



Footprint efficiency for human development: An international analysis

Jorge Gutiérrez-Goiria^{a,b,*} , Iker Etxano^{a,b} , Andrés-Fernando Herrera^a,
José Domingo García-Merino^c 

^a Hegoa Institute for International Cooperation and Development Studies, University of the Basque Country (UPV/EHU), Av. Lehendakari Agirre 81, 48015, Bilbao, Spain

^b Department of Applied Economics, University of the Basque Country (UPV/EHU), Av. Lehendakari Agirre 83, 48015, Bilbao, Spain

^c Department of Financial Economics II, University of the Basque Country (UPV/EHU), Av. Lehendakari Agirre 83, 48015, Bilbao, Spain

ARTICLE INFO

Keywords:

Human development
Data envelopment analysis
Footprint
Environmental efficiency
Sustainability

ABSTRACT

The aim of this study is to evaluate the efficiency of natural resource use by countries in their fostering of human development, taking into consideration the biophysical requirements (resource consumption and emissions) of development processes and the improvement in well-being. The *Footprint Efficiency for Human Development* (FEHD) is calculated using data envelopment analysis, which evaluates the efficiency of inputs (material footprint, total primary energy footprint, ecological footprint) in generating outputs (Human Development Index, CO₂ emissions) across 120 countries. Contrary to initial expectations, the results indicate that, in general, countries with higher FEHD tend to have lower human development levels, and *vice versa*. These countries with low human development also tend to exceed fewer sustainability thresholds, resulting in better overall environmental performance compared to those with high human development. The analysis makes it possible to contrast different groups of countries according to their FEHD, thereby enabling the exploration of policy orientations for a just and sustainable transition.

1. Introduction

The human development framework and its main measure, the Human Development Index (HDI), have been firmly established since the United Nations Development Program (UNDP) began publishing the *Human Development Report* in 1990. Its emergence represented a paradigm shift in development studies, redefining development beyond income-based measures. Human development essentially entails enhancing people's well-being by expanding their capabilities; broadening their life choices to be and do what they value. From this perspective, the focus shifts from what a person has (closely tied to income) to what they can be or do (more closely tied to the notion of freedom; [1]).

However, the human development framework is not without criticism. One of the main concerns is that ecological and sustainability issues are not adequately addressed, either conceptually or empirically (see [2]). In response to this critique, the UNDP itself has progressively incorporated the need to achieve sustainable human development into

its discourse by considering both strong sustainability [3] and the environmental constraints of the Anthropocene [4].

At the core of this challenge lies the material basis of human development. Expanding people's capabilities, which is promoted by human development, invariably requires the use of material and energy resources extracted from natural systems. These resources are transformed within economic systems to generate goods and services that sustain people's capabilities, and these systems generate emissions and waste that must be absorbed by ecosystems. Social metabolism becomes problematic when its scale exceeds the regenerative and absorptive capacities of ecosystems.

Empirical analysis of human development in ecological and sustainability terms has been facilitated by theoretical and empirical advances in environmental footprint accounting. This includes the ecological footprint [5], material footprint [6], energy footprint [7], water footprint [8], and the carbon footprint [9], among others. These indicators form what is known as the 'footprint family' [10,11], which captures the flows of materials, energy, and other resources consumed or

* Corresponding author at: Hegoa Institute for International Cooperation and Development Studies, University of the Basque Country (UPV/EHU), Av. Lehendakari Agirre 81, 48015, Bilbao, Spain.

E-mail addresses: jorge.gutierrez@ehu.eus (J. Gutiérrez-Goiria), iker.etxano@ehu.eus (I. Etxano), andresfernando_herrera001@ehu.eus (A.-F. Herrera), josedomingo.garcia@ehu.eus (J.D. García-Merino).

<https://doi.org/10.1016/j.wds.2026.100307>

Received 23 July 2025; Received in revised form 1 April 2026; Accepted 21 April 2026

Available online 22 April 2026

2772-655X/© 2026 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

used to generate human well-being. Environmental footprints account for the hidden flows embedded in traded goods and services, allocating resource use to the country where consumption occurs. As such, they serve as valuable indicators of (un)sustainability, both at the national level and on a global scale [12].

Parallel to these developments, a growing body of empirical research has sought to integrate environmental dimensions into the measurement of human development. Some studies have proposed adjustments to the HDI grounded on ecological footprint [13], while others have relied on measures such as CO₂ emissions and material footprint, leading to the so-called Sustainable Development Index (SDI; [2]). Following the development of this last index, the UNDP introduced the Planetary pressures-adjusted Human Development Index (PHDI; [4]), and in the same vein, other authors have proposed the Planetary Boundaries-adjusted HDI [14]. Additional approaches combine HDI data at the country level with various indicators related to natural resource use, including energy use [15,16], material resource use [17,18], the combination of material footprints and CO₂ emissions [19], or ecological footprint [20,21]. In fact, the Global Footprint Network, the leading institution for ecological footprint calculations worldwide, defines sustainable development for countries as the intersection of high human development and low ecological footprint, highlighting the need to reconcile well-being with planetary limits [5].

Building on this accounting framework, recent research has identified ecological limits based on planetary boundaries and the biocapacity to sustain material, energy, and other flows. These limits help establish *safe and just spaces* within which people can achieve reasonable levels of well-being [22–28]. Research linking human development with these footprints reveals significant disparities among countries. High-income countries exhibit high levels of human development but are also associated with high material and energy consumption and carbon emissions, exceeding safe and just ecological limits. In contrast, low- and middle-income countries generally have lower levels of human development coupled with lower consumption [15,16,29–31]. In this vein, Chen et al. [32] note that low-income countries tend to manage their available resources more efficiently than most advanced countries in generating human development. This disparity exposes the urgent need for a just and sustainable transition, enabling low-income countries to advance in human development while requiring high-income countries to reduce their consumption to stay within environmental limits.

