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Economic development and the carbon intensity of human well-being

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Humans use fossil fuels in various activities tied to economic development, leading to increases in carbon emissions[1–3], and economic development is widely recognized as a pathway to improving human well-being. Strategies for effective sustainability efforts require reducing the carbon intensity of human well-being (CIWB): the level of anthropogenic carbon emissions per unit of human well-being[4–7]. Here I examine how the effect of economic development on CIWB has changed since 1970 for 106 countries in multiple regional samples throughout the world. I find that early in this time period, increased development led to a reduction in CIWB for nations in Africa, but in recent decades the relationship has changed, becoming less sustainable. For nations in Asia and South and Central America, I find that development increases CIWB, and increasingly so throughout the 40-year period of study. The effect of development on CIWB for nations in the combined regions of North America, Europe and Oceania has remained positive, relatively larger than in other regions, and stable through time. Although future economic growth will probably improve human well-being throughout the world[8], this research suggests that it will also cost an increasing amount of carbon emissions.

The relationship between carbon emissions and economic development receives considerable attention in research across the social sciences[9], with studies finding notable changes in the emissions and development relationship through time[10,11]. Likewise, the relationship between human well-being and economic development is a foundational empirical question in public health research[12]. Although most research reveals strong associations between enhanced well-being and development, some studies find that the strength of the relationship weakens through time[8]. However, limited attention has been paid to the amount of anthropogenic carbon emissions generated per unit of well-being—that is, the CIWB, and how it might be impacted by economic development[4–6,13].

As important, most cross-national research on development and emissions or development and well-being overlooks differences in regional-level patterns and changes, and analyses of regional samples of nations are potentially important for scientific discovery. Such a level of aggregation allows for investigating broad-based relationships, while being situated within regional contexts[14]. For example, public health research shows that the effect of urban slum prevalence on child mortality varies greatly by region. This variation is unobserved if the analysis is conducted for all nations combined in one sample[15]. Similarly, longitudinal research shows that the estimated effect of population size on national-level carbon emissions differs greatly for nations in different regions, and the relationship changes through time in ways unique to each regional sample of nations[16]. These differences are overlooked if nations are not analysed in separate regionally defined groups.

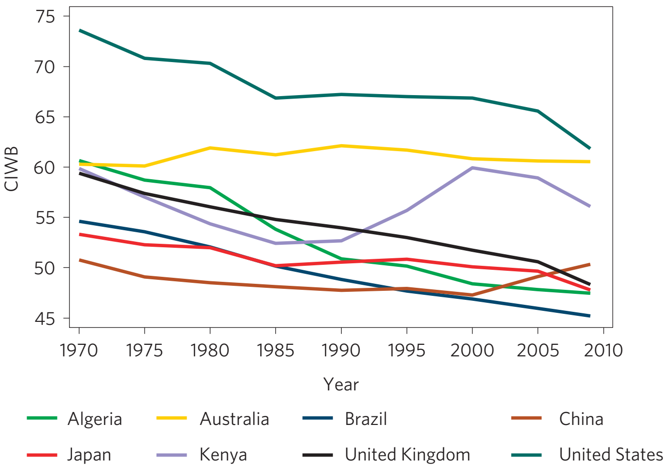

Figure 1 | The CIWB for eight nations, 1970–2009. The CIWB measures are reported for the years 1970, 1975, 1980, 1985, 1990, 1995, 2000, 2005 and 2009.

There are significant policy implications for research that focuses on development and CIWB. As economic growth is a common objective of governments and international organizations, given its potential for improving well-being, understanding the relationship between development and CIWB is critical. If development leads to reductions in CIWB, the pursuit of economic growth will have the beneficial side effect of enhancing sustainability. However, if economic growth has little or no beneficial effect on CIWB, then climate change mitigation and other sustainability efforts will be successful only if policies that supplement growth promotion are enacted. If economic growth increases CIWB, then development policies may pose additional challenges for climate change mitigation and must be reconsidered or balanced with new approaches to counter these unintended environmental impacts.

