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RESEARCH ARTICLE

Achieving good health with a low environmental footprint – A comparison of national indicators [version 1; peer review: awaiting peer review]

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Abstract

Background

Integrated metrics that account for resource use and human health are essential to help identify and support human development pathways that safeguard planetary health. We identify countries that achieved the highest levels of health and development at the lowest cost to Earth's natural capital and report ecological within-country analyses of associations between indicators of environmental sustainability, human health, and development.

Methods

We used mixed-effects multiple linear regression models of Healthy Life Expectancy (HALE) and Human Capital (HC) related to Ecological Footprint (EF) and CO_2 production emissions, controlling for Gini coefficient and population density applied to data of 216 countries from 1991-2016. We performed stratified analyses by country income level and used likelihood-ratio tests to test for interaction.

Results

Only Jamaica (1991) and Sri Lanka (2016) achieved high HALE at sustainable EF levels. Each 10% increase in EF was associated with 0·20 (95%CI 0·16,0·24) and 0·21 (95%CI 0·19,0·23) increases in HALE and HC respectively; increases in CO_2 production emissions were also associated with increased HALE and HC. There was strong evidence for interaction by income level for each model ($p<0·016$). Stratified analyses showed that in high income nations HALE and HC decreased with increased levels of EF and CO_2.

Conclusions

Countries with high health metrics at sustainable EF levels may offer valuable lessons for sustainable national development policies.

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Any reports and responses or comments on the article can be found at the end of the article.

Increased environmental footprint and CO_2 emissions appear associated with higher levels of human health and development only up to a certain level of income.

Keywords
Planetary health, Sustainable development, Ecological Footprint, Emissions, Population health, Environmental change, Human development, Association analysis

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List of abbreviations

GDP = Gross domestic product

SDGs = Sustainable development goals

EF = Ecological footprint

HALE = Healthy life expectancy

HC = Human capital

CO_2 = Carbon dioxide

GHGs = Greenhouse gases

GNI = Gross national income

UK = United Kingdom

US = United States

UAE = United Arab Emirates

Introduction

Despite the advent of newer, more holistic measures of human development, gross domestic product (GDP) is still often prioritised in politics and continues to exert influence over policy decisions. The short time in which human activity has been the dominant force acting on Earth systems suggests an urgent need for changes in resource use[1]. There is a strong argument that the depreciation of natural capital should be accounted for to ensure economy and nature are no longer falsely separated[2].

The concept of planetary boundaries aims to identify key Earth system processes and determine for each a boundary level which should not be crossed to avoid unacceptable risks from global environmental change[3,4]. Defining a safe operating space within which humanity can thrive based on an understanding of the resilience of the Earth's natural systems requires integrated country-level metrics of planetary health[5]. These would allow better tracking of resource use and health, to help relevant stakeholders make evidence-based decisions[3]. Furthermore, integrated country-level metrics would enable better monitoring of progress towards the UN's Sustainable Development Goals (SDGs), 11 of which are directly linked to human development and planetary health[6]. Currently the SDGs do not use integrated metrics to monitor overall progress but instead estimate progress towards each goal separately.

To develop more comprehensive planetary health metrics, the interplay between environmental resource use and human health and development must be better understood and factors that confound these associations or modify their effect identified. A deeper understanding of these associations could help shape integrated monitoring of planetary health and highlight countries that have been successful in achieving high levels of health with low environmental footprints. This could foster mutual learning to accelerate progress.

In this paper, we aim to identify countries that come closest to achieving high levels of health and development without exhausting Earth's natural capital. Additionally, we undertake exploratory analyses of associations between indicators of environmental sustainability and human health and development, across countries, controlling for potential confounding factors. We also investigate how these associations vary with country income level.

Methods

We performed an ecological study using open access, country-level data, for up to 216 countries and nation states (hereafter countries) from 1991–2016. To put together our comprehensive study dataset we downloaded country-level data for globally expansive metrics from the following sources:

Healthy life expectancy (HALE) – https://ghdx.healthdata.org/record/ihme-data/gbd-2017-dalys-and-hale-1990-2017 (accessed: June 2020).

Human capital (HC) – https://ghdx.healthdata.org/record/ihme-data/global-human-capital-estimates-1990-2016 (accessed: June 2020).

Ecological footprint (EF) – https://www.footprintnetwork.org/licenses/public-data-package-free/ (accessed: June 2020).

Carbon dioxide emissions – http://www.globalcarbonatlas.org/en/CO2-emissions (accessed: June 2020).

Gini coefficient – https://data.worldbank.org/indicator/si.pov.gini (accessed: July 2020).

Population density – https://data.worldbank.org/indicator/EN.POP.DNST (accessed: July 2020).

Gross national income (GNI) per capita – https://data.worldbank.org/indicator/NY.GNP.PCAP.PP.CD (accessed: July 2020).