Understanding efficient use of materials, energy, and other resources is required to achieve sustainability. Equally important, however, is the ability to achieve meaningful levels of human well-being through the use of these resources. Therefore, while pursuing resource-use efficiency is an essential step towards greater sustainability and well-being, it is not sufficient on its own [12,32]. Environmental efficiency involves reducing environmental footprints relative to the level of well-being achieved. The key issue therefore lies in translating environmental efficiency into human development. This challenge has not been sufficiently explored theoretically or empirically (see [33,34]), which raises the following research questions: How efficient are countries in converting their environmental footprints into human development? Do the most efficient countries respect ecological limits? How do the different components of human development explain efficiency?

Our analysis seeks to address this research gap by, first, deepening our understanding of the human development–sustainability nexus and, second, exploring its policy implications for a just and sustainable transition that supports human well-being. The aim of this study is therefore to analyse the efficiency of resource use in terms of environmental footprints for human development, for which an efficiency measure across countries is proposed (*Footprint Efficiency for Human Development*, FEHD). Specifically, the study aims to evaluate the environmental efficiency of countries in generating human development, taking into account the biophysical requirements (resource consumption and emissions) of development processes and improvements in well-being. This approach seeks to maintain an appropriate level of human

development while minimising the resources required to achieve it.

The methodology combines data envelopment analysis (DEA) with a subsequent multivariate analysis, an approach widely used in efficiency studies on sustainability-related issues [35]. DEA has been employed for a broad range of topics, including those related to human development. In this regard, Mariano et al. [36] distinguish between approaches aimed at revising human development measurement: one constructing composite indices, and another that uses DEA to measure efficiency in generating quality of life or achieving social goals. Our study aligns with the latter approach.

Although DEA has been used to analyse the efficiency of human development processes [36] and to address sustainability more broadly [35], to our knowledge no study has specifically examined the efficiency of both material- and energy-resource use together in driving human development at the country level. This paper therefore makes a novel contribution due to the specificity of the DEA application. The multivariate analysis, in turn, helps determine the significance of the different components of human development influencing this efficiency.

The remainder of the paper is structured as follows. Section 2 outlines the methodological aspects and specifies the data sources. Section 3 presents the hypotheses to be tested, and Section 4 the results of the analysis, which are discussed in Section 5. Finally, the conclusions are presented in Section 6.

2. Methods and data

2.1. Data envelopment analysis

DEA, a technique developed by Charnes et al. [37] in the economic-financial field, enables the performance of similar or homogeneous entities to be evaluated. It constructs a theoretical frontier enabling the assessment of the efficiency of decision-making units (DMUs) in transforming inputs to generate outputs [38,39]. The method uses the values achieved by the units (countries, in our case) in terms of their outputs and inputs to calculate their efficiency in converting inputs into outputs. The resulting efficiency scores are placed on a scale from 0 to 100, indicating the relative efficiency of units (higher values represent higher efficiency). It is important to note that the results reflect relative rather than absolute efficiency, as they are contextualised within the framework of the cases analysed.

DEA has been widely applied in the field of human development, particularly concerning the HDI [36]. For instance, a number of trailblazing studies have estimated the relative efficiency of countries in converting income or financial resources into human development [40, 41]. Along similar lines, more recent studies have incorporated various factors into this conversion to human development, such as economic complexity [42], financial constraints [39], or conversely, the level of human development as a determinant of financial inclusion [43]. In some cases, DEA has even been used to adjust and propose new indices based on the HDI [44].

Zhou et al. [35] find that DEA applications in sustainability are mainly focused on environmental sustainability. Research related to environmental sustainability linked to human development has followed two main directions. Some studies have focussed on creating composite indices that integrate environmental variables [45], while others have included environmental dimensions as part of the social analysis of human development (see [36]). However, applications that address the conversion of material and energy inputs as indicators of the social metabolism in human development are scarce. Amowine et al. [33] use ecological footprint as an input in a dynamic DEA model combined with the meta-frontier technique, with CO₂ emissions as an undesirable output. The use of CO₂ emissions as output is, in fact, commonplace in DEA regional sustainability assessment applications [35].

To incorporate an undesirable input, Seiford and Zhu [46] propose two main approaches: treating it as an input or applying a monotonically

decreasing transformation. In the present study, the inverse of emissions (1/CO₂ emissions) has been included, following a common and well-established practice in the DEA literature [47]. In addition, the incorporation of CO₂ emissions as an input has been tested, as well as their incorporation as an output using another decreasing transformation (obtained in each case by subtracting each country's emissions from the maximum in the sample). The results show virtually equal efficiencies, demonstrating the robustness of this approach.

Although slacks-based measure (SBM) models have recently been shown to be an alternative for working with undesirable outputs [48], they are not without problems in terms of their interpretation and inferential capacity [49,50]. In our case, we computed the SBM model as a robustness check and found that the outcomes showed a high degree of similarity with those obtained from the proposed DEA model. Therefore, we opted to use the traditional DEA model, which has been widely adopted in the empirical literature.

Although there are other methodologies for analysing efficiency, DEA is particularly suitable when multiple inputs and outputs are considered. It does not require aggregation or pre-established weights, nor does it rely on pre-established functional forms or assumptions about a priori conditions. In situations where the relationship between the outputs and the inputs necessary to obtain them is not clear, DEA, as a nonparametric technique that does not require strong distributional assumptions, offers an advantage over traditional parametric methods [51].

Our study aims to advance the field by analysing the efficiency of countries in transforming material and energy resources into human development. We adopted an input orientation approach which implies that, for a given level of output (primarily human development), efficiency increases to the extent that there is less consumption of inputs. The analysis employs a constant returns to scale (CRS) model which measures overall technical efficiency without decomposing it into pure technical efficiency and scale efficiency (given that this issue is less relevant in our study, as the variables are measured in per capita terms or as an index). The CRS model allows for greater differentiation between study units [52,53]. This greater capacity for discrimination, compared to variable returns to scale (VRS) models, is also important for the subsequent regression analysis, as it increases the variability of the dependent variable. Input-oriented CRS DEA models are commonly used in studies measuring environmental efficiency between countries and regions [54,55].

The selected inputs (material footprint, total primary energy footprint, ecological footprint) and outputs (HDI and inverse of CO₂ emissions, where higher emissions mean lower output) are shown in Table 1. Table 2 details the variables and their sources.