In this study I use national-level panel data for the 1970–2009 period to quantify CIWB as a ratio between per capita anthropogenic carbon dioxide emissions (from fossil fuel combustion and cement manufacturing) and average life expectancy at birth. Using measures of gross domestic product (GDP) per capita (measured in constant 2000 US dollars, based on exchange rates), I employ statistical modelling techniques and interaction variables between GDP per capita and time to assess the extent to which the effect of economic development on CIWB changes through time. Figure 1 graphs the CIWB measures for eight nations from different regions

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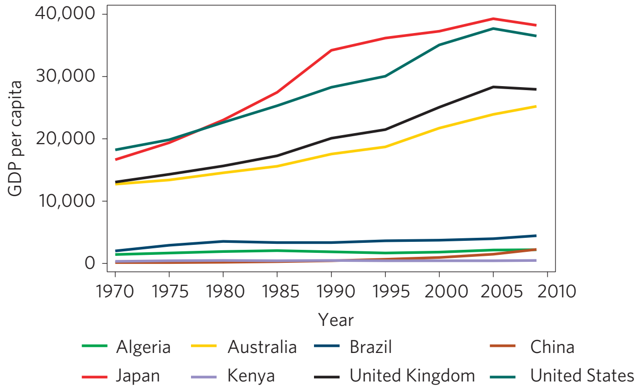

Figure 2 | GDP per capita for eight nations, 1970–2009. The GDP per capita measures are reported in 2000 US dollars (adjusted for inflation), and provided for the years 1970, 1975, 1980, 1985, 1990, 1995, 2000, 2005 and 2009.

Table 1 | Elasticity coefficients for the estimated effects of GDP per capita on the CIWB, 1970–2009.

	Africa	Asia	South and Central America	North America, Europe and Oceania
1970	−0.068	0.047	0.024	0.126
1975	−0.062	0.057	0.024	0.119
1980	−0.059	0.069	0.036	0.119
1985	−0.068	0.067	0.046	0.108
1990	−0.068	0.074	0.064	0.109
1995	−0.068	0.082	0.068	0.115
2000	−0.035	0.088	0.084	0.119
2005	−0.015	0.094	0.096	0.120
2009	−0.006	0.090	0.106	0.126

Estimates derived from Prais–Winston two-way fixed-effects elasticity models with panel-corrected standard errors and AR(1) corrections; full information on the estimated models is provided in Supplementary Table 2.

of the world for the 1970–2009 period, and Fig. 2 shows their GDP per capita measures. The eight nations are chosen to illustrate the diversity in levels and trajectories of national-level CIWB and economic development throughout the world, and the importance in assessing the relationship between them.

In Fig. 1, where lower values of CIWB are desirable from a sustainability perspective, we see that the CIWB for the United States moderately decreased through time, but its value in 2009 remained larger than the other seven nations in the figure. The CIWB for Australia is relatively large and slightly increased in value through time, whereas the CIWB measures for Japan, the United Kingdom, Brazil and Algeria all decreased in value, but at different rates. The CIWB for Kenya is similar in value in 1970 and 2009, but experienced periods of increases and decreases between those two years. For China, now the largest national greenhouse gas emitter, the CIWB decreased slightly in the earlier decades, followed by a steady upward trend beginning in 2000 and continuing until 2009.

Figure 2 shows that Japan, the United States, the United Kingdom and Australia experienced overall increases in GDP per capita, with all but Australia experiencing modest decreases from 2005 to 2009, corresponding with the world economic recession. Brazil and China both experienced noteworthy rates of economic growth that are overshadowed by the scaling of the figure, whereas Algeria and Kenya both experienced modest increases in GDP per capita.

I estimate separate models of the potentially changing effects of GDP per capita on CIWB for four regional samples of nations, where regions are largely defined by continent. The four samples include 36 nations in Africa, 22 nations in Asia, 21 nations in South and Central America and 27 nations in the combined regions of North America, Europe and Oceania. To preserve degrees of freedom, which are limited owing to the use of the fixed effects described below, I combine the last three regions of countries into one sample.

The combined regions of North America, Europe and Oceania include most high-income Organization for Economic Cooperation and Development nations. Whereas past research often compares this group of high-income nations to the rest of the world[8–10], I take a more nuanced approach where I disaggregate the rest of the world that consists of mostly lower- and middle-income nations into three regional samples and analyse them separately. The limited degrees of freedom preclude me from considering smaller-scale regional samples, such as separate samples of nations for Northern Africa and Southern Africa. (The list of all nations included in the study, organized by the four samples, is presented in Supplementary Table 1.)

