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Pathways of human development and carbon emissions embodied in trade

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It has long been assumed that human development depends on economic growth, that national economic expansion in turn requires greater energy use and, therefore, increased greenhouse-gas emissions. These interdependences are the topic of current research. Scarcely explored, however, is the impact of international trade: although some nations develop socio-economically and import high-embodied-carbon products, it is likely that carbon-exporting countries gain significantly fewer benefits. Here, we use new consumption-based measures of national carbon emissions[1] to explore how the relationship between human development and carbon changes when we adjust national emission rates for trade. Without such adjustment of emissions, some nations seem to be getting far better development 'bang' for the carbon 'buck' than others, who are showing scant gains for disproportionate shares of global emissions. Adjusting for the transfer of emissions through trade explains many of these outliers, but shows that further socio-economic benefits are accruing to carbon-importing rather than carbon-exporting countries. We also find that high life expectancies are compatible with low carbon emissions but high incomes are not. Finally, we see that, despite strong international trends, there is no deterministic industrial development trajectory: there is great diversity in pathways, and national histories do not necessarily follow the global trends.

Seriously addressing climate change requires drastically cutting carbon emissions. To 'avoid dangerous climate change'[2] would require rapid reductions in emissions, from 1.2 t C per capita on average in 2005 (ref. 3) to well below 1 t C per capita by 2050, with proposals ranging from 0.35 to 0.2 t C per capita (refs 4,5). These emission reductions, however, need to be achieved in an equitable manner[2]. The implications of such reductions for national economies and human development are at the core of international disagreements over addressing climate change. As a result, the empirical links between fossil-fuel-based energy and economic and human progress are now central topics of research[6–10]. High life expectancy is attainable at ever-declining levels of income[11], and economic growth is increasingly challenged as the precondition of development[12]. Moreover, human development has been steadily decoupling from energy and carbon emissions[13].

Recently, the relative decarbonization of wealthy nations' economies has been questioned, because these countries may be benefiting not only from the carbon emitted within their national territory (which are recorded in national and international statistics), but also from the carbon emissions embodied in the goods and services they import[1,14–18]. Several pioneering studies based on environmentally extended input–output methodologies have recently provided the first robust estimates of international trade-corrected consumption-based carbon[14,15] and greenhouse-gas emissions[16]. Conventional carbon accounting covers emissions occurring in the country's territory, and these are the basis of the Kyoto Protocol agreements. Consumption-based accounting corrects territorial emissions by adding emissions generated to produce imported goods and services, and subtracting those generated to produce exports. This method has now been extended to estimate consumption-based emissions for a large set of countries in the time span 1990–2008 (ref. 1).

This Letter focuses on differences between consumption-based and territorial emissions in their relation to human development. The underlying factors causing certain countries to be net importers or exporters of carbon are thus beyond its scope. In fact, the drivers of traded carbon and energy have proved elusive, and cannot simply be ascribed to higher environmental standards or cleaner production patterns in one country or region driving carbon-intensive production to another[17,18].

Our hypothesis is that consumption-based emissions, which include the carbon embodied in all goods and services consumed in a country, should reflect the socio-economic benefits (measured by life expectancy and income) accruing from these emission processes better than territorial emissions. It has already been shown that carbon emissions per unit gross domestic product (GDP) converge to similar values in a consumption perspective[19].

It is currently unknown, however, how consumption-based emissions related to life expectancy and income. Figure 1 shows the relationship between carbon emissions and life expectancy and GDP per capita, with and without corrections for carbon embodied in trade (using consumer emissions from ref. 1). In Fig. 1, we show countries and regions as horizontal arrows moving from territorial to consumption-based carbon emissions. The start of the arrow thus corresponds to conventional national accounting (such as was used in the Kyoto Protocol), whereas the centre of head of the arrow takes into account the emissions embodied in trade. Carbon-exporting countries move from right to left (grey arrows, solid lines), and carbon-importing countries move from left to right (red arrows, dashed lines). Countries whose total emissions are mostly unaffected by trade are shown as blue circles. The area of the points is proportional to population.