On this basis, the mathematical formulation of the model is as follows:

$$\theta^*_i = \text{Min } \theta_i$$

subject to:

$$\sum_{i=1}^{120} \lambda_i X_{ji} \leq \theta X_{j0}$$

$$\sum_{i=1}^{120} \lambda_i Y_{ri} \geq Y_{r0}$$

Table 1
DEA model.

Inputs	Outputs
Material footprint	HDI
Total primary energy footprint	Inverse of CO ₂ emissions (1/CO ₂ emissions)
Ecological footprint	

Source: compiled by the authors.

Table 2
Variables used in the DEA model.

Variable	Description	Year of reference	Source
Material footprint	This is the attribution of global material extraction to the internal final demand of a country. It is estimated as the national extraction of materials (biomass, fossil fuels, metallic minerals, and non-metallic minerals) plus the raw material equivalents of imports, minus the raw material equivalents of exports. The material footprint indicates the average use of materials for final demand. The material footprint is measured in tons (t) per capita and takes non-negative values.	2015	UNEP, International Resource Panel: https://www.resourcepanel.org/global-material-flows-database
Total primary energy footprint	This accounts for the energy consumed globally to satisfy the internal final demand (private and public consumption, and investment) of a country, thus including both the direct energy consumption of households and the global energy requirements to produce the goods and services demanded by users; adding the energy requirements of imports and subtracting those of exports [16] The energy footprint is measured in megawatt-hours (MWh) per capita and takes non-negative values.	2015	Villamor et al. [56]
Ecological footprint	This is an indicator that measures the consumption of a country's population in terms of the hectares of land needed to provide resources and absorb waste. In other words, it transforms the consumption and waste generated by a country's consumption into global hectares of land area, a unit that allows for international comparisons. The ecological footprint is measured in global hectares (hag) per capita and takes non-negative values.	2015	Global Footprint Network: https://www.footprintnetwork.org/
Human Development Index (HDI)	This is a synthetic index that combines indicators of health, education, and income, taking values between 0 and 1. The health	2015	Data Centre, UNDP: https://hdr.undp.org/data-center/human-development-index#/indicies/HDI

(continued on next page)

Table 2 (continued)

Variable	Description	Year of reference	Source
	index is constructed based on life expectancy at birth; the education index is based on years of schooling of adults and expected years of schooling for children; and the income index is based on per capita income in PPP dollars (purchasing power parity). Countries with an HDI close to 1 are those with the highest human development, while those with an HDI closer to 0 are those with the lowest human development. This measure was developed by the UNDP, which has published it annually since 1990, and is a well-established and widely validated development indicator.		
CO ₂ emissions	These are carbon dioxide emissions, measured in tons per capita, generated by human activity through the use of coal, oil, and gas for combustion and industrial processes, gas flaring, and cement production. The values represent territorial emissions, meaning they are attributed to the country where they occur. This variable takes non-negative values.	2015	Global Carbon Project. Sourced Data Centre, UNDP: https://hdr.undp.org/data-center/human-development-indicators/HDI

Source: compiled by the authors.

$$\lambda_j \geq 0$$

$j = 1, \dots, 3$ number of inputs

$r = 1, 2$ number of outputs

$i = 1, \dots, 120$ number of countries

θ^*_i denotes the efficiency score of the DMU_{*i*}

λ_i are the intensity weights associated with DMU_{*i*}

x_{ji} denotes the values of the *j*-th input utilised by the DMU_{*i*}

y_{ri} denotes the value of the *r*-th output obtained from the DMU_{*i*}.

Countries with solution $\theta^* = 100$ are considered relatively efficient or benchmark countries and determine θ as the efficient frontier. In contrast, countries with < 100 are considered inefficient.

The database is made up of 120 countries, those with data for all the variables considered in the calculation of FEHD. The analysis was carried out for 2015, which is the most recent year with available information for all the variables (see key statistics of the variables in the Appendix, Table A1 and Table A2).

Efficiency Measurement System (EMS) software was used; it employs a scale ranging from 0 to 100 and is commonly used in DEA studies [51]. The further a country is from the frontier (which is determined by the group of DMUs that achieve maximum efficiency), the less efficient it is, and the value approaches zero. The procedure generates a measure of

relative efficiency, but not absolute efficiency. In our case, it identifies the most efficient countries in the sample.

2.2. Multivariate analysis

Next, a multivariate analysis was completed. The aim was to explain efficiency based on human development levels by breaking down its components. The dependent variable was the efficiency score obtained in the DEA. However, due to the potential problems generated by this type of variable, we used a bootstrapping procedure (in this case with 1000 replicates) to estimate a truncated regression, as recommended by Simar and Wilson [57].

Thus, the equation to explain efficiency is as follows:

$$FEHD = \beta_0 + \beta_1 \text{Life_expectancy_index} + \beta_2 \text{Education_index} + \beta_3 \text{GNI_index} + \epsilon$$

where the variables are:

Footprint Efficiency for Human Development (FEHD): Dependent variable calculated with the DEA model.

Life expectancy index: As an indicator of health (a long and healthy life), calculated for each country following the UNDP formula:

$$\text{Life expectancy index}_i = (\text{Life expectancy}_i - 20) / (85 - 20)$$

Education index: calculated using the UNDP formula for each country:

$$\text{Education index}_i = (\text{expected years of schooling}_i / 18 + \text{average years of schooling}_i / 15) / 2$$

In cases where the expected years of schooling are >18 , then this value is taken as the limit.

Gross national income (GNI) index: calculated using the UNDP formula for each country:

$$\text{GNI index}_i = (\text{Ln (GNI per capita 2015)} - \text{Ln (100)}) / (\text{Ln (75.000)} - \text{Ln (100)})$$

3. Hypotheses

FEHD is defined here as the capacity to generate human development while minimising biophysical requirements and environmental pressures captured by footprints. In capability-based terms, higher human development tends to coincide with improvements in education and health, institutional quality, infrastructure, and innovation capacity. These conditions can raise the efficiency with which societies convert energy and materials into the goods, services, and public provisions that underpin well-being. As a result, the marginal resource requirements of improvements in life chances may fall as human development rises, implying a positive association between development and FEHD.