The estimated models include country-specific fixed effects and year-specific fixed effects to account for factors unique to each nation that do not change through time (such as latitude), and for factors common to all nations that are unique to each time point in the study (such as energy price fluctuations)[17]. The country-specific fixed-effects model removes the influence of factors unique to each country, and focuses on explaining within-country variation. Including year-specific fixed effects also lessens the likelihood of biased model estimates resulting from dependent variables and independent variables with relatively similar time trends.

Before the analysis, all variables were converted into logarithmic form (base 10), allowing for the estimation of elasticity models. In such models, the elasticity coefficient for an independent variable is the estimated net percentage change in the dependent variable associated with a 1% increase in the independent variable. The effects of development on CIWB are estimated and reported in five-year increments from 1970 to 2005, and also for the year 2009, the most recent year in which adequate data are available for the analysis.

Table 1 presents the estimated effects (elasticity coefficients) of economic development on CIWB from 1970 to 2009 for the four samples of nations, and Fig. 3 graphs the elasticity coefficients (full information for the estimated models is provided in Supplementary Table 2). A negative coefficient would imply a beneficial effect from a sustainability perspective, because it would suggest that to some extent an increase in economic development leads to a reduction in CIWB. Comprehensive sensitivity analyses, which involve estimating the models while systematically excluding each nation, indicate that none of the samples contains any overly influential cases. An additional analysis presented in the Supplementary Information that uses an alternative measure of CIWB yields results consistent with the reported findings for all four samples.

For the sample of 36 nations in Africa, the elasticity coefficient for the effect of development on CIWB was −0.068 in 1970, indicating that a 1% increase in GDP per capita led to a decrease of slightly less than 0.07% in CIWB, and this negative effect remained relatively stable until at least 1995. This stable negative effect is encouraging, given that it suggests development during this period would lead to a reduction in CIWB. However, after 1995 the effect of development became less negative, and almost close to zero by 2009.

The analysis reveals patterns in the changing effects of economic development on CIWB for the sample of 22 nations in Asia and the sample of 21 nations in South and Central America that are similar to one another. The elasticity coefficient for the effect of GDP per capita in 1970 was positive for both samples (0.047 for Asia, 0.024 for South and Central America), which is problematic from a sustainability perspective because the positive coefficients suggest that economic development increases CIWB. The positive coefficients generally increased in value throughout the four

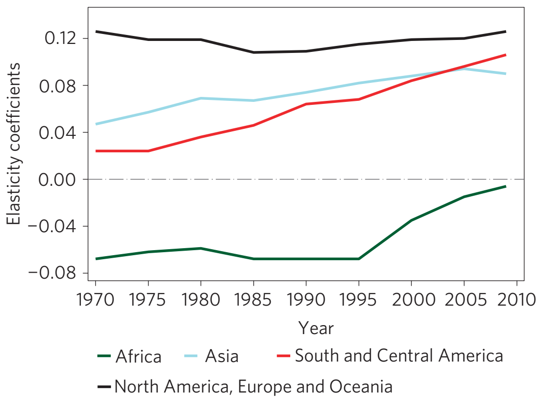

Figure 3 | Elasticity coefficients for the estimated effect of GDP per capita on the CIWB. The estimates are derived from two-way fixed-effects Prais–Winston regression models with panel-corrected standard errors and AR(1) corrections; full information on the estimated models is provided in Supplementary Table 2; Africa sample includes 36 nations; Asia sample includes 22 nations; South and Central America sample includes 21 nations; North America, Europe and Oceania sample includes 27 nations.

decades, where the elasticity coefficient in the year 2009 was 0.090 for the Asia sample and 0.106 for the South and Central America sample. For the Asia sample, the effect of development was slightly larger in 2005 (elasticity coefficient = 0.094) than in 2009.

For the sample of 27 nations in North America, Europe and Oceania, the elasticity coefficient for the estimated effect of development on CIWB has remained positive in value and relatively stable through time. The coefficient was 0.126 in 1970, meaning that during this year, a 1% increase in GDP per capita led to a 0.126% increase in CIWB. This relationship slightly decreased during the mid-1970s to the early 1990s. After 1990 the estimated coefficient began increasing, returning to a value of 0.126 by the year 2009.

