A less poor world, but a hotter one?

Carbon emissions, economic growth and income inequality

Martin Ravallion, Mark Heil and Jyotsna Jalan[1]

World Bank

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Abstract: We find that the distribution of income matters to aggregate carbon dioxide emissions and hence global warming. Higher inequality, both between and within countries, reduces carbon emissions at given average incomes. We also confirm that economic growth raises emissions. Thus our results indicate that trade-offs exist between climate control (on the one hand) and both social equity and economic growth (on the other). However, economic growth improves the trade off with equity, and lower inequality improves the trade off with growth. By combining growth with equity, more pro-poor growth processes yield better longer-term trajectories of carbon emissions.

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[1] Address for correspondence: Martin Ravallion, Development Research Group, World Bank, 1818 H Street NW, Washington DC. These are the views of the authors, and should not be attributed to the World Bank or any affiliated organization. Not to be cited without permission. Financial assistance was provided by a joint British-Dutch-Swedish trust fund for studying the Social and Environmental Consequences of Growth-Oriented Policies. Helpful comments were received from Thomas Selden and seminar participants at the World Bank.

1 Introduction

The evidence from cross-country comparisons indicates that economic growth generally increases emission rates of carbon dioxide, the main anthropogenic “greenhouse gas”. This suggests that a trade off might exist between raising average living standards and controlling global warming. There is also evidence that the marginal impacts of economic growth on carbon emissions decline as average income increases. This suggests that reducing inequality between countries might well increase global warming, by redistributing income from countries with a low marginal propensity to emit carbon dioxide to those with a high one. Thus it can be conjectured that the world also faces a trade off between climate control and social equity. Together these two trade offs suggest that fighting poverty, by either higher average income or lower inequality, will exacerbate global warming.

This paper tests that argument. Carbon dioxide emissions once thought to be a benign by-product of combustion are now believed to be responsible for the bulk of greenhouse warming. A consistent and seemingly reliable time series of emission rates is now available for most countries from the Carbon Dioxide Information Analysis Center at the Oak Ridge National Laboratory, U.S.A. By collating these data with data on incomes and their distribution, we can test for nonlinearities in the relationship between aggregate carbon emissions and average incomes, and test for an independent effect on emissions of inequality within countries. We can also explore the extent of the interaction effects between inequality and average incomes for it is only by identifying the interactions that one can assess the role played by inequality in mediating the environmental impact of economic growth.

The following section provides an overview of the issues addressed here, and their relation to recent literature. Section 3 outlines the theoretical considerations which motivate our econometric specification. Section 4 describes our data, which are also available in machine readable form. Our econometric model is described in section 5, while the estimation results are presented and discussed in section 6. Our conclusions can be found in section 7.

2 Motivation

Empirical evidence from cross-country comparisons suggests that economic growth in poor countries entails worsening environmental outcomes by a number of indicators. For a number (but not all) indicators, however, the evidence also suggests that the direction of the relationship eventually reverses, so that with enough economic growth environmental outcomes improve (World Bank, 1992; Grossman and Krueger, 1995; Selden and Song, 1994; Shafik, 1994). This does not, however, appear to hold for carbon emissions which (over the range of the data) rise monotonically as average income rises (World Bank, 1992; Shafik, 1994; Holtz-Eakin and Selden, 1995). There is also evidence that both the income elasticity of emissions and the marginal propensity to emit decline as income rises (Holtz-Eakin and Selden, 1995; Schmalensee et al., 1995; Heil, 1997).

The existence of nonlinearities in the cross-country relationship between environmental indicators and average incomes has implications for the relationship between income inequality and environmental outcomes, although those implications seem to have largely gone unnoticed. If the marginal propensity to cause environmental harm is lower in rich countries than in poor ones, then higher (lower) inequality between countries will improve (worsen) aggregate environmental outcomes at any given level of world mean income. By implication, attempts to improve the world distribution of income through international development assistance may come at a cost to the environment. There is evidence that inequality between countries has been on a trend increase since about 1960 (Berry et al., 1991; Pritchett, 1997).[2] This adverse distributional trend may well have reduced pollution levels over what one would have otherwise expected, and helped attenuate global warming.