Gross domestic product (GDP) per capita – https://data.worldbank.org/indicator/NY.GDP.PCAP.CD (accessed August 2020).

Healthcare expenditure per capita – https://data.worldbank.org/indicator/SH.XPD.CHEX.PC.CD (accessed August 2020).

We used healthy life expectancy (HALE) and ecological footprints (EF) to highlight countries achieving good health at low resource use levels. Additionally, we used HALE, EF, CO_2 production emissions, human capital (HC), and additional candidate metrics to begin to investigate the associations between resource use and human health and development. The last year for which data was available varied between metrics so we used those years for which availability was most comprehensive.

Healthy life expectancy

HALE is a form of life expectancy measurement which applies disability weights to various states of health to determine the number of years of good health expected for an individual born in a given year[7,8]. We used HALE to represent human health.

Human capital

HC is a measure of human health and education quality based on the total levels of skills, training, education and health within a population which combines data on educational attainment, learning, and functional health status[9,10]. It counts the expected years lived in an age group from 20–64, adjusted for functional health, educational attainment, and learning/education quality and has a theoretical maximum of 45[9]. We used HC as a measure of human health and development.

Ecological footprint

EF is a measure of the demand that populations place on the biosphere each year[11,12]. EF is comprised of six environmental demand types which make up the total score, including: built-up land, cropland, grazing land, fishing grounds, forest land, and carbon uptake land (land required to sequester anthropogenic CO_2 emissions)[12]. It is expressed in units of world-average bioproductive area, global hectares, which allows for the addition of values from each demand type into a single score[11]. The total EF is given as an annual measure of global hectares per capita for each country. We investigated the association between EF for each country and HALE and HC.

Carbon dioxide emissions

CO_2 emissions are used as a proxy measure for greenhouse gas emissions (GHGs) as CO_2 makes up the majority of GHGs emitted worldwide[13]. CO_2 emissions are presented as territorial emissions of production[13]. Production emissions are generated from the domestic production of goods and services, regardless of whether they are consumed domestically or exported[14]. This reflects the emissions for which countries set domestic and international targets and often report as their emissions, for example under the Paris Agreement[13]. We investigated the association of CO_2 production emissions in tonnes per capita (http://www.globalcarbonatlas.org/en/CO_2-emissions) with HALE and HC. In addition, consumption-based CO_2 emissions were used to perform a sensitivity analysis[13]. Consumption-based emissions highlight whether emissions reductions are achieved by "offshoring" production to other countries by considering emissions from traded goods and services[13].

Additional candidate data sources

Gini coefficient (https://data.worldbank.org/indicator/si.pov.gini) and population density (https://data.worldbank.org/indicator/EN.POP.DNST) were included to account for potential confounding. Gini coefficient is a measure of economic inequality which ranges from 0 to 100, 0 being perfect equality and 100 representing perfect inequality[15]. Country income level, using gross national income (GNI) (https://data.worldbank.org/indicator/NY.GNP.PCAP.PP.CD) and World Bank cut-offs were used for interaction testing and stratified analyses. Additionally, GDP (https://data.worldbank.org/indicator/NY.GDP.PCAP.CD) and healthcare expenditure data (https://data.worldbank.org/indicator/SH.XPD.CHEX.PC.CD) (both measured in USD per capita) were included, to perform sensitivity analyses.

These variables were selected because they were open source, available for a long time period, and were expected to confound the association between resource use and health in some way. Gini coefficient was included as we suspected that countries with less income inequality would have better HALE and HC outcomes than otherwise similar counterparts. Population density was included as countries with higher population density may have better access to healthcare and lower transport emissions and possibly better overall socio-ecological performance[16]. EF and CO_2 emissions provide per capita estimates so adjusting for total population was not necessary. Additionally, our main analysis did not adjust for country income. We argue per capita income could be on the causal pathway, instead of being a potential confounder, and may even have a bi-directional affect. For example, resource use (such as manufacturing) increases GDP/GNI (which in turn may affect health), while increased income is also likely to increase domestic resource use.

Gini coefficient was completely missing for 11·6% of country-years. Mean imputation was used for Gini coefficient when some country-year data was incomplete from 1991-2016, then complete-case analysis was performed. Two outlier data points, the Rwandan genocide (1994) and the earthquake/tsunami in Haiti (2010) were excluded. Prior to analysis, EF, CO_2 production emissions, population density, total production and consumption-based CO_2 emissions (hereafter total CO_2 emissions), GDP, and healthcare expenditure were log transformed. Since EF includes CO_2 production emissions, the latter were used separately, and to analyse the effect of combined production and consumption CO_2 emissions.