As expected, both territorial and consumption-based carbon emissions are highly correlated to the human development indicators shown in Fig. 1. However, the shape and strength of the relationship between carbon and income is very different from the one between carbon and life expectancy. Carbon emissions

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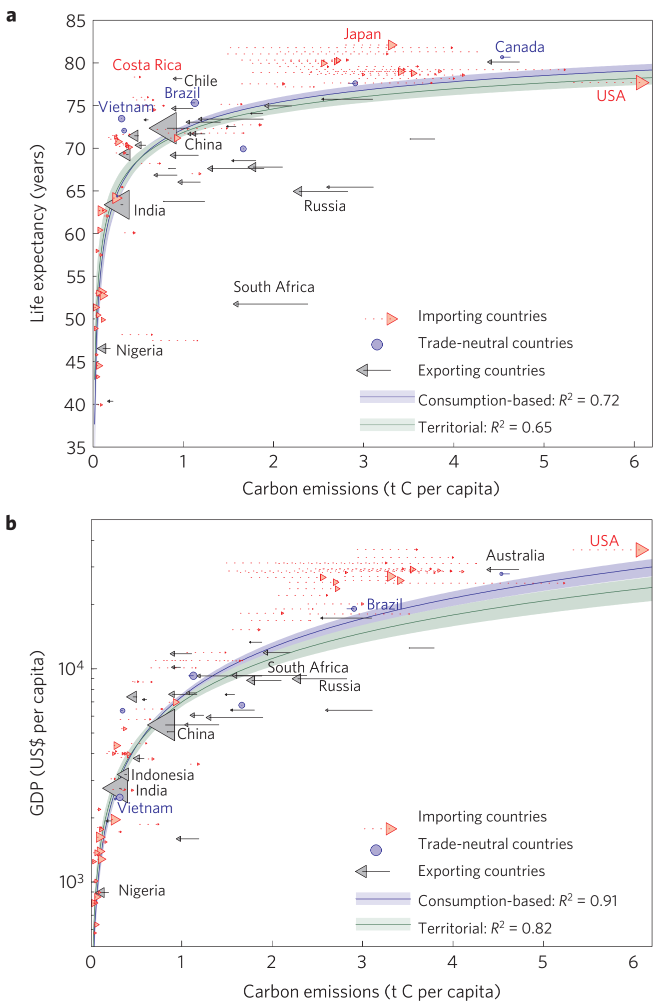

Figure 1 | Correcting for trade: how moving from territorial to consumption-based emissions changes the relation between carbon and human development. a,**b**, Each arrow represents a country/region moving horizontally from territorial (arrow base) to consumption-based (centre of arrowhead) carbon emissions, in the year 2004. The vertical axes are life expectancy (**a**) and income (**b**). The arrowhead size represents national population. Carbon importers are red; exporters, grey; net-neutral countries are blue circles. The fit curves are shown for both consumption-based (blue) and territorial (green) emissions, with the shaded bands corresponding to one standard error intervals. Note that the arrows do not represent residuals from the fit curves.

scale roughly proportionally with income, with a high goodness of fit, whereas life expectancy grows with carbon emissions in the lower range, but then seems to decouple, reaching a level where higher emissions do not generate much benefit, and has a lower goodness of fit. These different behaviours can be seen in Fig. 1: life expectancy has a turning point, which is absent for income (the income–carbon plot is linear in log–log space). Adjusting emissions for international trade tends to move the countries closer to the fit curves and improves the goodness of fit R^2. Countries that are above (same carbon emissions, higher socio-economic performance), or to the left (same socio-economic performance, lower carbon emissions), of others in Fig. 1 are more carbon efficient in delivering socio-economic wellbeing to their populations.