Possibly the nonlinearity is spurious. A lower marginal propensity to emit (MPE) greenhouse gasses in rich countries may have little to do with their being rich per se, but arise from other country-level fixed effects, correlated with average income, such as policies which promote lower emission rates. There is cross-country evidence of a positive income effect on demand for regulations to protect natural resources and control pollution (Dasgupta et al., 1995). There appear to have been very few regulations explicitly designed to limit carbon emissions in the periods included in the data used in the recent literature,[3] and since the problem is a global one, local effects on the demand for regulation may well be small. However, policies which promote more energy-efficient use of fossil-fuel will indirectly help in reducing the MPE, and there may well be a positive income effect on demand for such policies. The results of Holtz-Eakin and Selden (1995), Schmalensee et al., (1995) and Heil (1997) using longitudinal data indicate that the nonlinearity in the relationship between carbon emissions and average income

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[2] However, there is conflicting evidence on this point (Levy and Chowdhury, 1994).

[3] A non-binding emissions curtailment policy applicable only to the developed nations was negotiated in 1992 (UN, 1992).

persists when one allows for country-level fixed effects, which gives us confidence that the declining MPE in cross-sectional data is not picking up some other country-specific variable.

Assuming that the nonlinearities are not spurious, where do they come from? Consumer demand behavior appears to be the most likely source of nonlinearities in the effect of higher incomes on carbon emissions, given that the latter depend in large part on what goods are consumed in an economy. However, the demand effects would appear to be hard to predict. With anything but homothetic preferences, one would expect distributional effects on aggregate fossil fuel demand and (hence) carbon emissions via demand behavior.[4] It would seem implausible that the marginal propensity to directly consume fossil-fuel energy is the same for the world's poor as the rich. Poor people tend to devote extra income to food and clothing, rather than goods which entail high rates of fossil fuel combustion during consumption such as motor vehicles. However, poor people may use fossil fuel less efficiently, and so generate higher carbon emissions per unit of fuel consumption. Consumer demand studies have tended to show an income elasticity of demand for energy over one, but there is also evidence that the elasticity declines as income rises (see, for example, Rothman et al., 1994, based on cross-country data). Then the direction of the effect of higher incomes on the MPE is ambiguous. Furthermore, the direct consumer demand for energy is only part of the story. Many goods which do not require fossil fuel combustion as part of their consumption do require it for their production. Both the

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[4] Though this effect does not appear to have been discussed in the literature on environmental economics, it is widely appreciated in the literature on consistent aggregation of consumer demand models where inequality is often introduced as an additional variable in aggregate models.

direct and indirect demands are relevant to carbon emissions.

There are other possible structural links from inequality to environmental outcomes. Boyce (1994) argues that higher inequality reinforces the power of the rich to impose environmental costs on the poor. Inequality may reduce the ability of a society to achieve cooperative solutions to environmental problems; this has been a theme of some of the literature on preservation of environmental public goods (Ostrom, 1990). Higher inequality between countries may reduce carbon emissions, but make it harder to achieve a global consensus on emission control.

The literature has typically postulated that the environmental indicator for a country is solely a function of average income. The contingent factors in the underlying structural relationship linking economic growth to environmental outcomes are as yet poorly understood, but are plainly relevant to the implications drawn. If the nonlinearity does arise from the aforementioned consumer demand effects then inequality within countries would presumably have the same direction of effect as inequality between countries. Indeed, within one country at one date, the demand for regulation can be taken as fixed, and then the consumer demand effect on emissions would be the main factor. So it is of interest to also introduce within-country inequality into the relationship.

There may also be significant interaction effects between growth and redistribution. Suppose that lower inequality initially entails a higher current level of emissions (because the poor have a higher MPE), but that it also entails that future economic growth brings larger absolute gains to the poor, bringing down their MPE. For example, one might expect to see wider use of more efficient technologies for converting fossil fuels into energy in more equal growing economies. Then the trade off between equity and climate control may improve with growth, and (by similar reasoning) redistribution may also improve the trade off between growth and climate control.

Another contingent factor is population growth. Past work has treated this in a rather special way. The literature appears to have assumed universally that population does not matter to per capita emissions (or other environmental indicators) independently of income per capita, i.e., that the relationship is homogeneous. There is no obvious a priori reason to assume this. There may be independent effects of population growth on emissions, such as through demand for public goods. Public spending on defense and infrastructure are both thought to entail high rates of carbon emission. But even if they did not, a positive effect of higher population on emissions at given income per capita may simply reflect the existence of public goods, such that both income per capita and total income determine demands for (amongst other things) carbon-emitting goods. And these effects could well be contingent on inequality.

3 Modeling the impact of growth and inequality on carbon emissions

Here we only consider the simplest possible theoretical model which can generate a dependence of aggregate carbon emissions on the distribution of income, as well as its mean.