Analyses

We produced scatter plots of HALE and log transformed EF. Cut-off values were added to identify countries achieving high HALE at low EF. EF cut-offs used were the maximum EF, as calculated by the National Footprint Accounts, which reflects sustainable resource use for that year (1991=2·1 gHa/capita, 2016=1·7 gHa/capita), based on the Earth's regenerative capacity and the growing population[12]. The HALE threshold represented countries in the top 25% HALE for each year (1991=63·5 years, 2016=67·6 years)[7,8]. Lastly, change in HALE versus change in EF from 1991 to 2016 was plotted for each country, as a progress indicator, to identify countries which improved human health while reducing environmental resource use. Plots were prepared for all countries, countries achieving sustainable EF (or within +0·5 of sustainable EF) in either 1991 or 2016, G20 countries, and countries identified by the sustainability analysis.

Having multiple years of data for each country allowed us to study associations at the within-country level. Within-group mean centring was performed to produce "centred variables" which were used to investigate the observed within-country effects[17]. To explore the associations between outcomes and EF and CO_2 production emissions, accounting for potential confounders, mixed-effects multiple linear regression was used. Mixed-effects linear regression using country-level random intercepts and the centred variables were used to account for between-cluster (i.e. country) variation and provide estimates of the within-country associations[17]. A general estimation equation for these models is: $Y(it) = a + bX(it) + u(i) + e(it)$.

Where *Y* is the outcome, *X* is a matrix of covariates, *u(i)* is a country-specific random effect and *e(it)* is the residual in country *i* at time *t*. Crude centred models were compared to models with both candidate factors, assessing confounding and standard errors. There was evidence of confounding, but no substantial changes to standard errors were observed. Thus, the fully adjusted centred models were used for the analyses.

Although per capita income was not adjusted for, we reasoned that a country's ability to exploit its natural resources (and subsequent effects on health) could vary with income level. Thus, we considered the possible interaction effects of income on resource use and health[18]. Likelihood-ratio tests using adjusted models, country income level, and an interaction term between exposures and income level were performed. Interaction models were fit using income categorised by the World Bank classification of income level (low, middle, or high-income) using annual GNI data (https://data.worldbank.org/indicator/NY.GNP.PCAP.PP.CD).

Four sensitivity analyses were performed. Firstly, CO_2 emissions of consumption were combined (i.e. added/subtracted based on import/export of emissions) with production-based emissions to perform the same analysis using total CO_2 emissions as the exposure. To test the robustness of using country groupings based on World Bank income categories, a stratified analysis using annual GNI quintiles was performed. To test the associations with an additional potential confounder, an analysis including healthcare expenditure (USD per capita), for the years that data was available (2000–2016), was performed. Lastly, to investigate the confounding effects country-income may have had on the observed associations, models were adjusted for GDP and interaction tests performed.

All analyses were performed using Stata version 17. An open-source alternative software, R can be obtained at https://www.r-project.org/.

Results

Descriptive statistics

The study dataset included 6,097 country-year observations for the years 1991-2016. Table 1 presents country-level summary statistics. In 1991, HALE ranged from 39·1 in Ethiopia to 69·8 in Japan with a mean of 57·8 (Table 1). The highest EF in a single year was 17·7 in Luxembourg in 2003. In 1991, total CO_2 emissions were lower than CO_2 production emissions for Qatar, likely due to its exports of oil and gas (Table 1). Economic inequality remained roughly constant with the lowest Gini coefficient recorded in Slovenia in 2008 with a score of 23·7.

Sustainability analysis

In 1991 and 2016 only one country from each year achieved high HALE at sustainable EF levels, Jamaica (1991) and Sri Lanka (2016) (Figure 1B and 1D). In 1991 seven countries: Dominican Republic, Albania, Ecuador, Dominica, Cuba, Panama, and Costa Rica came very close to achieving high HALE and sustainable EF (Figure 1B). Mexico was the G20 member country closest to achieving high HALE at a sustainable EF in 1991 (Figure 1B). Of the countries that achieved, or came close to achieving, sustainable EF and high HALE, Albania, Cuba, Ecuador, and Jamaica were highlighted in both years (Figure 1B and 1D).

Progress indicator

From 1991 to 2016, almost every country's HALE improved but this was accompanied by increases in EF for most countries. United Arab Emirates had the largest decrease (albeit from a very high level) in EF (Figure 2A). Uruguay, Cuba, and Panama saw noticeable increases in HALE while decreasing their EF, with Uruguay achieving a substantial decrease in EF (-2·9 gHa/capita) (Figure 2C). Ten of the G20 countries saw a decrease in EF over the study period, with nine of them also achieving increased HALE (except South Africa) (Figure 2D). Uruguay saw the largest decrease in EF amongst the high-performing countries, while also achieving a 2·8-year increase in HALE (Figure 2E).

Mixed-effects regression and stratified analysis

Crude models showed strong evidence of a positive association between EF and both HALE and HC (Table 2). After adjustment for Gini coefficient and population density, each model displayed strong evidence of an association, albeit of reduced magnitude (Table 2).