From a sustainability perspective, under ideal circumstances nations throughout the world would experience, simultaneously, economic development, enhanced human well-being, and reductions in carbon emissions and other environmental impacts. The findings for the analysis of mostly high-income nations in North America, Europe and Oceania indicate that, rather than becoming more sustainable, economic growth continues to increase CIWB. These nations continue to use significant amounts of fossil fuels and other inputs to benefit the well-being of their inhabitants. This is particularly troubling from a climate change perspective, because the per capita emissions for these relatively affluent nations continue to be, on average, much higher than the nations in all other world regions, and their cumulative emissions are by far greater than any other grouping of nations[10,18].

The analysis indicates that through time, economic development has become less sustainable for nations in Africa, Asia and South and Central America, at least as measured by CIWB. The trends for these particular regions, that include many less-developed and developing nations, point to the future challenge of addressing the environmental impacts of economic development which is of central priority for nations to increase the quality of life for their citizens and future generations. However, the trends of increasing effects of economic development on CIWB for these regions are far from monolithic, suggesting that future policies and programmes can take into account these important differences and their underlying causes.

Overall, the effect of economic development on CIWB differs across regions, and the effect changes through time, but in ways unique to each of the four samples of nations. In 2009 the relationship between CIWB and development in Africa was close to null. This might suggest that in this region climate change mitigation will be more effective if policies that supplement economic development are enacted. However, one must recognize that in recent decades the CIWB and development relationship for nations in Africa became increasingly less sustainable, and if this pattern continues, it could lead to more problematic circumstances and new challenges for balancing economic development, human well-being, and environmental impacts.

In all other regional samples economic development increases CIWB, with relatively similar elasticity coefficients in 2009. However, in 1970 the elasticity coefficient measuring the effect of development on CIWB was over five times smaller for nations in South and Central America and over two and a half times smaller for nations in Asia, relative to nations in North America, Europe and Oceania. Although these groups of nations have notable differences in their economic histories and past trajectories, the pattern of relative convergence towards the end of the study period underscores the increasingly similar sustainability challenges faced by the nations across these regions. The overall results of this study are also consistent with recent research that uses consumption-based measures of national carbon emissions and finds that enhanced human development is compatible with patterns of decarbonization, but economic development above a certain threshold is not[19].

This study increases our understanding of the dynamic relationships between carbon emissions, human well-being, and economic development. Like past research that it draws from, this study highlights the importance of taking an integrated approach that incorporates the environmental, social and economic dimensions of sustainability[4–7,13]. As important, this study suggests that future research should involve in-depth case studies to identify the conditions in each region that shape their specific CIWB and development relationships. As carbon emissions data become available for more recent years, future studies should assess the CIWB and development relationship in all regions past the year 2009. This could be quite fruitful, given the recent world economic recession and important unanswered questions about its impacts on rates and levels of greenhouse gas emissions throughout the world[20].

Methods

I use country-level data obtained from the Word Bank[21]. The data are annual observations measured in five-year increments from 1970 to 2005 as well as for the year 2009, the latter of which is the most recent year where adequate data are available to perform the analysis. I include nations where data are available for each of the study's time points, allowing for perfectly balanced panels consisting of nine observations per country.

Perfectly balanced panels are ideal for the study's research design, because interaction variables for GDP per capita and dummy variables for each yearly observation are employed to assess the extent to which the effect of development on CIWB might change through time[10,16,17]. Thus, it is preferred to have data for the same nations at each time point. An unintended consequence of this approach is the exclusion of nations where data are not available for each time point. Although the overall sample that is analysed accounts for most of the world's population and the study covers a large time frame, future studies that focus on shorter and recent time periods could include additional nations, but at the expense of a more limited temporal scope[22].

I employ anthropogenic carbon dioxide emissions per capita, measured in metric tons, as the numerator for CIWB. These data include emissions from the burning of fossil fuels and the manufacture of cement. They exclude emissions from land use. As noted in other studies on similar topics[4,7], future research that instead employs measures of carbon emissions from land use would offer additional insights on the relationship between economic development and CIWB. As various economic activities contribute to land-use change, such as deforestation in many developing nations[14,23], the analysis reported in this study, which excludes emissions from land use, might underestimate the effects of economic development on CIWB, especially in the regions with mostly developing nations.