In addition, the widely known Environmental Kuznets Curve (EKC)-type mechanism [58] provides a further rationale for expecting higher FEHD at higher development levels: once certain development thresholds are reached, technological upgrading, regulatory capacity, and structural change can reduce environmental pressures relative to socio-economic outcomes. Since income is one component of the HDI, and education and health are enabling factors for innovation and effective governance, the three HDI dimensions may each contribute to

greater FEHD.

Existing DEA evidence provides a mixed picture on the independent effect of environmental stressors on well-being once income is controlled [34,59] and documents systematic cross-country differences in well-being generation efficiency (e.g. African countries are considered inefficient in generating well-being; [33]). Related DEA studies also identify non-linear patterns between development and environmental efficiency consistent with EKC reasoning [60,61]. Building on this theoretical logic and prior evidence, we tested the following hypotheses.

Hypothesis 1: FEHD is higher in countries with higher levels of human development.

Sub-hypothesis 1.1: FEHD increases with improvements in the education component of human development.

Sub-hypothesis 1.2: FEHD increases with improvements in the health component of human development.

Sub-hypothesis 1.3: FEHD increases with improvements in the income component of human development.

Hypothesis 2: FEHD is higher in countries that exceed sustainability thresholds.

4. Results

4.1. Analysis of FEHD by country

The DEA model calculated the efficiency level (FEHD) for the 120 countries in the sample, with values in the range of 0–100. Fig. 1 shows the country map of these efficiency values, according to a colour scale. The lowest recorded FEHD value is 9.46 (red), while the highest is 100 (green). Broadly speaking, the highest FEHD values are observed in countries in Africa and Asia, while the lowest are found in countries in

North America, Europe, and Oceania.

Table 3 shows the efficiency measures for the 20 countries with the best performance and the 20 countries with the worst performance in FEHD. Along with the efficiency calculated according to the model, the relative rank of the countries in the sample based on their HDI is shown, with a ranking from 1 (Switzerland, HDI: 0.954) to 120 (Niger, HDI: 0.376).

Table 3 shows that, among the most efficient countries, those with lower HDI tend to predominate, although there are also some cases (Sri Lanka, Republic of Moldova) with intermediate HDI values. Among the least efficient countries, those with high HDI tend to dominate, although there are cases such as Mongolia or Kuwait, which are further from the top places in the HDI ranking.

Fig. 2 illustrates this decreasing relationship, which is quite marked ($R^2 = 0.70$) but not without some exceptions. Among these are two high-HDI countries (between 0.7 and 0.8), already mentioned (Sri Lanka and the Republic of Moldova), with high efficiencies (72.10 and 100, respectively), along with some medium-HDI countries with notable efficiencies (Philippines, Tajikistan, Bangladesh). Very high-HDI countries (above 0.8) have low efficiency values (an average of 24.95, with a maximum of 44.95, which is far from the 100 that could be achieved).

Figs. 3–5 show the relationship between FEHD and the components of the HDI; that is, between FEHD and the health index (Fig. 3), FEHD and the education index (Fig. 4), and FEHD and the income index (Fig. 5).

Fig. 3 shows an inverse relationship between the level achieved in the health index and FEHD, although some values are distant from linearity (R^2 of 0.51). The country with the lowest health index (and therefore the lowest life expectancy) is Nigeria, with a value of 0.490 and a FEHD of 63.49. In contrast, countries with the highest life expectancy (Japan, Malta, Switzerland, Australia) have low FEHD values

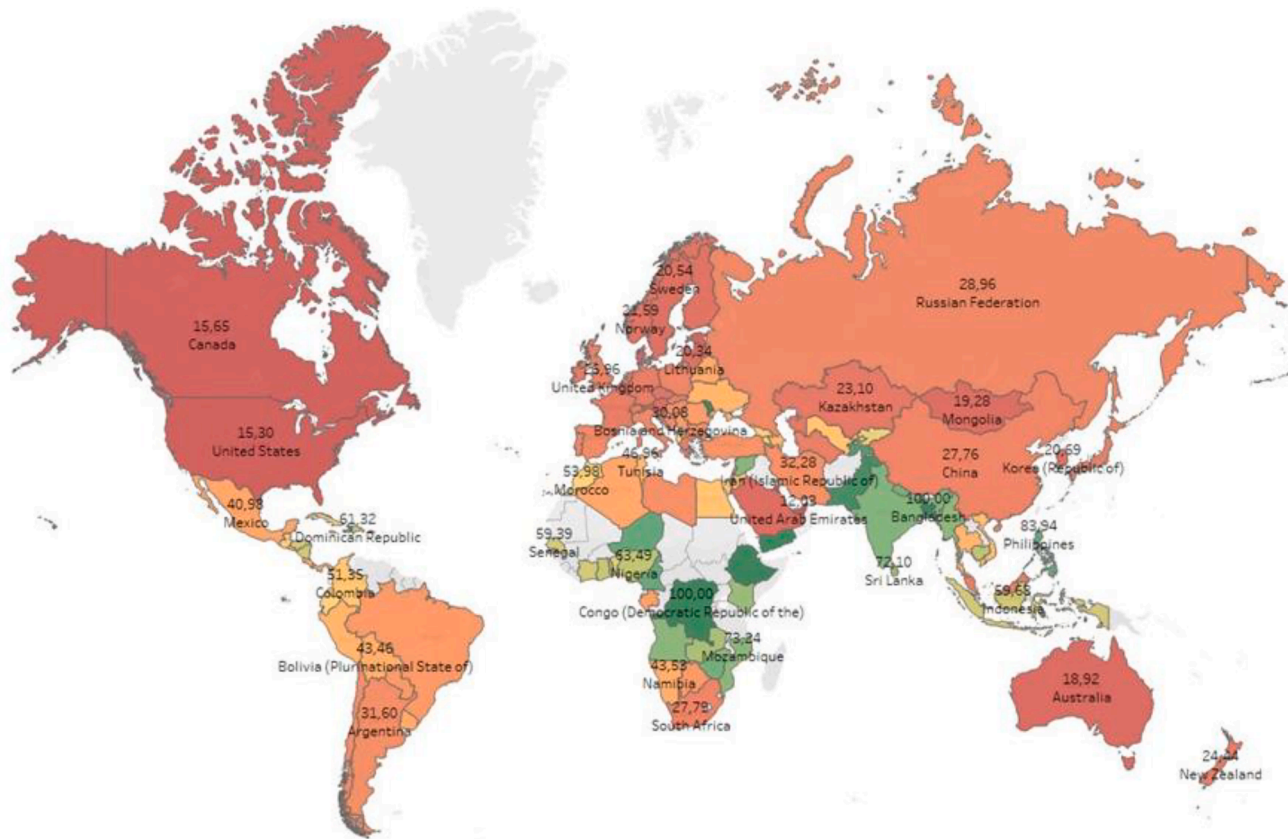


Fig. 1. Map of Footprint Efficiency for Human Development by country. Source: compiled by the authors

Table 3
Ranking of countries according to their FEHD and HDI.