The consumption of almost every good entails some rate of carbon and other emissions, either directly (due to consumption of that good) or indirectly (via its production). We can postulate that each individual has an implicit derived demand function for carbon emissions. In principle this function will depend on a host of variables, but for the present purposes we postulate that it is a smooth function of income alone, such that $f\,(Y_{ij})$ is the demand for emissions by person *i* in country *j*, with income Y_{ij}. The MPE is $f'(Y_{ij})$. The aggregate level of emissions is assumed to be a simple sum of individual demand for emissions; the average emission rate in a country *j* is given by:

$$E_j = \frac{1}{N_j}\sum_{i=1}^{N_j} f\,(Y_{ij})$$

The way in which differences in income inequality impact on the rate of emissions will then depend on the properties of the function *f*. Consider the following alternative models:

A trade-off model: Assume that emissions are a normal good ($f'(Y_{ij}) > 0$) and that the MPE falls as income rises ($f''(Y_{ij}) < 0$). One can then apply results from inequality analysis to show that the aggregate rate of emissions is an increasing function of mean income and that any inequality-reducing redistribution of income will increase the aggregate rate of emissions.[5] We

$$E_j = E(\overline{Y}_j\,,\ I_j\,,\ N_j\ )$$

can thus re-write (1) as (dropping subscripts for time and country to simplify notation):

which will be increasing in the first argument, average income $\overline{Y}$, and decreasing in the second, an inequality measure I ; generally it will also vary with population size, though this effect is ambiguous. The inequality measure has the generic form (dropping the country subscripts):

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[5] Here we use a well-known result from the literature on measuring inequality; see Atkinson (1970).

$$I = I(Y_1/\overline{Y}, Y_2/\overline{Y}, \ldots, Y_N/\overline{Y})$$

where the function *I* satisfies the Pigou-Dalton transfer principle, whereby a small transfer from a rich person to a poor person (preserving the mean) will always reduce the value of the function. Global emissions for *M* countries will be

$$E = \sum_{i=1}^{M} E(\overline{Y}_j,\ I_j,\ N_j)\, N_j$$

By the same logic, the effect on global emissions of inequality <u>between</u> countries depends on the second partial derivative of E with respect to $\overline{Y}$. Since this derivative holds inequality constant, all incomes change by the same proportion as the mean. The second derivative of E with respect to $\overline{Y}_j$ is then simply the mean of $f''(Y_{ij})$ over all N_j. Thus inequality reducing redistributions between countries will increase global emissions under the above assumptions. There will be a trade off between reducing inequality and controlling global warming.

<u>A “win-win” model</u>: Again assume that emissions are a normal good, but now assume that the MPE rises with rising income. The argument of the trade-off model is reversed. Lower inequality either within or between countries will reduce carbon emissions.

These two models do not exhaust the logical possibilities. Suppose that emissions are a normal good, but the marginal propensity to consume does not change monotonically as income rises. The effect of inequality will then be ambiguous, depending on the precise properties of the demand function and inequality measure.

There may also be more complex ways in which the aggregate emission rate depends on the distribution of income, arising from external effects on individual demand (whereby the derived demand for emissions by person *i* depends on other incomes besides *i*'s), or non-additivities in the relation between aggregate emissions and individual emissions. There may also be effects operating through public policies influencing emissions; for example, more equal societies may be more disposed to public transport, or might more easily agree to the use of cleaner energy sources. These are conjectures only. But one must remain skeptical of any simple statement that higher inequality would have an unambiguous effect (let alone an unambiguously positive effect) on aggregate carbon emissions at any given level of average income.

The above discussion relates to the impact of inequality on the level of the emissions rate. We are also interested in examining the effects of inequality on the elasticity of aggregate emissions to increases in average incomes, for this will determine whether the distributional pattern of growth matters. Quite generally, the derivatives and elasticities (log derivatives) of equation (2) with respect to average income will also be a function of inequality (as well as the other variables). Differentiating equation (1) and re-arranging, the aggregate income elasticity of emissions can be written as:

$$\frac{d \ln E}{d \ln \overline{Y}} = \frac{1}{N} \sum_{i=1}^{N} S_i^E \, x_i \, (1 + w_i)$$

where $S_i^E = f(Y_i)/E$ is person i's share of total emissions, and

$$x_i \equiv \frac{d \ln f(Y_i)}{d \ln Y_i}$$

$$w_i \equiv \frac{d \ln S_i^Y}{d \ln \overline{Y}}$$

is i’s income elasticity of demand for emissions, and

is the elasticity of person i’s income share, $S_i^Y = Y_i / \overline{Y}$, with respect to average income. Equation (5) shows how the aggregate income elasticity of carbon emissions is a weighted mean of the individual income elasticities of emission demand, where the weights are the product of the emission shares and a distributional effect.