There was good evidence that all of the associations examined varied with income level (Table 3). For all associations a similar pattern was observed. In low and middle-income countries improved health outcomes tended to be associated with increased resource use, while in high-income countries increasing resource use did not appear to be associated with improved health and may even lead to poorer health outcomes.

Sensitivity analyses

Using total CO_2 emissions, stratified analysis showed the same association of improved health outcomes for low and middle-income countries. In high-income countries, each 10% increase in total CO_2 emissions saw decreases in HALE and HC of -0·17 (95%CI -0·22,-0·12) and -0·09 (95%CI -0·13,-0·05) respectively (Table A2[19]). When using GNI quintiles, the same trend was observed for both EF and CO_2 emissions (Table A3[19]). When healthcare expenditure was included, each of the four models showed strong evidence of a negative association between increasing EF/CO_2 and HALE/HC in high-income countries (Table A4[19]). Lastly, adjustment for GDP reduced the effect size and strength of observed associations in each of the included models (Table A5[19]). However, during stratified analysis of the GDP models, three of the four models displayed strong evidence of the same associations described above (Tables A6 & A7[19]).

Discussion

This study highlights countries achieving high levels of health at low resource use and also explores associations between environmental resource use and human health and development.

Table 1. Descriptive statistics for study variables in 1991 and 2016.

Summary statistic	Year	Countries observed	Mean	Median	Standard deviation	Minimum	Maximum
Healthy life expectancy (years)	1991	194	57·8	60·7	7·9	39·1 (Eritrea)	69·8 (Japan)
	2016	194	62·9	64·3	6·2	44·6 (Central African Republic)	74·1 (Singapore)
Human capital (years)	1991	195	9·9	8·7	6·7	0·4 (Mali)	25·0 (Finland)
	2016	195	13·6	13·7	6·9	1·6 (Niger)	28·4 (Finland)
Ecological footprint (gHa/capita)	1991	157	3·0	1·9	2·5	0·5 (Bangladesh)	13·9 (United Arab Emirates)
	2016	188	3·2	2·6	2·3	0·5 (Timor-Leste)	14·4 (Qatar)
CO_2 production emissions (tonnes/capita)	1991	157	4·6	2·2	6·0	0·005 (Cameroon)	36·2 (Qatar)
	2016	160	4·5	2·7	5·6	0·05 (Somalia)	38·5 (Qatar)
Total CO_2 emissions (tonnes/capita)	1991	95	5·8	3·3	6·8	0·07 (Rwanda)	32·9 (Qatar)
	2016	98	5·9	4·4	6·2	0·09 (Rwanda)	39·3 (Luxembourg)
Gini coefficient	1991	164	39·6	38·2	8·5	25·3 (Slovenia)	61·7 (South Africa)
	2016	164	39·0	38·3	8·1	25·0 (Ukraine)	61·7 (South Africa)
Population density (people/km²)	1991	212	338·6	65·5	1,660·0	0·2 (Greenland)	17,681·3 (Macao SAR, China)
	2016	214	444·7	94·1	2,021·9	0·1 (Greenland)	20,159·1 (Macao SAR, China)
GNI (USD/capita)*	1991	158	6·1	1·5	9·2	0·1 (Vietnam)	50·0 (Liechtenstein)
	2016	193	13·9	5·1	20·2	0·3 (Burundi)	157·0 (Liechtenstein)
Healthcare expenditure (USD/capita)	2000~	184	442·9	95.0	768·5	4·3 (Myanmar)	4,564·5 (United States)
	2016	185	1,030·1	327·5	1,685·3	20·6 (Democratic Republic of Congo)	9,877·9 (United States)
GDP (USD/capita)	1991	178	6,482.4	1,616.8	10,757.2	138.5 (Vietnam)	83,738.3 (Monaco)
	2016	204	15,783.5	5,701.9	24,019.7	282.15 (Burundi)	169,904.2 (Monaco)

**GNI values are given in thousands*

~Healthcare expenditure data was only available starting in the year 2000

CO_2 = carbon dioxide, GNI = gross national income, GDP = gross national product

Vogel *et al.* argue that currently no country meets all human needs at sustainable resource levels, but propose it is possible[16]. Additionally, Millward-Hopkins *et al.* highlight that drastic changes are required to avoid ecological breakdown, but also model levels of sufficiency for human living that are more materially generous than many might think necessary[20]. This study builds on these ideas, identifying countries achieving good health at sustainable (or close to sustainable) levels of resource use for further research. We also present more detailed analyses of the associations that were evidenced by some of the prior research. For example, the association between increased EF and improved life expectancy and evidence that the environmental efficiency with which wellbeing is produced increases at low and moderate levels of economic development, but declines at high levels[21–23]. For the first time, we used data covering 26 years to perform analyses of the associations of EF and CO_2 production emissions with human health and development metrics, HALE and HC, stratified by income level. Our results appear consistent with the prior research[23].