Most efficient countries	Ranking IDH (2015)	FEHD	Least efficient countries	Ranking IDH (2015)	FEHD
Haiti	111	100.00	Norway	2	21.59
Bangladesh	99	100.00	Czechia	22	21.29
Congo (Democratic Republic of the)	117	100.00	Finland	9	21.26
Ethiopia	118	100.00	Israel	18	20.91
Moldova (Republic of)	67	100.00	Korea (Republic of)	19	20.69
Yemen	116	99.92	Sweden	4	20.54
Pakistan	109	95.15	Lithuania	31	20.34
Tajikistan	91	89.95	Austria	17	20.26
Philippines	85	83.94	Mongolia	75	19.28
Niger	120	83.55	Saudi Arabia	32	19.19
Cameroon	107	81.87	Australia	6	18.92
Nepal	102	78.28	Belgium	12	18.89
Zimbabwe	101	78.26	Latvia	34	18.79
India	95	75.52	Denmark	5	17.64
Syrian Arab Republic	108	74.16	Estonia	25	16.34
Angola	100	73.69	Canada	10	15.65
Mozambique	119	73.24	United States	14	15.30
Myanmar	104	72.71	Kuwait	40	13.00
Sri Lanka	61	72.10	United Arab Emirates	30	12.03
Togo	113	70.80	Luxembourg	16	9.46

Source: compiled by the authors.

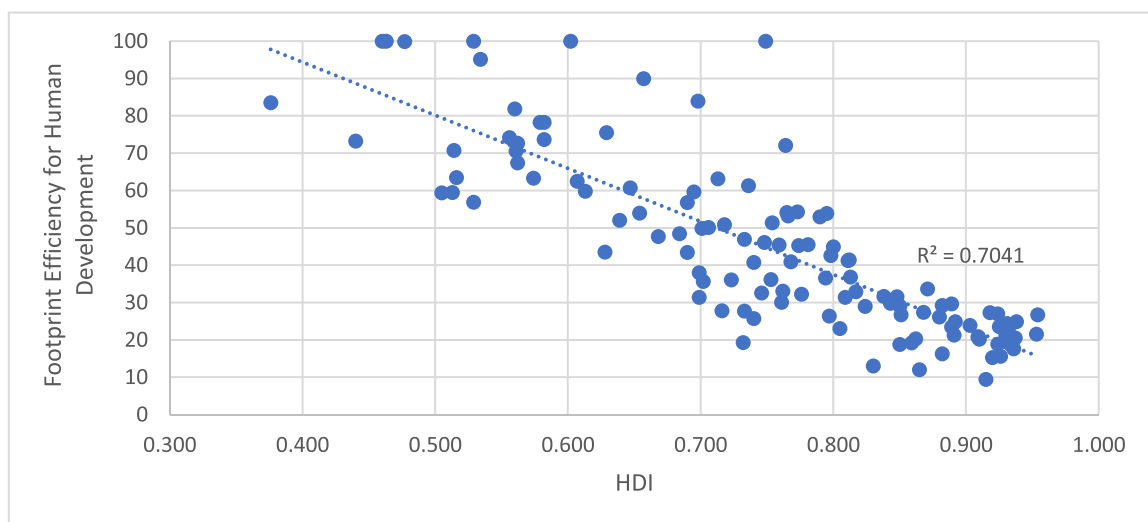


Fig. 2. Footprint Efficiency for Human Development versus HDI.
Source: compiled by the authors

(between 18.92 and 27.35). However, as we see in the case of education, there are some cases of relatively high values on both axes (for example, Bangladesh and the Republic of Moldova, which are among the most efficient, have health indexes above 0.750).

Fig. 4 also shows an inverse relationship between the level achieved in the education index and FEHD, in this case with a better fit (R^2 of 0.60). Again, values distant from linearity can be observed. Among them, we find outliers that suggest the possibility of reconciling relatively high values on both axes (for example, the Republic of Moldova achieves the maximum FEHD value in the sample, with an education index of 0.783).

Fig. 5 reflects that FEHD decreases as income increases or, conversely, FEHD increases as income decreases. Of the relationships between FEHD and human development, or its components, the one with income is the most pronounced, with an R^2 of 0.76. If we consider the classification of countries in the sample by income groups from the World Bank, we find that FEHD moves from 23.17 for the high-income group to 80.04 for the low-income group. As in previous figures, we find cases like the Republic of Moldova, with relatively high income (0.709) and maximum efficiency.

Finally, when studying efficiency by geographic regions, South Asia, followed by Sub-Saharan Africa and Latin America and the Caribbean are the regions with the highest FEHD, while Europe and Central Asia and North America are the areas with the lowest FEHD (Fig. 6). While South Asia has an average FEHD of 84.12, North America has an average of 15.48.

4.2. Footprint efficiency for human development and sustainability thresholds

Beyond FEHD, it is important to assess whether countries fall within thresholds that can be considered sustainable. This analysis is rooted in the concept of *ecological limits*, and it has been explored in various studies, such as on the formulation of planetary boundaries for a good life [23], the establishment of energy limits for meeting human needs [28], and the need to set limits according to the principle of sufficiency [2].