Does inequality also matter to the aggregate income elasticity of emissions? Neither the trade-off model nor the win-win model allow us to determine the effect of higher inequality on the income elasticity of aggregate emissions. However, suppose that the following conditions hold: (i) Growth is distribution neutral, so that the income elasticity of aggregate emissions is the share-weighted average of the individual elasticities:

$$\frac{d \ln E}{d \ln \overline{Y}} = \frac{1}{N}\sum_{i=1}^{N} S_i^E x_i = \frac{1}{N}\sum_{i=1}^{N} f'(Y_i)Y_i / E$$

(ii) The individual derived demand for emissions has a non-negative third derivative, so that $f'(Y_i)Y_i$ will be a strictly increasing convex function of Y_i . Then, on applying the same argument as used above to determine the effect of inequality on the level of emissions, the aggregate income elasticity will be an increasing function of inequality. We can relax these assumptions somewhat, and obtain the same result. For example, a non-neutral growth process with rising inequality will also entail that the aggregate elasticity is increasing in inequality. Again, this is only one possible outcome, and the extra conditions under the trade-off model are just as strong.

It is theoretically possible that the direction of the effect of higher inequality on the level of emissions, at some given initial mean income, is opposite to its effect on the growth elasticity of emissions. Continue to assume that growth is distribution neutral, so that equation (6) gives the income elasticity of aggregate emissions. But suppose instead that the emission demand function is concave (diminishing MPE) but with a non-negative third derivative. Then the trade-off model will characterize the "static" impact of inequality; higher inequality will attenuate emissions holding income constant. Yet higher inequality will also result in a more elastic response of emissions to income growth. This raises the possibility that the static trade off, at given average incomes, may be more acute than the dynamic trade off in a growing economy.

4 Data

The U.S. Oak Ridge National Laboratory (ORNL) provides estimates of national carbon emissions from fossil fuel use and cement manufacturing data. Data on fuel use are drawn from the UN Statistical Division's (UNSTAT) database by ORNL, while the U.S. Department of Interior's Bureau of Mines furnishes data on cement production. The method of Marland and Rotty (1984) is applied to these data in order to convert apparent fuel consumption and cement manufacturing into carbon emissions. For each fuel type (solid, liquid, and gas), the estimated level of emissions is the product of three factors: (i) the quantity of that fuel type consumed annually,[6] (ii) the proportion of consumption which is oxidized for that fuel type, and (iii) the average carbon content for that type of fuel. Summing across all fuel types for each country generates the emissions from fossil fuels. Emissions from cement manufacturing are computed by multiplying the quantity of cement produced by a coefficient representing the average mass of carbon generated in production. Adding fossil fuel carbon emissions to those from cement production yields total emissions.[7]

The data are not ideal. They do not include effects of deforestation and land-use changes, nor the use of collected wood fuel as an energy source. Deforestation and land-use changes have been estimated to account for 17-23% of all annual anthropogenic emissions (World Resources Institute, 1996; Intergovernmental Panel on Climate Change, 1990). Data on the effects of deforestation, land-use changes, and firewood combustion on carbon emissions are not sufficiently developed to be included in this study. We suspect that these omissions would tend to lead to an underestimation of carbon emissions in poor countries, and hence an overestimation

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[6] Consumption accounts for trade, stored fuel, and changes in stocks; see Boden, Marland, and Andres (1995).

[7] We include carbon emissions from gas flaring, using estimates given in the UNSTAT database. Gas flaring emissions are generated as an unused by-product of oil drilling and typically constitute only about one percent of total emissions from fossil fuel use. Past work has often omitted this component. However, Heil (1997) found that models of emissions could be sensitive to the inclusion of gas flaring.

of the income elasticity of emissions. Even aside from these problems, emissions estimates also have an uncertainty of 6-10 percent at the global level, and perhaps higher at the national level. Still, these estimates represent the best information available from a single source, and have the advantage of using a uniform estimation method for all countries. Annual data are now available for many countries back to the 1950s. However, country coverage widens considerably after 1975 (including, for example, data for the former soviet union). Also taking account of other data requirements (discussed below), we confined the analysis to the period 1975-92.

We have assembled other data from what appear to be the best available sources. The Penn World Tables (Mark 5.6) are the source of population and per capita GDP data. Per capita GDP is given in purchasing power parity (PPP) adjusted values based on 1985 U.S. dollars. GDP according to PPP has the advantage of expressing income in comparable units in terms of living standards across countries (as compared to GDP by market exchange rates). Details are provided by Summers and Heston (1995). Population data are used to convert total national emissions to per capita emissions.