Most of the carbon-exporting countries and regions are grouped at intermediate life expectancy (between 63 and 75 years) and income (between US$2,000 and US$12,000 per capita). They perform worse than non-exporting countries and the global trend, in terms of socio-economic achievement given their level of carbon emissions. Even when their emissions are corrected for the embodied carbon in international trade, most of them are still below other countries and the global trend. This result indicates that there is a systematic disadvantage, in terms of socio-economic benefits, for carbon-exporting economies. In addition to China and India, which are relatively close to the global trend, these countries are mainly from the former Soviet Union, Eastern Europe, Middle East, and South Africa. They are the fossil fuel-exporting and raw material-exporting economies. This suggests the double negative of specializing in natural resource extraction and earlier stages of processing and manufacturing[20,21], and can be interpreted as evidence for the environmentally unequal exchange theory[22].

The carbon-importing countries, in contrast, are an extremely diverse group. They consist of high-socio-economic-status OECD (Organisation for Economic Co-operation and Development) countries (life expectancies above 75 years and national average income above US$12,000 per capita), some intermediate countries from Asia and Latin America and most of the countries with low socio-economic status (life expectancies below 63 years, income below US$2,000 per capita), which are overwhelmingly African. The membership of the carbon-importing club thus consists of two extremes: the most socio-economically well off, and the poorest of the poor. The plight of development is particularly acute for the poorest countries, which are constrained to import not just energy itself, but also carbon-intensive goods and services from the global market, sometimes relying on large amounts of foreign assistance for this purpose[23]. These countries are thus doubly vulnerable to price increases in fossil fuels.

Importantly, at lower incomes and carbon emissions the consumption-based fit curve lies below the territorial ones (although this difference is not visible in Fig. 1b, because of the steepness of the curves; see Supplementary Information for details). This indicates that low income levels require higher carbon emissions than previously thought, when trade is taken into consideration. The leftwards shift of carbon-exporting middle-income economies, and rightwards shift of importing high-income countries, tends to dispel the apparent ‘environmental Kuznets curve’, according to which, at very high levels of income, economic growth results in a decline of emissions. This supports the finding that the environmental Kuznets curve for carbon per capita, already contested for territorial emissions[24], does not exist after correcting for embedded carbon emissions of imports[14,25,26]. Indeed, the monetary wealth achieved by most OECD countries corresponds to consumption-based carbon emissions significantly above the territorial emissions taken into account by the Kyoto Protocol[1].

Consumption-based emissions are consequently the most appropriate for comparison with human development. The three-variable plot (Fig. 2) enables the simultaneous visualization of life expectancy, consumption-based emissions and income, and thus summarizes important global patterns and variation in 2004. A life expectancy between 75 and 80 years of age was achieved by countries with emissions ranging from a modest 0.5 t C per capita for Costa Rica to 6.2 t C per capita for the United States. The income range for these countries was also extreme, from US$4,500 (Albania) to US$36,000 per capita (United States again). If we zoom in on the countries with lifespan of over 70 years and less than 1 t C per capita (the ‘Goldemberg corner’[13]), we see a large range in possible incomes, from US$2,500 to US$12,000 per capita. The countries in this virtuous group are geographically diverse: from Latin America, Asia, Eastern Europe and North Africa.

The large range in carbon emissions and incomes at the highest life expectancies could be seen as good news. However, there is a clear pattern within these ranges: the countries at the lowest carbon ranges of their life-expectancy cohort are also the ones