This analysis of *sustainability thresholds* for human development allows us to connect the FEHD levels of countries with their (un)sustainable status. Specifically, this section connects environmental efficiency,

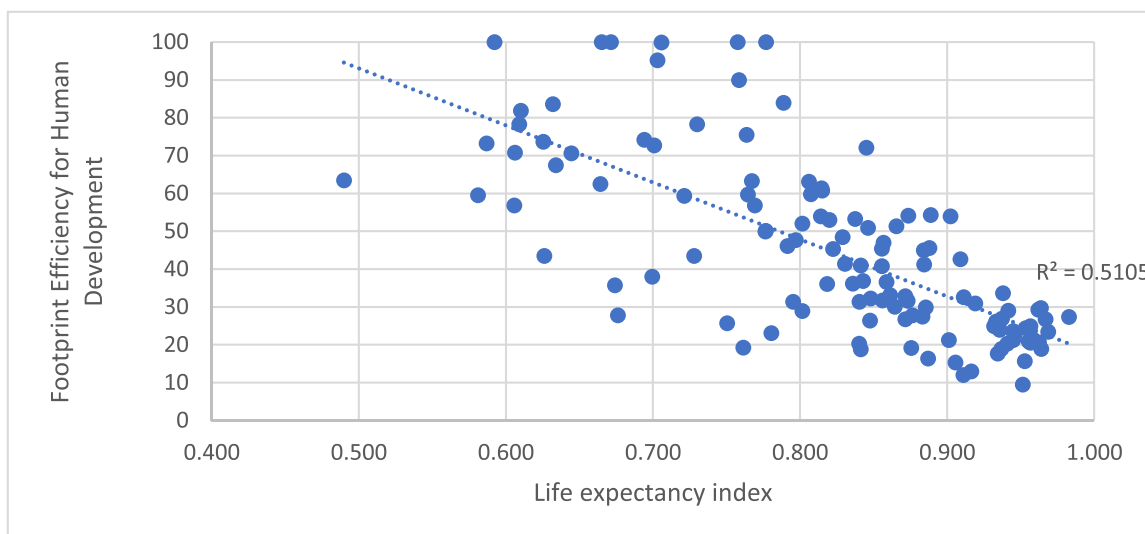


Fig. 3. Footprint Efficiency for Human Development versus Life expectancy index. Source: compiled by the authors

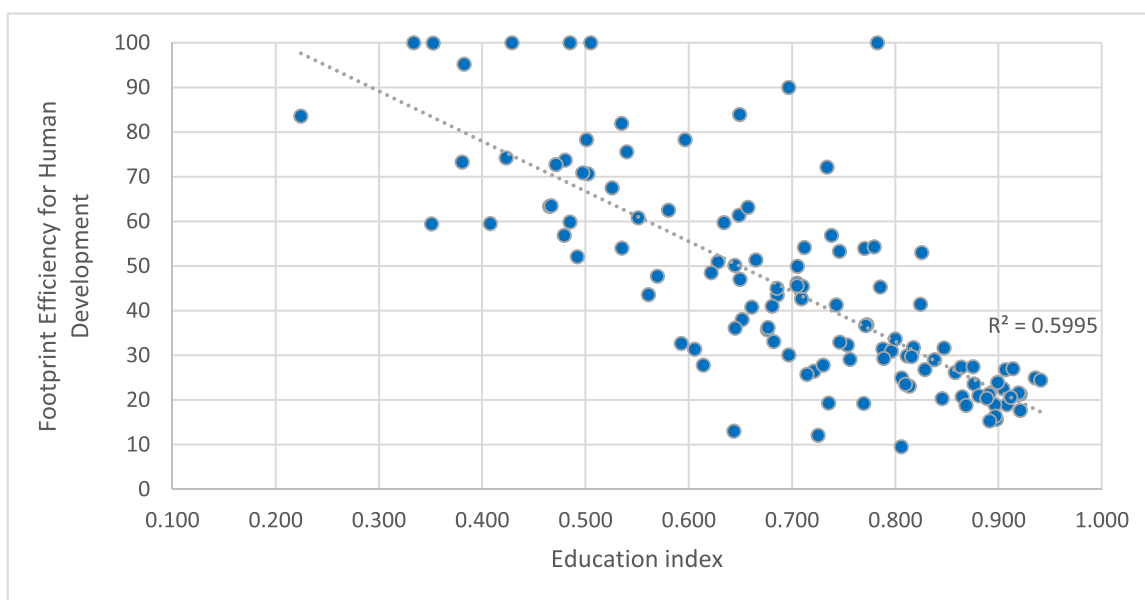


Fig. 4. Footprint Efficiency for Human Development versus Education index. Source: compiled by the authors

HDI, and resource consumption level, examining whether countries exceed sustainability thresholds in terms of their environmental footprints (ecological footprint, total energy primary footprint, material footprint) and CO₂ emissions. To support the analysis, Table 4 shows the sustainability threshold values commonly considered in the literature. The values are presented in per capita measures, in line with the variables used for the FEHD calculation.

Based on these values, the 120 countries in the sample are classified according to whether they exceed one or more sustainability thresholds. As shown in Table 5, 60 % of the countries (72) exceed all thresholds, making them unsustainable according to any of these measures. At the other extreme, 27 countries (22.5 % of the sample) do not exceed any threshold. The remaining 21 countries (17.5 %) fall between these two extremes, exceeding one, two, or three thresholds.

Table 5 shows a clear pattern in which countries that exceed fewer sustainability thresholds achieve higher FEHD levels and vice versa. Thus, the average FEHD value goes from 77.66 in countries that exceed

no thresholds to 29.43 in those that exceed all thresholds. In terms of HDI, countries with a lower HDI tend to exceed fewer thresholds, while the HDI value increases as more thresholds are exceeded. This trend is also observed in the three indexes (health, education, income) that make up the HDI.

Analysis of the thresholds shows that higher FEHD is observed in countries that respect sustainability thresholds but have insufficient human development levels (Table 6). The average HDI value of countries that do not exceed any sustainability thresholds is 0.565, and nearly half of these countries are in Africa. In this group, only two countries exceed an HDI of 0.7 (considered high): Republic of Moldova (0.749) and Sri Lanka (0.764). In contrast, countries with high human development are mostly in the group that exceeds all thresholds but shows lower efficiency.