Although over 40% of countries reduced their EF between 1991 and 2016, many had very high EF in 1991. Countries like the UK, US, Japan, and UAE achieved improvements in HALE while noticeably decreasing EF, but EF remained substantially above sustainable levels at the end of the study period. There were, however, some examples of countries with much lower baseline EFs achieving improvements in HALE

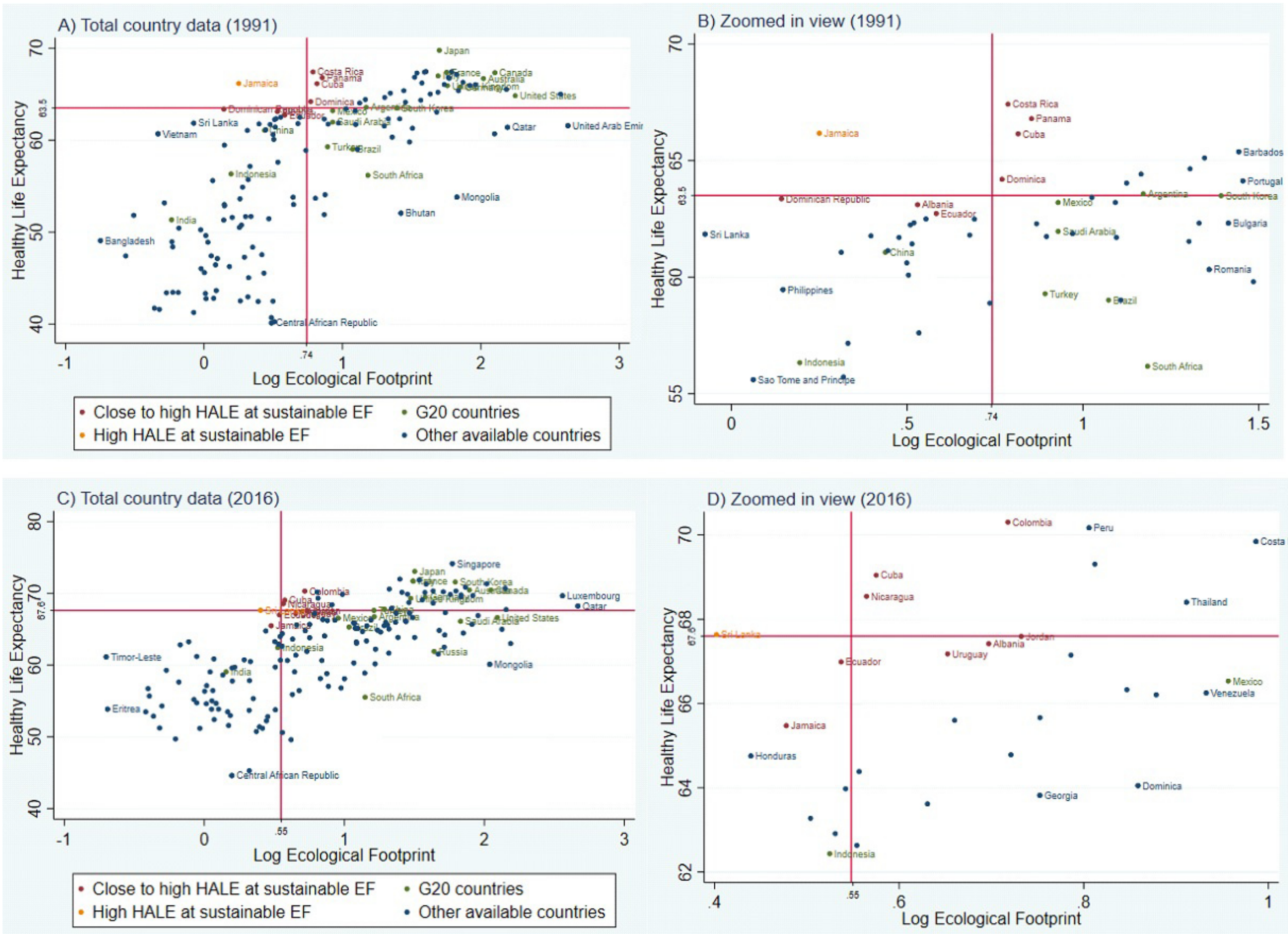

Figure 1. Sustainability analysis, plotting healthy life expectancy (HALE) (years) versus log transformed ecological footprint (EF). A) Plot for all countries with complete HALE and EF data in 1991. **B**) Plot zooms in on a reduced region of the plot highlighting countries which come close to and achieve high HALE at sustainable EF levels in 1991. **C**) Plot for all countries with complete HALE and EF data in 2016. **D**) Plot zooms in on a reduced region of the plot highlighting countries which come close and achieve high HALE at sustainable EF levels in 2016.