Life expectancy at birth, the denominator for CIWB, indicates the average number of years a newborn infant would live if prevailing patterns of mortality at the time of its birth were to persist throughout its life. Although life expectancy is an appropriate, valid and reliable measure of human well-being, future work on CIWB could certainly employ other well-being measures.

In the overall data set the coefficient of variation (standard deviation/mean) for carbon emissions per capita is 1.489. For life expectancy the coefficient of variation is 0.180. The coefficients of variation indicate that the relative variation in per capita carbon emissions is substantially larger than the variation in life expectancy. Under such conditions the variation in the numerator could drive variation in the ratio. To resolve this complication I take the same approach as Dietz and colleagues[4] and Jorgenson and colleagues[22], which involves constraining the coefficient of variation for the numerator and denominator to be equal by adding a constant to one of them, shifting the mean without modifying the variance, thereby allowing for the equalization of the coefficient of variation for the two initial measures. The coefficients of variation for the two variables can be made equal (a value of 0.180) by adding 31.0 to the measures of carbon emissions. The measure of the CIWB is:

$$\text{CIWB} = [(\text{CO}_2\text{PC} + 31.0)/\text{LE}] * 100$$

where CO_2PC is carbon dioxide emissions per capita in metric tons and LE is average life expectancy in years. To scale the ratio, I multiply by 100 (refs 4,22).

I use a Prais–Winsten regression model with panel-corrected standard errors, allowing for disturbances that are heteroskedastic and contemporaneously correlated across panels[24]. I control for both year-specific and country-specific effects, the equivalent of a two-way fixed-effects model. I also correct for AR(1) (that is, autoregressive) disturbances within panels, and I treat the AR(1) process as common to all panels[24]. All variables are transformed with the base 10 logarithm. Thus, the regression models estimate elasticity coefficients where the coefficient for an independent variable is the estimated net percentage change in the dependent variable associated with a 1% increase in the independent variable.

I estimate the same two-way fixed-effects elasticity model for each of the four samples of nations. The estimated model is as follows:

$$\begin{aligned}\text{CIWB}_{\text{it}} = {} & \beta_1\text{GDP per capita}_{\text{it}} + \beta_2\text{year1975}_{\text{t}} + \cdots + \beta_9\text{year2009}_{\text{t}} \\ & + \beta_{10}\text{GDP per capita}_{\text{it}} * \text{year1975}_{\text{t}} + \cdots \beta_{18}\text{GDP per capita}_{\text{it}} * \text{year2009}_{\text{t}} \\ & + u_{\text{i}} + e_{\text{it}}\end{aligned}$$

where the dependent variable, CIWB_{it}, is the CIWB, and the model includes GDP per capita ($\beta_1\text{GDP per capita}_{\text{it}}$), the period-specific intercepts ($\beta_2\text{year1975}_t + \cdots + \beta_9\text{year2009}_t$), the interactions between GDP per capita and the dummy variables for each year ($\beta_{10}\text{GDP per capita}_{\text{it}} * \text{year1975}_{\text{t}} + \cdots + \beta_{18}\text{GDP per capita}_{\text{it}} * \text{year2009}_{\text{t}}$) where 1970 is the reference category, the country-specific intercepts (u_{i}), and the disturbance term unique to each country at each point in time (e_{it}). The u_{i} intercepts control for potential unobserved heterogeneity that is temporally invariant within countries (country-specific intercepts), and the period-specific intercepts control for potential unobserved heterogeneity that is cross-sectionally invariant within periods. The coefficient for GDP per capita is the unit change in the dependent variable in 1970 for each unit increase in GDP per capita for the same year. The overall effect of GDP per capita for the other time points equals the sum of the coefficient for GDP per capita (that is, its effect in 1970) and the appropriate interaction term if the latter is statistically significant[17].

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Author contributions

A.K.J. designed the research, analysed the data, and wrote the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to A.K.J.

Competing financial interests

The author declares no competing financial interests.