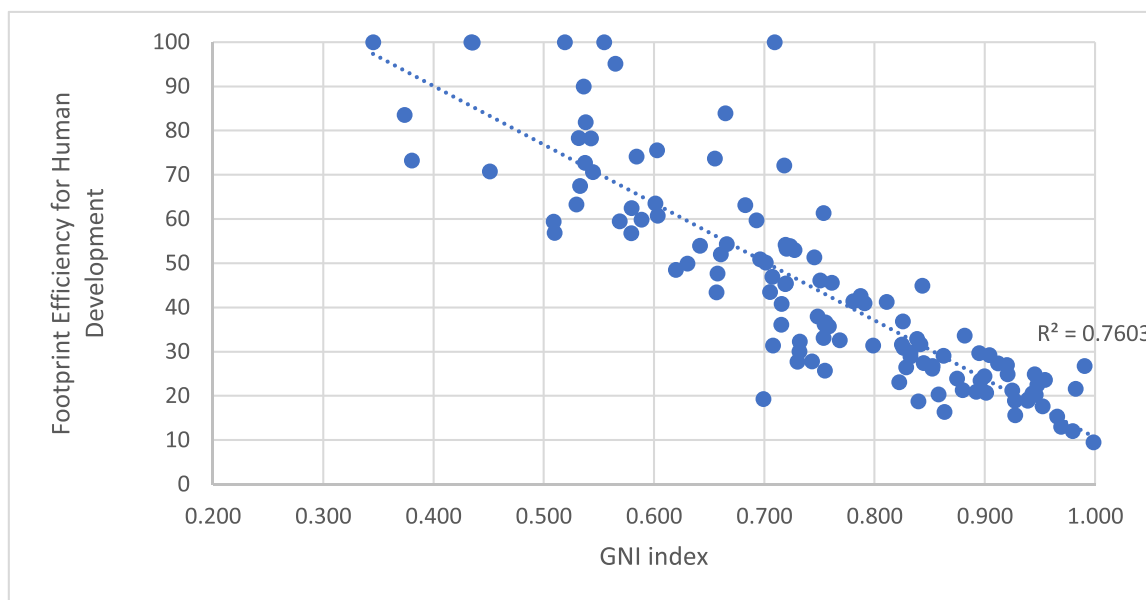


Fig. 5. Footprint Efficiency for Human Development versus GNI index. Source: compiled by the authors

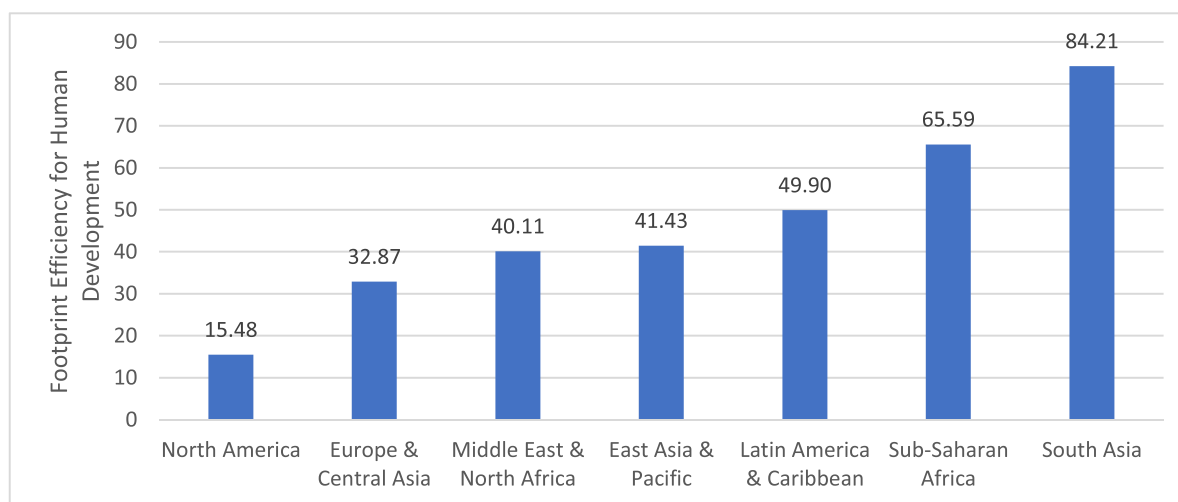


Fig. 6. Footprint Efficiency for Human Development by Geographical Regions. Source: compiled by the authors

Table 4 Sustainability thresholds.

Indicator	Value of sustainability threshold	Year of reference	Source
Ecological footprint	1.6 hag p/c	2015	[5]
Total primary energy footprint	10.8 MWh p/c	2015	[15]
Material footprint	6.8 t p/c	2015	[62]
CO ₂ emissions	1.74 t p/c	2015	[63]

Source: compiled by the authors from the sources cited.

4.3. Determinants of FEHD: a multivariate analysis

The analysis conducted so far clearly indicates the difficulty of reconciling high human development with efficient use of natural resources. The fact that all very high and high human development countries (except two) exceed one or more thresholds highlights the

importance of resource consumption levels and the need to enhance their efficiency in the pursuit of human development. This makes it necessary to examine the factors that determine FEHD. To this end, a multivariate analysis was used. The results are shown in Table 7.

The model, which captures the combined effects of the variables, once again highlights the difficulties of reconciling efficiency in the use of natural resources with human development. Starting with a good fit (pseudo-R² = 0.758), income is shown as the key component explaining FEHD, being the only one with statistical significance.

The income index in the sample ranges from 0.345 (Democratic Republic of the Congo) to 0.998 (Luxembourg), and the model estimates that an increase of 0.1 points in the income index (a variable whose values range from 0 to 1) leads to a decrease of 13.66 points in FEHD (a variable whose values range from 0 to 100).

The education variable shows a negative β, while the health variable has a positive β. In any case, these variables do not attain significance, so it cannot be concluded that advances in these areas lead to losses in FEHD.

Table 5
Number of countries and variables on average according to the thresholds exceeded.

Number of thresholds exceeded	Number of countries	FEHD (0–100)	HDI	Life expectancy index	Education index	GNI index
0	27	77.66	0.565	0.684	0.495	0.542
1	5	68.34	0.603	0.730	0.516	0.594
2	6	51.11	0.720	0.814	0.671	0.689
3	10	48.45	0.720	0.801	0.675	0.694
4	72	29.43	0.837	0.883	0.792	0.841

Source: compiled by the authors.