while still decreasing EF, such as Cuba, Panama, and Uruguay. These countries and countries which achieved high HALE at sustainable/almost sustainable levels tend to be geographically small, with warmer climates (majority in Central/South America), have relatively small populations, and be middle or low-income with the exception of Panama and Uruguay (in 2016). Furthermore, these countries have implemented various laws and policies to protect the environment while supporting social development. Albania introduced eight new environmental protection laws over the course of the study period and incorporated sustainable development into their constitution[24]. Cuba scaled up its biopesticides industry and promoted urban farming such that 60% of vegetables and fruit consumed in Havana are supplied by local urban farmers[25]. More radical changes have included the elimination of the military in Panama (1994). Lastly, Uruguay's improvements in HALE and marked reduction in EF may be explained by their commitment to social programmes, while heavily investing in clean energy in 2011–2012[26]. From 2011 Uruguay's EF fell from 4·0 to 1·9 gHa/capita and at the end of the study period over half of electricity in the country came from renewable sources[26]. Our findings support evidence presented by Millward-Hopkins *et al*. as these countries have implemented societal and technological changes prior to reaching levels of consumption similar to high-income counterparts; allowing them to lead healthy lives at close to sustainable levels[20].

We also undertook exploratory association analyses of resource use and human health to further develop the understanding around these associations and generate hypotheses. The evidence of a negative association for EF/CO_2 production emissions with HALE (and CO_2 production emissions with HC), at the high-income level, builds on Knight and Rosa's findings, supporting the idea that human health, and not just efficiency of wellbeing, is adversely affected by continued resource exploitation[23]. These findings, although exploratory,

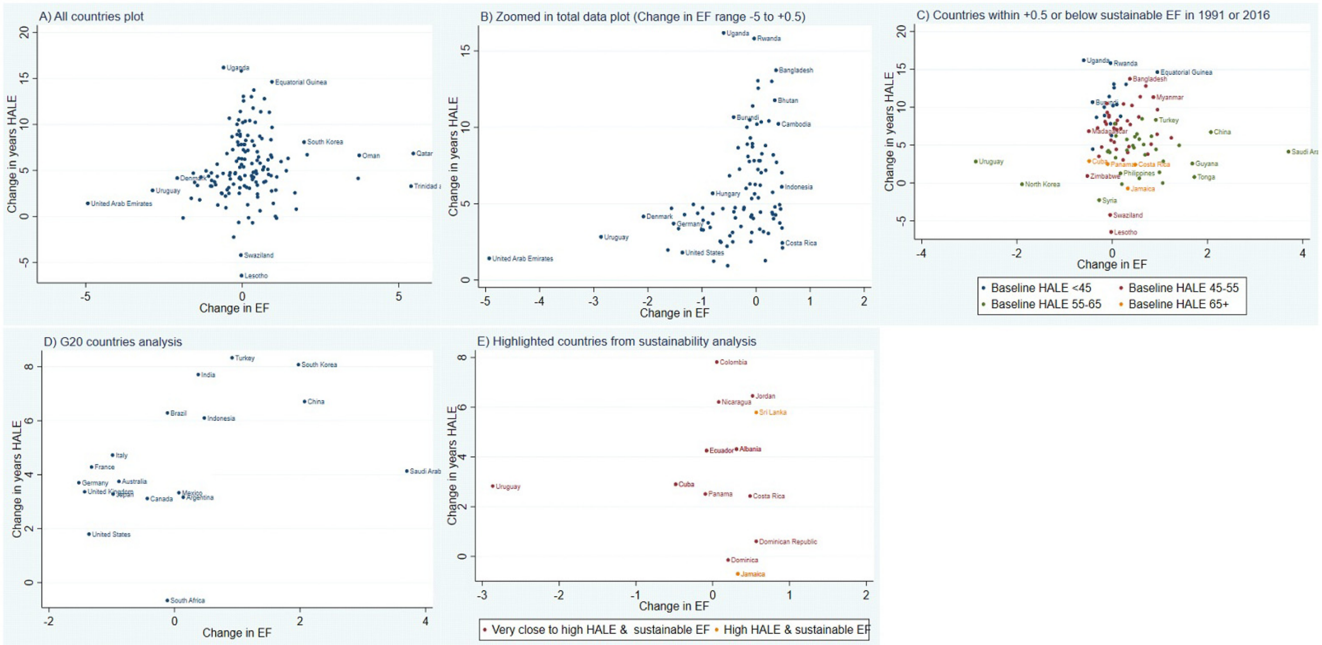

Figure 2. Progress indicator, plotting a country's change in healthy life expectancy (HALE) (in years) versus change in ecological footprint (EF) over the course of the study period, ranging from 1991 to 2016. A) Plot for all countries with available HALE and EF for the study period. **B**) Plot zooms in on a reduced region of the plot mostly highlighting countries with increased HALE or decreased EF over the study period. **C**) Plot for countries that started or finished the study below, or within +0·5 of an EF that is considered sustainable for either year (1991=2·1 gHa/capita or 2016=1·7 gHa/capita) with highlighted baseline HALE. **D**) Plot for performance of the G20 countries. **E**) Plot for countries highlighted by sustainability analysis (see Figure 1) as having high HALE at sustainable (or very close to sustainable) EF.