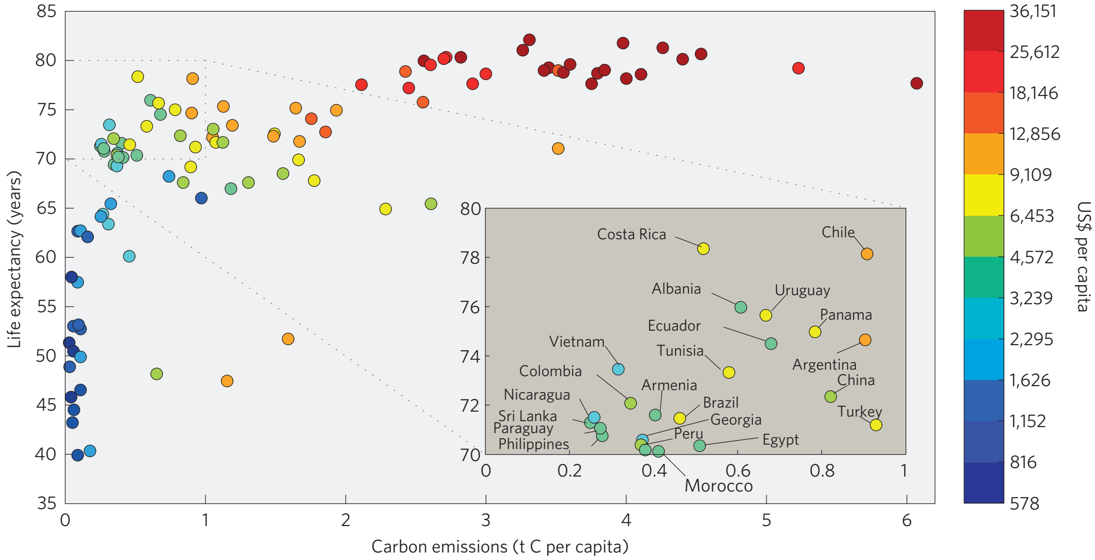

Figure 2 | Simultaneous visualization of international life expectancy, income and consumption-based carbon emissions in 2004. Three-dimensional representation of life expectancy (vertical axis), consumption-based emissions (horizontal axis) and income (colour scale). The inset is the 'Goldemberg corner', with life expectancy over 70 years and less than one tonne of carbon emissions per capita. The highest life-expectancy levels are attained at a wide range of carbon emissions and incomes.

