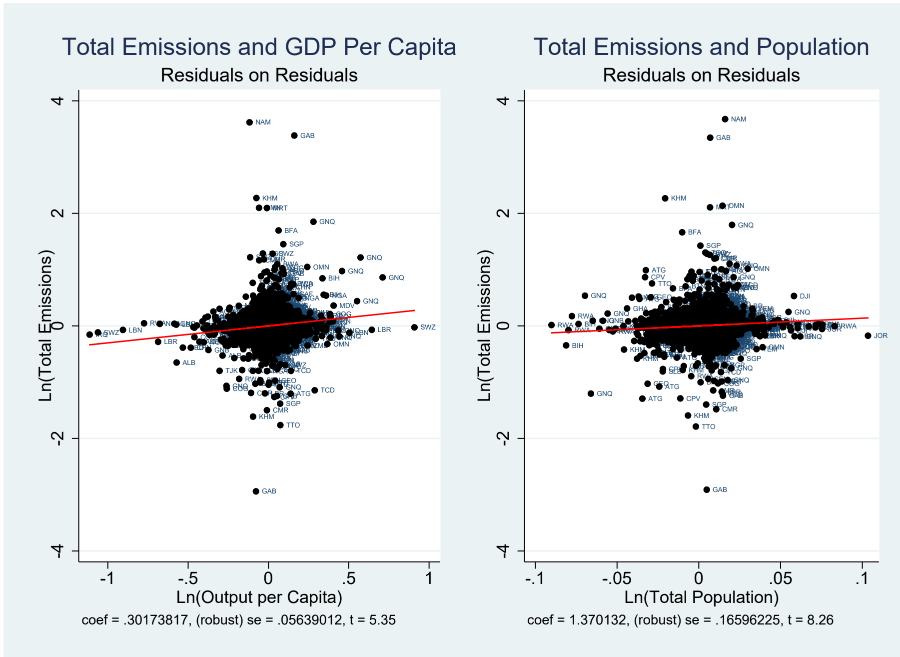

Figure 10: Partial residual plot. Note that the x-axis is different in the two panels of the figure. This obscures the difference in slopes, which are listed below each scatter plot. The coefficient on population is significantly larger. The difference in scales is necessary for visual inspection of the role of outliers.

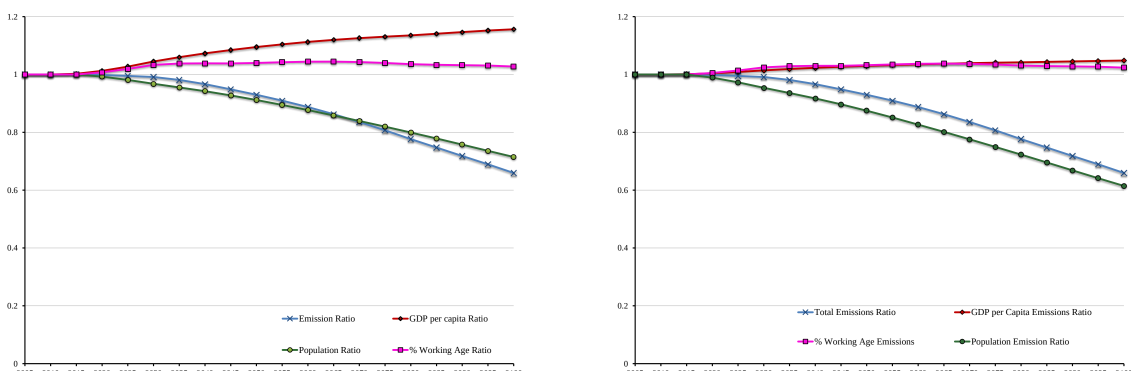

Figure 11: Results from the economic-demographic model. All variables are the the ratio of the outcome of the low fertility scenario over the medium fertility scenario. *Panel A* (left) plots the main outcome variables. *Panel B* (right) decomposes the difference in emissions between sources.