Table 2. Crude and adjusted association analysis of outcomes and Ecological Footprint and CO_2 production emissions

Models	Assessed outcomes					
	Healthy life expectancy^			Human capital^		
	Observations (groups)	Change in HALE per 10% increase EF/CO_2 (95% CI)*	Standard Error	Observations (groups)	Change in HC per 10% increase EF/CO_2 (95% CI)*	Standard Error
Crude EF model	3,725 (149)	0·37 (0·32,0·43)	0·03	3,751 (150)	0·29 (0·26,0·31)	0·01
Adjusted EF modelᵠ	3,725 (149)	0·20 (0·16,0·24)	0·02	3,751 (150)	0·21 (0·19,0·23)	0·01
Crude CO_2 production emissions model	3,438 (133)	0·40 (0·37,0·42)	0·01	3,463 (134)	0·21 (0·20,0·23)	0·01
Adjusted CO_2 production emissions modelᵠ	3,438 (133)	0·13 (0·11,0·16)	0·01	3,463 (134)	0·09 (0·08,0·10)	0·01

**Results presented as change in outcome per 10% change in EF/CO_2 to account for log transformation of data*

^Within-country effects assessed using within-group mean centring, centring mean values around country name and using centred variables for each model

ᵠAdjusted for Gini coefficient, and population density

EF = ecological footprint, CO_2 = carbon dioxide, HALE = healthy life expectancy, HC = human capital

could be indicative of a "development threshold" where, once this threshold has been crossed, there are negative rather than positive effects of continued excessive resource use on population health and development. This concept of a development threshold is strengthened by the strong evidence of positive associations, for EF and CO_2 production emissions with HALE and HC, in low and middle-income countries. Low-income countries need continued input of natural

Table 3. Stratified association analysis of HALE/HC and Ecological Footprint/CO_2 production emissions.

Models	Income level^	Observations (groups)	Change in outcome per 10% increase in exposure (95% CI)	p-value for interaction*
Adjusted HALE and EF model^ψ	All income levels	3,725 (149)	0·20 (0·16,0·24)	0·016
	Low-income	1,004 (63)	0·20 (0·10,0·30)	
	Middle-income	1,823 (105)	0·15 (0·10,0·20)	
	High-income	759 (42)	-0·07 (-0·14,-0·01)	
Adjusted HC and EF modelψ	All income levels	3,751 (150)	0·21 (0·19,0·23)	<0·001
	Low-income	1,004 (63)	0·16 (0·13,0·18)	
	Middle-income	1,847 (106)	0·20 (0·17,0·23)	
	High-income	759 (42)	-0·05 (-0·10,0·003)	
Adjusted HALE and CO_2 production emissions modelψ	All income levels	3,438 (133)	0·13 (0·11,0·16)	<0·001
	Low-income	850 (53)	0·13 (0·08, 0·17)	
	Middle-income	1,749 (95)	0·16 (0·13,0·19)	
	High-income	691 (39)	-0·24 (-0·29,-0·18)	
Adjusted HC and CO_2 production emissions modelψ	All income levels	3,463 (134)	0·09 (0·08,0·10)	<0·001
	Low-income	850 (53)	0·07 (0·06,0·08)	
	Middle-income	1,773 (96)	0·13 (0·11,0·15)	
	High-income	691 (39)	-0·16 (-0·20,-0·11)	

ψAdjusted for Gini coefficient and population density

**p-value presented for the LRT of interaction applied to adjusted models with the country income category variable*

^Income level classification using World Bank GNI cut-offs for each year of study

EF = ecological footprint, CO_2 = carbon dioxide, HALE = healthy life expectancy, HC = human capital

resources and consumption of their (and others') natural capital to reach this threshold, at least with current technologies. Additionally, each sensitivity analysis performed supported the findings in our stratified analysis. However, it must be noted that identifying the role of country income (i.e. GDP) within these associations remains a challenge. In our main analyses we reasoned that per capita income could be on the causal pathway for these associations and thus did not adjust for it. Even so, it was reassuring that after adjustment for GDP there was still strong evidence of the previously observed associations in three of the four models.