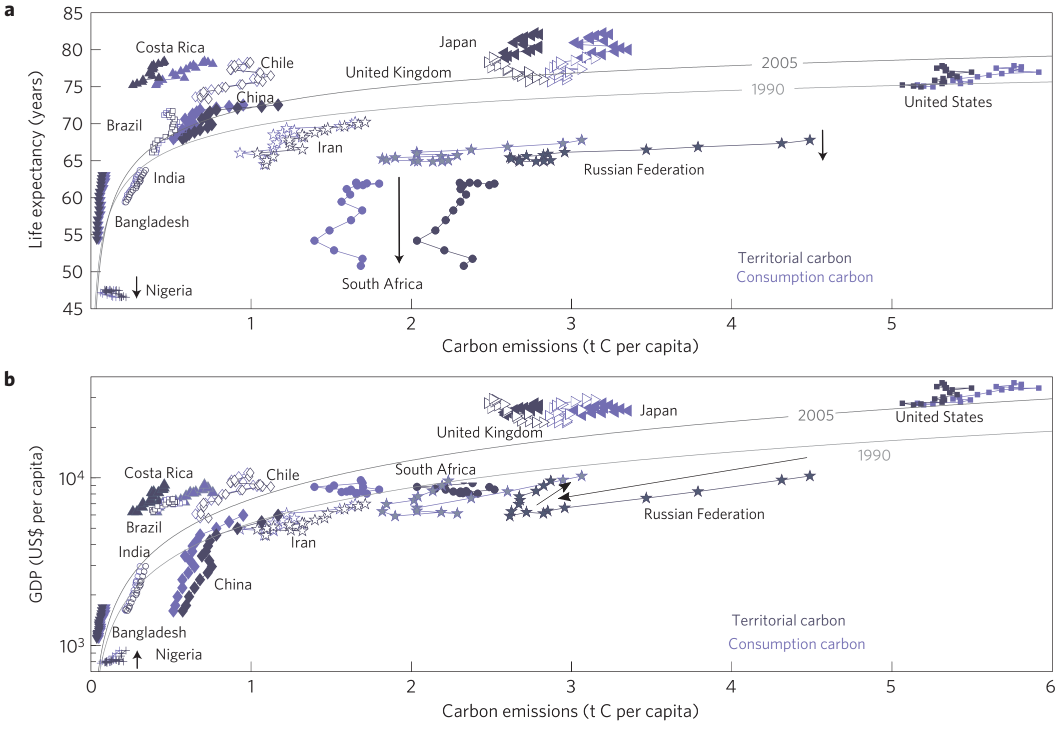

Figure 3 | National development trajectories 1990–2005 for life expectancy, income and territorial and consumption-based emissions. **a**,**b**, Territorial-emission trajectories are dark blue; consumption-based ones are pale blue, shown for life expectancy (**a**) and income (**b**), and contrasted with the global fit curves for consumption-based carbon in 1990 and 2005. The trajectories are upwards except when the arrows indicate otherwise. South Africa's trajectory in **b** is clockwise.

at the lowest incomes. This suggests that higher incomes make lower carbon profiles difficult, especially if we factor in embodied carbon in imports.

Our final objective is to move beyond global trends to find examples of countries with more sustainable pathways of economic and social development, and to assess whether their relative sustainability holds up even when their emissions from the import of goods and services are taken into account.

We address this question by observing the development trajectories of 13 key countries and regions from 1990 to 2005, in terms of our four variables: life expectancy, income and per capita carbon emissions (both territorial and consumption based), and comparing these trajectories with the global trend lines. The countries in Fig. 3 were selected for geographical diversity, size and interest, and they represent over half of the world's population and carbon emissions.

Table 1 | Regression results for the trend curves shown in Figs 1 and 3.

	Number of countries/regions and fraction of global population	Year	Emission accounting	R^2	Ordinate at origin *a*	Slope *b*	Saturation value
Fig. 1a: life expectancy	109; 99.1%	2004	Territorial	0.65	2.92 (0.02)	−0.23 (0.02)	90.03
			Consumption based: MRIO	0.72	2.89 (0.02)	−0.26 (0.02)	90.03
Fig. 1b: income	106; 97.9%	2004	Territorial	0.82	8.85 (0.05)	0.68 (0.03)	
			Consumption based: MRIO	0.91	8.91 (0.03)	0.77 (0.02)	
Fig. 3a: life expectancy	108; 98.9%	1990	Consumption based: TSTRD	0.78	2.85 (0.02)	−0.24 (0.01)	86.8
	109; 99.1%	2005		0.71	2.91 (0.02)	−0.27 (0.02)	90.5
Fig. 3b: income	104; 97.5%	1990	Consumption based: TSTRD	0.81	8.59 (0.06)	0.70 (0.04)	
	105; 97.9%	2005		0.90	8.92 (0.03)	0.77 (0.03)	

Values in parentheses are the standard errors of the coefficients.

Although the typical trajectory in Fig. 3 is one of growth in all three dimensions, the Russian Federation and many African countries suffered decreases in life expectancy over the period, due to political and economic collapse and the AIDS epidemic respectively. The trajectories in Fig. 3 are thus upwards, except when indicated otherwise. The UK experienced a significant decrease in its territorial emissions per capita, although emissions grew when embodied emissions in trade were considered[27,28]. For some countries, the trajectories show the consequences of political upheaval (Russian Federation) and economic crises (Chile, Japan).

Overall, the development trajectories in Fig. 3 are consistent with the trends seen in Figs 1 and 2: high life expectancy is attainable at a large range of carbon emissions, whereas income is much more closely linked with carbon. However, and perhaps surprisingly, several countries do not follow the global trends (shown for 1990 and 2005, consumption-based emissions): in general, the growth in socio-economic benefits is larger than the growth in carbon emissions could account for, if the trend curves were followed. This explains why the global trend curves are steadily moving upwards, as we have shown previously[13]. This is evidence of relative, but not absolute, decoupling of socio-economic gains from carbon-intensive processes. Moreover, the diversity of development pathways shown in Fig. 3 is evidence that there is no deterministic single development trajectory, despite the fact that all the countries shown are linked by global trade and rely to a large extent on similar technologies.