The coverage of distributional data over time and countries is quite uneven, reflecting the availability of household-level survey data. The Gini index is (by far) the most widely used measure of inequality, though even then observations are sporadic.[8] We use the average Gini index for each country, averaged over all the data available for that country from the "high-

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[8] This is one half of the area between the Lorenz curve and the diagonal, where the Lorenz curve gives the cumulative share of total income (on the vertical axis) held by the poorest x% of the population. If everyone has the same income then the Gini index is zero; if the richest person has all the income then its value is unity. Gini indices for income or consumption by country vary from 0.20 to 0.60. For a compilation of recent estimates by country see World Bank (1997).

quality" sub-set of the data base on Gini indices compiled by Deininger and Squire (1996). We use the average Gini index for the 1980s. This reduces the number of countries for which all data (including carbon emissions) are available to 42.[9] To test robustness to this choice, we also tried the average Gini index since 1975, the first year of the carbon emissions data; our results were affected little by this choice. The inequality data are not strictly comparable across countries, since there are underlying differences in the type of survey data; for example, some of the Gini indices are based on household incomes per person, while some are based on consumption expenditure.

5 Econometric model

We estimate an econometric model of emission rates motivated by the arguments in section 3, using the panel of data over time by countries described in the last section. We begin by focusing on the bivariate relationship with average income. This will motivate our specification choice for estimating a richer model incorporating inequality within countries.

To capture the issues raised in section 3, we want a specification which allows the third derivative to be non-zero. In Figure 1 we plot the data; there are 738 observations.[10] We also give fitted values from a cubic function of income, estimated as a simple pooled model by OLS,

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[9] The countries in the data set are Australia, Bangladesh, Belgium, Brazil, Bulgaria, Canada, Chile, China, Colombia, Costa Rica, Cote d'Ivoire, Czechoslovakia, Finland, France, Honduras, Hong Kong, Hungary, India, Indonesia, Italy, Japan, Korea, Malaysia, Netherlands, New Zealand, Norway, Pakistan, Philippines, Poland, Portugal, Singapore, Soviet Union, Spain, Sri Lanka, Sweden, Taiwan, Thailand, Trinidad, Tunisia, United Kingdom, USA, and West Germany.

[10] This is the same data we use later, after introducing within-country inequality. The picture looks very similar if we add the extra countries for which we do not have the inequality data.

as given in Table 1.[11] In addition to a cubic function of income, the regression includes a time trend and population. The time trend is negative and the population effect is positive.[12]

The bivariate relationship between carbon emissions and average income suggests a decreasing MPE up to relatively medium-high incomes, but a significantly positive third derivative so that the MPE starts to rise above some point. It follows that the trade off between emissions and inequality between countries improves as income grows. Indeed, the relationship becomes convex at sufficiently high incomes, eliminating the trade off.

This result is not, however, robust to allowing for country-level fixed effects; as can also be seen from Table 1, adding country dummy variables renders the cubic term in average income insignificant (Table 1). The evidence of a positive third derivative in Figure 1 is clearly driven by the differences between countries rather than changes over time within countries.

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[11] There is negative time trend independently of income, and we included this in the OLS regression. To correct for the spread of the observations over time we have used the estimated regression coefficient on time to line up all the observations to 1992. Thus, for the purpose of the graph in Figure 1, we add α(1992-t) from the measured emission rate for each year t, where α is the OLS estimate of the time trend.

[12] We also tried deleting the two largest countries, China and India, but population remained significant, and other results were very similar.

While the cubic model in income levels provides a straightforward test for how the MPE varies with average income, it can be improved upon as a specification for the bivariate relationship. We also tried regressing the log of the emission rate against both a quadratic and cubic function of the log of average income. The cubed term in log income was not needed and even with one less parameter, the quadratic in logs gave a higher R^2 than the cubic in levels (0.78, as compared to 0.64 for the cubic model in levels above). However, as Davidson and Mackinnon (1993) point out, it is not strictly valid to compare the R^2's of these models. Under the assumption of normally distributed errors, one can compare the values of the log likelihood functions from the two competing models. The loglikelihood function from the linear cubic model is -2978.82 and from the log quadratic model is -2500.69.[13] These values suggest that the log quadratic model fits the data better than the linear model, and is more parsimonious. We thus use the log specification in our subsequent analysis.

As noted in the last section, while the data on carbon emissions and average incomes are fairly complete over time, that on inequality is sparse. In our view, there can be little hope of meaningful results treating inequality as time varying in this context. This entails that rather strong assumptions are needed about omitted variables to identify the effects of inequality on emissions, although (as we will see) effects on the growth elasticity of emissions can be identified more confidently.