The design of this study offered a quick and cost-effective way to generate hypotheses and provide recommendations for future research. We limited our selection of potential confounders to produce a globally representative dataset, covering a substantial time period, allowing us to highlight high-performing countries and explore associations between resource use and human health. Furthermore, we aimed to address as far as possible the main limitation of studies of this nature, the ecological fallacy; when conclusions at the group level are incorrectly applied to individual members of the group. The use of country-level data over multiple years, and within-group mean centring, allowed us to investigate within-country associations in the data. Additionally, we performed four sensitivity analyses to assess the robustness of our findings.

Several limitations should be acknowledged. First, the observed associations may be influenced by important differences in data availability, including for potentially important confounders, between countries. There may be systematic differences in the recording of outcomes, exposures, and variable data, which could result in differential measurement error, particularly when comparing high and low-income countries. Furthermore, Gini coefficient data may have suffered information bias due to considerable missing data. However, most countries' Gini coefficient did not vary considerably throughout the study, thus, mean imputation was used. In an effort to limit selection/information bias introduced in our dataset we selected robust outcomes and exposures, available for a long time period, while limiting the selection of potential confounders to those that were scientifically meaningful and had little missing data. During the adjusted analyses, the observed associations changed indicating the presence of confounding. Due to the limited number of factors included, the results presented will undoubtedly contain residual confounding and our analyses should be considered exploratory in nature. We aimed to achieve balance between including the largest number of countries for the longest time period and adjusting for multiple confounding factors. We also aimed to address potential confounding using the healthcare expenditure and GDP sensitivity analyses. Thus, as time passes and monitoring improves, future research should aim to include data on other important factors such as universal access to healthcare, Water Footprint, and other GHGs such as methane. Finally, with the methods used in this study temporality of exposure and outcome cannot be determined. The causal pathways linking EF/CO_2 emissions and HALE/HC, particularly regarding the indeterminate role of GDP (i.e. effect modifier vs. confounder), are complex and detailed analysis is beyond the scope of this paper. However, despite limitations, these findings suggest the presence of important associations between environmental resource use and human health and development outcomes, while indicating variables that require continued monitoring to inform more comprehensive development metrics.

In summary, the analyses highlight high-performing countries that could serve as examples of sustainable development moving forward. Our results provide some evidence of an association between increased EF and CO_2 emissions and reduced health and development measures in high-income countries, while providing some evidence that low and middle-income countries benefit from increasing resource use up to a certain point. This result is supported by existing efficiency of wellbeing research and implies high-income countries, which are historically the highest consumers of resources, should strengthen commitments to reducing their EF and CO_2 emissions and that this would not negatively affect the prospects of improving health and human capital[23]. They should also be held to stricter resource use standards than their lower income country counterparts. The highlighted case-study countries could serve as good examples of how to achieve good health sustainably in low and middle-income countries. Our findings raise important questions for high-income countries about how they can limit GHG emissions and resource use by moving away from unlimited economic growth, towards economies that focus on the achievement of wellbeing and improved population health outcomes. In conclusion, future work should build on these association analyses, aiming to elucidate causal relationships between resource use and human health to help inform more comprehensive metrics of planetary health. Much can be learnt from country case studies linking specific policies and public health interventions with changes in resource use and human health and development in space and time.

Data availability

Underlying data

figshare: Achieving good health with low environmental footprint - A comparison of national indicators dataset. https://doi.org/10.6084/m9.figshare.21547854.v1[27]

This project contains open-source data from 1991-2016 from the following sources:

Healthy Life Expectancy (HALE) - https://ghdx.healthdata.org/record/ihme-data/gbd-2017-dalys-and-hale-1990-2017

Human Capital (HC) - https://ghdx.healthdata.org/record/ihme-data/global-human-capital-estimates-1990-2016

Ecological Footprint (EF) - https://www.footprintnetwork.org/licenses/public-data-package-free/ To download the ecological footprint data, use the hyperlink above, scroll down the page, and fill out the free public data request form. A download link will then be sent to you via the email to the address you provide.

Carbon dioxide emissions - https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions

Gini coefficient - https://data.worldbank.org/indicator/si.pov.gini

Population density - https://data.worldbank.org/indicator/EN.POP.DNST

Gross national income (GNI) - https://data.worldbank.org/indicator/NY.GNP.PCAP.PP.CD

Gross domestic product (GDP) - https://data.worldbank.org/indicator/NY.GDP.PCAP.CD

Healthcare expenditure - https://data.worldbank.org/indicator/SH.XPD.CHEX.PC.CD

Extended data

figshare: Achieving good health with a low environmental footprint - A comparison of national indicators extended data. https://doi.org/10.6084/m9.figshare.21547869.v1[19]

Authors' contributions:

CM – literature search, data collection and analysis, data interpretation, tables and figures, writing manuscript.

AH, KB, and SC – contributed to conceptualisation and design, contributed to drafting and approval of final draft

Ethics committee approval

No ethics approval was required for this study as it was a secondary data analysis using publicly available data.

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