Ideally, nations could achieve all three of the objectives required for sustainable development: low carbon emissions, high life expectancy and high income. However, the evidence from our analysis demonstrates that it is indeed possible to achieve simultaneous environmental and social sustainability (in the form of lower carbon emissions and high life expectancy), but only at levels of income below US$12,000 per capita (Fig. 2). Indeed, the coupling between economic activity and carbon emissions (Fig. 1b) is stronger than the correlation between life expectancy and carbon emissions (Fig. 1a), or between life expectancy and income. This enables certain combinations of desirable outcomes, but not all: high life expectancies and high incomes are compatible, so are high life expectancies and low carbon emissions, but economic and environmental goals seem to be at odds with each other, at least at the highest levels of GDP per capita.

In other words, a moderate income is currently a necessary (but not sufficient) requirement for environmental sustainability: 'necessary' because no high-income country has carbon emissions below 1 tC per capita when correcting for embodied carbon in imports; 'not sufficient' because moderate incomes do not guarantee either high life expectancy or low carbon emissions.

This study suggests avenues for further research. The causal factors underlying development pathways need to be explored to identify viable low-carbon transitions going forward. A better understanding of the obvious regional differences in the national trajectories seen in Fig. 3 is of clear interest. There is much further work to do on scenarios, projecting current trends of nations and groups of nations that are moving in a measurable direction. What will the structure of global pathways look like if these countries continue in the directions they are heading? Can this approach better inform socio-economic elements of global climate models? The implications of these findings are substantial, then, both for climate modellers and for development planners. For planners and decision-makers, the findings provide hope that national choices and pathways matter, and policies are available that do not prioritize growth at the expense of climate stability and a long life for our societies.

Methods

The data used here come from the following sources: consumption-based carbon emissions from ref. 1; territorial carbon emissions from the Carbon Dioxide Information and Analysis Center[3]; life expectancy and population from the United Nations Population Division[29]; GDP in purchasing power parity constant US$2,000 from the World Bank[30]. These data sources were combined to match the Global Trade Analysis Project countries/regions used in ref. 1 by estimating regional values, using the full 2004 multi-regional input–output (MRIO) for the data shown in Figs 1 and 2 and the time-series with trade (TSTRD) approximation for the trajectories in Fig. 3.

Our quantitative analysis consists in the examination of two pairwise relationships: the first between carbon and life expectancy, the second between carbon and income (Figs 1 and 3). For the sake of comparison, this analysis is conducted in parallel for consumption-based and territorial emissions. The method we use is population-weighted[13] linear least-square fitting. The functional form for income versus carbon is log–log: $\log(\text{GDP per capita}) = a + b\log(\text{carbon per capita})$.

The functional form for life expectancy is hyperbolic[13]: $\log(\text{life expectancy} - \text{saturation value}) = a + b\log(\text{carbon per capita})$. These functional forms do not assume a specific causal relationship between the variables. The regression results are summarized in Table 1. It should be noted that these results are not intended to represent the exact relationship between the variables (although, in the case of incomes, the goodness of fit is high enough that it is probably a very good approximation). Moreover, the exact values of the results will depend on the sample of countries and regions under consideration. We have noted the geographical coverage in Table 1, and have indicated the 1 standard error bands around the fit curves in Fig. 1.

Non-parametric analysis constitutes a less prescriptive alternative to linear least-square fitting. We conducted a complementary non-parametric analysis on our data, which confirms our findings. This analysis is described in more detail in Supplementary Information.

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Author contributions

J.K.S. and J.T.R. designed the research; J.K.S. and G.B. conducted the analysis; G.P.P. provided the consumption-based carbon data and feedback on its analysis; J.K.S., J.T.R. and G.P.P. wrote the paper.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/natureclimatechange. Reprints and permissions information is available online at http://www.nature.com/reprints. Correspondence and requests for materials should be addressed to J.K.S.