We want to introduce inequality within countries into the emission-income relationship in

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[13] Note that one must subtract the sum of log emissions from the OLS log likelihood in order to calculate the modified log likelihood required by this test. See Davidson and MacKinnon (1993, p.491) for details.

as flexible a way as possible. So we postulate that all parameters in the relationship are a function of measured inequality. Combining these considerations, our econometric model of carbon emissions in country *j* at date *t* takes the form:

$$\ln E_{jt} = \beta_{1j}\ln \bar{Y}_{jt} + \beta_{2j}(\ln \bar{Y}_{jt})^{2} + \beta_{3j}\ln N_{jt} + \beta_{4j}t + \eta_{j} + \varepsilon_{jt}$$

$$\beta_{kj} = \beta_{k0} + \beta_{k1}I_{j} \;\; (k = 1,..,4)$$

where the β parameters are assumed to be linear functions of measured income inequality:

Equation (7) also includes a country fixed effect (η) which is a linear function of inequality:

$$\eta_{j} = \eta_{0} + \eta_{1}I_{j} + \nu_{j}$$

where ν is an unobserved country fixed effect.

$$\frac{d\ln E}{d\ln \bar{Y}} = \beta_{10} + \beta_{11}I + 2(\beta_{20} + \beta_{21}I)\ln \bar{Y}$$

The income elasticity of carbon emissions implied by equation (7) is

$$\frac{d\ln E}{d\, I} = \eta_{1} + \beta_{11}\ln \bar{Y} + \beta_{21}(\ln \bar{Y})^{2} + \beta_{31}\ln N + \beta_{41}t$$

The effect of inequality on emissions is given by:

In defining the elasticity of emissions to population growth one has to be careful about whether one is referring to per capita emissions, and whether or not one is holding total income or income per capita constant. Presumably one is more interested in the effect on total emissions. If total income is held constant then the elasticity is given by:

$$\frac{d \ln E.N}{d \ln N} = 1 - b_{10} + b_{30} - (b_{11} - b_{31}) I - 2(b_{20} + b_{21} I) \ln \overline{Y}$$

If instead income per capita is held constant then the elasticity is given by:

$$\frac{d \ln E.N}{d \ln N} = 1 + b_{30} + b_{31} I$$

We estimate equation (7) under two alternative assumptions. First we assume that ν is uncorrelated with the other variables, and estimate (7) as a simple pooled model using a heteroscedasticity-robust OLS method (the mean-deviations of ν simply go into the error term, and one adds an intercept and term in *I* to (7)). The second method recognizes that the unobserved fixed effect could be correlated with the other regressors in the model, creating bias in the OLS estimator of (7). We eliminate the fixed effect by adding country dummy variables.

It is difficult to say on a priori grounds which of these approaches should be preferred. Ignoring measurement error, we would generally expect the income and population elasticities to be better estimated by the fixed effects model, since it purges the estimates of correlated fixed effects. However, with time varying measurement errors it may well be that the signal to noise ratio deteriorates so much in the fixed effects estimator that it may entail an even greater bias than the OLS pooled model (Griliches and Hausman, 1986; Biørn, 1996).

6 Results and implications

Table 2 gives (under “unrestricted model”) our estimate of the pooled regression. The standard errors are high. Yet the joint restriction that all coefficients are zero is comfortably rejected (at probability levels below the 0.01% level). This suggests that multicollinearity may be inflating the standard errors. Two joint restrictions were very easily accepted; the first is the restriction that $\beta_{21}=\beta_{41}=0$ and the second is that $\beta_{11}= \beta_{41}= 0$ (a joint F-test accepted both at the 45% level or better). Standard model selection criteria (adjusted R^2, mean square error) do not suggest any non-arbitrary way to choose between these two restricted forms. So we present both in Table 2. There were no other linear parameter restrictions that could be accepted statistically. The standard errors drop substantially in the restricted forms, and most individual coefficients are significantly different from zero at the 1% level or better.

Table 3 gives the fixed effects model. The same two restrictions perform well, and no other restrictions do. Again individual parameters are significantly different from zero in the restricted model, and in most cases this is true at the 1% level or better. There are strong population growth effects, implying a rejection of the commonly imposed homogeneity restriction.

Table 4 gives the implied elasticities at sample mean points. The choice between the two restricted forms matters little to the estimated elasticities. However, the pooled and fixed effects regressions yield quite different results. Those from the pooled model appear to be more believable. Our reasoning is as follows. Holding income per capita constant, total income must grow at the same rate as population. So the population elasticity of emissions when holding average income constant should equal the income elasticity when holding population constant.