8.7 Results with WDI Measure of GDP

Table A7: Determinants of Carbon Emissions: WDI

	(1)	(2)	(3)	(4)
Ln pop. (a)	1.485***	1.553***	1.496***	1.568***
	(0.221)	(0.216)	(0.214)	(0.226)
Ln gdppc (wdi) (b)	0.547***	0.544***	0.541***	0.588***
	(0.082)	(0.083)	(0.083)	(0.090)
% Age 15-64		0.014**	0.014**	0.011*
		(0.006)	(0.006)	(0.006)
% Urban			0.007	0.010*
			(0.005)	(0.005)
Trade (% of GDP)				0.0004
				(0.0002)
Year FE	Yes	Yes	Yes	Yes
Observations	5817	5755	5755	5549
Countries	153	151	151	146
R-Squared	0.07	0.07	0.07	0.07
Within R-Squared	0.040	0.041	0.042	0.044
P-value: a = b	0.000	0.000	0.000	0.000
P-value: a = 1	0.030	0.012	0.022	0.013

Notes: $*p < 0.1, **p < 0.05, ***p < 0.01$. Robust standard errors clustered at country level in parentheses. Equation estimated in first differences. In all specifications, the dependent variable is the natural log of total CO_2 emissions. The sample covers 1950-2010. *Within R-squared* is the percentage of variation in the dependent variable explained by the independent variables after removing variation due to time and year fixed effects.

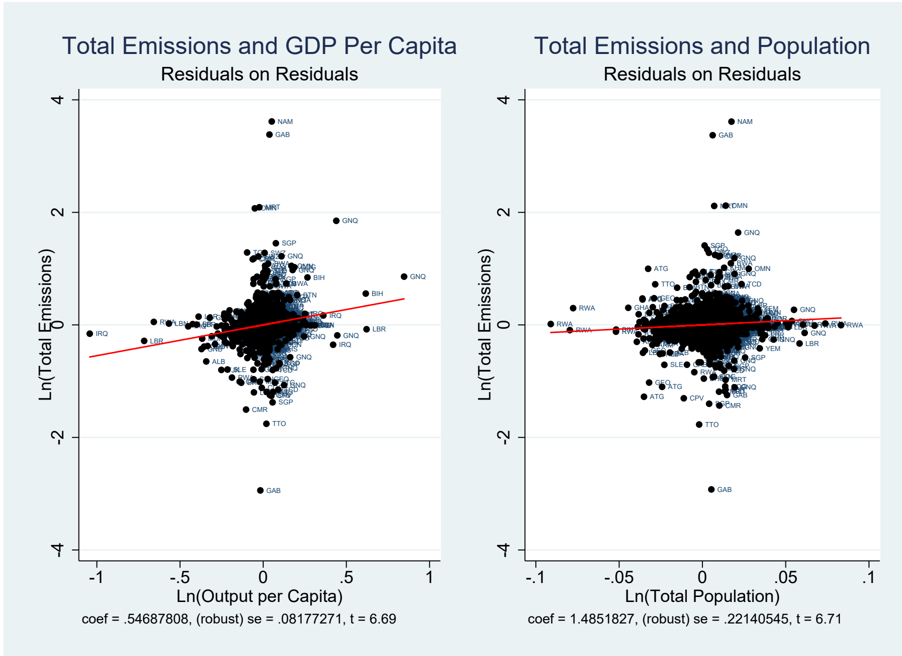

Figure 12: Partial residual plot. Note that the x-axis is different in the two panels of the figure. This obscures the difference in slopes, which are listed below each scatter plot. The coefficient on population is significantly larger. The difference in scales is necessary for visual inspection of the role of outliers.

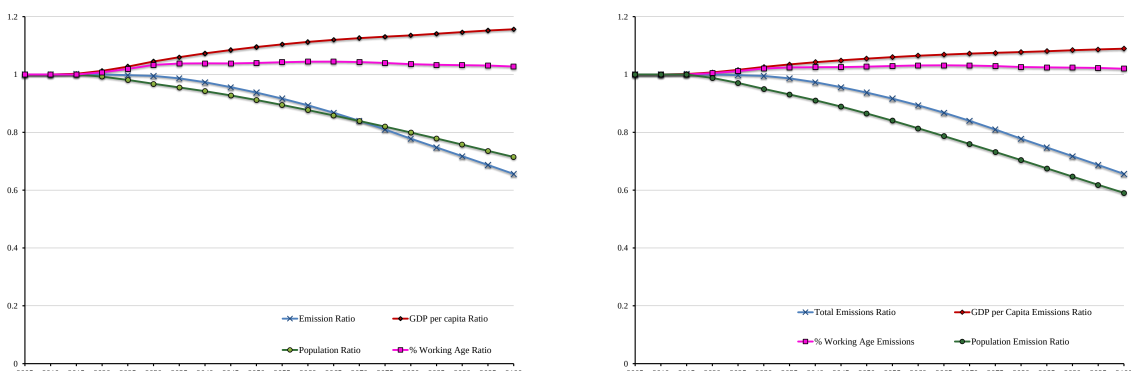

Figure 13: Results from the economic-demographic model. All variables are the the ratio of the outcome of the low fertility scenario over the medium fertility scenario. *Panel A* (left) plots the main outcome variables. *Panel B* (right) decomposes the difference in emissions between sources.

8.8 Results with Alternate Technology Assumptions

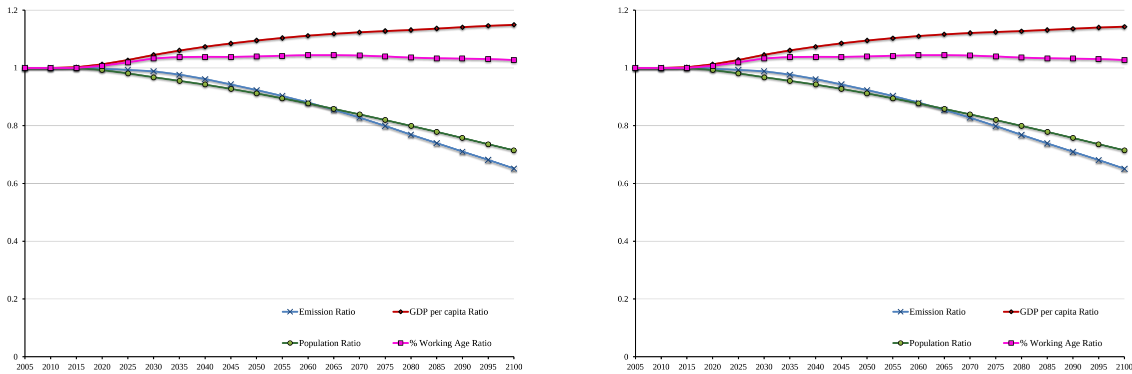

Figure 14: *Panel A* (left) plots the main outcome variables assuming a 2% per year growth rate for TFP. *Panel B* (right) plots the main outcome variables assuming a 5% per year growth rate for TFP. The results are nearly identical to our main results presented in figure 2.

8.9 Results with Nigeria Interaction

Table A8: Determinants of Carbon Emissions: Nigeria Interactions

	(1)	(2)	(3)	(4)
Ln pop. (a)	1.361***	1.461***	1.398***	1.431***
	(0.173)	(0.176)	(0.175)	(0.203)
Ln gdppc (b)	0.203***	0.207***	0.205***	0.226***
	(0.044)	(0.045)	(0.045)	(0.054)
(Ln gdppc)*NGA	-0.003	0.033	0.032	0.007
	(0.045)	(0.047)	(0.047)	(0.055)
(Ln pop)*NGA	0.260**	0.743***	0.724***	0.685***
	(0.106)	(0.114)	(0.111)	(0.115)
% Age 15-64		0.017**	0.016**	0.016**
		(0.007)	(0.007)	(0.007)
% Urban			0.008*	0.014***
			(0.004)	(0.005)
Trade (% of GDP)				0.0002
				(0.0002)
Year FE	Yes	Yes	Yes	Yes
Observations	7133	6426	6426	5679
Countries	156	153	153	147
R-squared	0.05	0.05	0.05	0.05
Within R-Squared	0.017	0.020	0.020	0.023
P-value: a = b	0.000	0.000	0.000	0.000
P-value: a = 1	0.038	0.010	0.025	0.036

Notes: $*p < 0.1, **p < 0.05, ***p < 0.01$. Robust standard errors clustered at country level in parentheses. Equation estimated in first differences. In all specifications, the dependent variable is the natural log of total CO_2 emissions. The sample covers 1950-2010. *Within R-squared* is the percentage of variation in the dependent variable explained by the independent variables after removing variation due to time and year fixed effects. *NGA* is a dummy variable for Nigeria.