This prediction is confirmed quite well for the pooled model; both elasticities are close to one. However, for the fixed effects model, the population elasticity is far too high relative to the income elasticity.

Our concerns about the fixed effects model were enhanced when we followed the suggestion of Griliches and Hausman (1986) of comparing it to a difference model (in which we took the first difference over time of equation 7). If there is a substantial time-varying measurement error problem leading to biases in the fixed effects estimator, then its parameter estimates should differ noticeably from those of the difference estimator. That is what we found. Coefficient estimates differed appreciably and many variables which are significant in the fixed effects model were insignificant in the difference model.

So our preferred specification indicates a significant negative impact of higher inequality on the level of emissions and an income elasticity of about one, with total emissions being roughly proportional to total income.

The pooled model in Table 2 indicates that the income elasticity of emissions declines as average income increases. And this effect persists when we allow for country-level fixed effects, as indicated by the results for the fixed effects model in Table 3.

To help see what this implies for the effects of redistribution between countries, we simulated the effect of taking 1% of the income of the richest five countries in our sample (in terms of income per capita) and transferring that sum of money to the poorest five countries; the transfer was assumed to preserve inequality within both the donor and recipient countries (so that the five rich countries lost a fixed percentage of their income, while the poorest five countries gained a fixed percentage). Obviously emissions fall in the five rich countries, and rise in the five poor ones. Taking the 10 countries as a whole, total emissions increased by 0.49%. If instead one transfers 5% of the income of the richest five countries to the poorest five, then emissions increase by 2.40%. Thus the elasticity of emissions to redistribution from the richest tenth of countries to the poorest tenth is about 0.5.

Both the pooled and fixed effects models also indicate that the income elasticity of carbon emissions (equation 9) is an increasing function of the Gini index (β_{11} and/or β_{21} positive). The higher the inequality the higher the impact of a given rate of growth on emissions. Figure 2 shows how the income elasticity rises with rising inequality (at the sample mean log income, and using restricted form B of the pooled model; the figure looks very similar for form A). At a relatively low Gini index of 25% the income elasticity is 0.75, while it is 1.98 at a Gini of 60%.

Similarly, the elasticity of emissions to inequality within countries is an increasing function of average income. (By symmetry of second cross-partial derivatives, the derivative of equation (9) w.r.t. I is identical to that of (10) w.r.t. $\ln Y$.) We could re-draw Figure 2 with the inequality derivative of emissions on the vertical axis and log mean income on the horizontal axis; with growth in average income the inequality derivative will increase, getting closer to zero. While higher inequality within a country lowers emissions, the impact is smaller at higher average incomes.

One must be skeptical of basing longer-term forecasts on models calibrated to data over only 15 years or so. However, as a means of understanding better the properties of the models we have estimated, it is of interest to ask whether our results suggest that carbon emissions could start to fall in a growing economy with sufficiently low inequality. With lower inequality, the income elasticity falls; with a higher mean income (due to growth) the elasticity falls even further.

So could the income elasticity become negative within reasonable bounds? Figure 3 gives forecasts implied by our pooled model for an economy with a growth rate in income per capita of 5% per year. We use the parameters of the unrestricted (pooled) model and all variables are set at the mean points (with income set at the mean initially), except for the Gini index which is set at one standard deviation above and below the mean. (The mean is 35.9 and the standard deviation is 8.6.) The low-inequality trajectory entails an initially higher emission rate, but it also results in a lower elasticity of emissions to growth, with the effect that it eventually achieves a lower emission level than even the high inequality trajectory; the low inequality path overtakes the other two after 27 years, and emissions start to decline after 19 years.

7 Conclusions

Our results suggest that trade offs do exist between reducing carbon emissions and promoting both lower inequality (between and within countries) and higher average incomes. In the short term, poverty reduction will tend to increase the carbon emissions that promote global warming. However, we also find signs of a flattening out of the relationship between emissions and average incomes at middle to high income levels, and some signs of a reversal in the curvature at high incomes. Thus it can be argued that the trade off between reducing inequality between countries and controlling carbon emissions will improve with growth, and eventually vanish, roughly when all countries reach the level of present-day middle income countries.

We also find strong interaction effects between average incomes and inequality in their effects on carbon emissions. In particular, there is a sizable positive impact of higher income inequality on the aggregate income elasticity of carbon emissions. Similarly, economic growth diminishes the adverse impact of pro-poor redistribution on carbon emissions. Thus it appears that the terms of the trade offs with global warming will improve over time when there is growth with equity, and become more acute under an inequitable growth process. Indeed, our results suggest that with sufficiently high growth and/or low inequality, emission rates will eventually start to decline.

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Table 1: Emissions regressed on a cubic function of average income

	Pooled levels model	Fixed effects model
GDP per capita	1.0423*	0.3258*
	(0.0692)	(0.0565)
(GDP per capita)^2	-0.1030*	-0.0136*
	(0.0092)	(0.0060)
(GDP per capita)^3	0.0037*	0.0002
	(0.0003)	(0.0002)
Population (thousands)	0.0010*	0.0012*
	(0.0001)	(0.0003)
Time trend	-0.0391*	-0.0146*
	(0.0067)	(0.0024)
Constant	-1.0233*	0.3510*
	(0.1125)	(0.1464)
R^2	0.6361	0.1744 (R^2 within)

Note: Huber-White standard errors in parentheses. 738 observations (annual data, 1975-92, for 42 countries). The * indicates that the coefficient is significantly different from zero at the 5% level or better.

Table 2: Pooled model for carbon emissions allowing for inequality within countries

		Unrestricted form	Restricted form A	Restricted form B
Log GDP per capita	β_{10}	1.830* (0.618)	1.242* (0.207)	2.309* (0.120)
Log GDP per capita interacted with Gini index	β_{11}	0.014 (0.018)	0.030* (0.005)	0
Squared log GDP per capita	β_{20}	-0.562* (0.204)	-0.348* (0.036)	-0.726* (0.067)
Squared log GDP per capita interacted with Gini index	β_{21}	0.006 (0.006)	0	0.011* (0.002)
Log population size	β_{30}	0.618* (0.071)	0.629* (0.068)	0.608* (0.068)
Log population size interacted with Gini index	β_{31}	-0.016* (0.002)	-0.016* (0.002)	-0.016* (0.002)
Time trend	β_{40}	-0.022 (0.018)	-0.014* (0.004)	-0.014* (0.004)
Time trend interacted with Gini index	β_{41}	0.000 (0.001)	0	0
Gini index	η_1	0.084* (0.021)	0.081* (0.021)	0.090* (0.019)
Constant term		-5.963* (0.788)	-5.809* (0.797)	-6.242* (0.755)
R^2		0.855	0.854	0.855

Note: The dependent variable is the log of the carbon dioxide emission rate per capita. 738 observations. Huber-White standard errors in parentheses. The * indicates that the coefficient is significantly different from zero at the 5% level or better.

Table 3: Fixed effects model

		Unrestricted form	Restricted form A	Restricted form B
Log GDP per capita	β_{10}	0.800* (0.396)	0.616* (0.169)	0.965* (0.053)
Log GDP per capita interacted with Gini index	β_{11}	0.005 (0.012)	0.010* (0.004)	0
Squared log GDP per capita	β_{20}	-0.139 (0.121)	-0.084* (0.016)	-0.193* (0.051)
Squared log GDP per capita interacted with Gini index	β_{21}	0.002 (0.003)	0	0.003* (0.001)
Log population size	β_{30}	3.055* (0.409)	2.994* (0.299)	2.907* (0.289)
Log population size interacted with Gini index	β_{31}	-0.049* (0.011)	-0.046* (0.007)	-0.045* (0.007)
Time trend	β_{40}	-0.021* (0.007)	-0.019* (0.002)	-0.019* (0.002)
Time trend interacted with Gini index	β_{41}	0.000 (0.000)	0	0
Constant		-14.299* (1.067)	-14.585* (0.938)	-14.298* (0.955)
Within R^2		0.599	0.599	0.599

Note: The dependent variable is the change in log carbon emissions per capita. 738 observations. Huber-White standard errors in parentheses. The * indicates that the coefficient is significantly different from zero at the 5% level or better.

Table 4: Elasticities at mean points

	Pooled model		Fixed effects model	
	Restricted form		Restricted form	
	A	B	A	B
Elasticity of carbon emissions per capita with respect to:				
Income per capita	1.209 (0.027)	1.222 (0.027)	0.697 (0.037)	0.696 (0.037)
Gini index	-0.036 (0.002)	-0.038 (0.002)	n.a.	n.a.
Elasticities of total carbon emissions with respect to:				
Population (holding total income constant)	-0.177 (0.029)	-0.170 (0.027)	1.632 (0.097)	1.605 (0.097)
Population (holding income per capita constant)	1.043 (0.013)	1.052 (0.013)	2.330 (0.094)	2.302 (0.095)

Note: Standard errors in parentheses.