Table 6
Countries that do not exceed any threshold.

	FEHD (0–100)	HDI	Life expectancy index	Education index	GNI index
Angola	73.69	0.582	0.625	0.480	0.655
Bangladesh	100.00	0.602	0.777	0.505	0.555
Benin	56.86	0.529	0.606	0.480	0.510
Cambodia	63.32	0.574	0.767	0.465	0.530
Cameroon	81.87	0.560	0.610	0.535	0.538
Congo (Democratic Republic of the)	100.00	0.463	0.592	0.485	0.345
Côte d'Ivoire	59.49	0.513	0.581	0.408	0.569
Ethiopia	100.00	0.460	0.672	0.334	0.434
Haiti	100.00	0.529	0.665	0.429	0.519
Honduras	59.84	0.613	0.807	0.485	0.589
India	75.52	0.629	0.764	0.540	0.603
Kenya	70.59	0.561	0.644	0.502	0.544
Moldova (Republic of)	100.00	0.749	0.758	0.783	0.709
Mozambique	73.24	0.440	0.587	0.381	0.380
Myanmar	72.71	0.562	0.701	0.471	0.537
Nepal	78.28	0.579	0.730	0.501	0.532
Nicaragua	60.76	0.647	0.815	0.551	0.603
Nigeria	63.49	0.516	0.490	0.467	0.601
Pakistan	95.15	0.534	0.703	0.383	0.565
Senegal	59.39	0.505	0.721	0.351	0.509
Sri Lanka	72.10	0.764	0.845	0.734	0.718
Syrian Arab Republic	74.16	0.556	0.694	0.423	0.584
Tajikistan	89.95	0.657	0.759	0.697	0.536
Togo	70.80	0.514	0.606	0.497	0.451
Yemen	99.92	0.477	0.706	0.353	0.435
Zambia	67.46	0.562	0.634	0.526	0.533
Zimbabwe	78.26	0.582	0.609	0.597	0.543
Average	77.66	0.565	0.684	0.495	0.542

Source: compiled by the authors.

Table 7
Estimation results from bootstrap truncated regressions for FEHD.

Variable	B (st.dv.)	Sig.	Percentile 95% Conf. Interval
Constant	129.330 (73.700)	<0.0001	114.885 143.775
Life expectancy index	20.799 (15.519)	0.180	−9.617 51.216
Education index	−15.068 (12.403)	0.218	−39.058 8.923
GNI index	−124.311 (14.640)	<0.0001	−153.005 −95.617
Sigma	9.639		

Source: compiled by the authors.

5. Discussion and policy insights

The DEA analysis reveals that the countries least efficient in converting the use of natural resources into human development are those with the highest human development. And *vice versa*, the most efficient countries in this regard are those with the lowest human development. This efficiency performance is mainly determined by income level. In addition, the least efficient countries in this conversion are also the least

sustainable, as they exceed a higher number of sustainability thresholds, while the most efficient countries are typically the most sustainable.

For example, the United States ranks as the fourth least efficient country among the 120 countries analysed, with an FEHD of 15.30, despite its very high human development status, reflected in an HDI of 0.920 (ranked fourteenth). It exhibits a material footprint of 28.33 t per capita (ranked twenty-first), a total primary energy footprint of 91.20 MWh per capita (ranked fifth), an ecological footprint of 7.96 global hectares per capita (ranked fourth) and CO₂ emissions of 16.74 tons per capita (ranked fifth). Countries with an efficiency profile similar to that of the United States are Canada, Denmark, Australia, Saudi Arabia, the Republic of Korea, Israel, Czechia, and Norway. In contrast, Pakistan is the seventh most efficient country of the sample with an FEHD of 95.15, yet it is ranked as a low human development country, with an HDI of 0.534 (twelfth lowest) and exhibits a material footprint of 3.09 tons per capita (ninth lowest), a total primary energy footprint of 5.38 MWh per capita (eighteenth lowest), an ecological footprint of 0.74 global hectares per capita (third lowest) and CO₂ emissions of 0.85 tons per capita (twenty-first lowest). Countries such as the Democratic Republic of Congo, Bangladesh, Ethiopia, Tajikistan, Cameroon, Nepal, Mozambique, India, and Myanmar show performance levels more comparable to Pakistan.

Taken together, the results suggest that in low human development countries, increases in resource consumption generate substantial improvements in human development levels, but beyond a certain point, at higher levels of human development, increases in resource consumption generate little or no improvement in human development levels. In other words, a country with low human development has a higher FEHD, being able to convert the use of resources into improved well-being; it is also within *sustainable* limits. In contrast, countries with a high human development find it more difficult to convert resources into human development and therefore have a lower FEHD and exceed sustainability thresholds.

The results are consistent with the plateau or saturation hypothesis [64,65]. This hypothesis indicates that at low levels of human development, small increases in energy use and carbon emissions lead to large changes in human development, but once a high level of human development is reached, higher energy use and carbon emissions no longer lead to significant changes in human development levels.

There are a number of studies that refer to environmental efficiency in the context of human development [2,13,66,67], although they typically adopt methodological approaches different from ours. These studies have generally considered indicators such as ecological or material footprint in relation to the HDI in a new proposed index that serves as a proxy for environmental efficiency. In contrast, our study treats environmental footprints as inputs in the DEA. Nonetheless, despite the methodological differences, some of their conclusions align closely with ours.

Our results are consistent with those obtained by Zhang et al. [13], although their study (of 82 countries) covers a smaller sample. Among the 20 most efficient countries identified in both studies, 10 overlap (Haiti, Bangladesh, the Democratic Republic of Congo, Pakistan, Philippines, Nepal, India, Angola, Mozambique, and Sri Lanka), and among the 20 least efficient, 7 countries are common to both studies (Czechia, the Republic of Korea, Saudi Arabia, Australia, Belgium,

Canada, and the United States). Hickel [2], although less precisely, reaches similar conclusions in that the countries with the highest income and HDI are generally the worst performers in terms of environmental efficiency, and *vice versa*. Chen et al. [32] also show that low-income countries are more efficient at generating human development from their resources.

These results highlight the importance of fair global environmental governance. They reflect a persistent divide between the global North and South and suggest a need to address the sustainability challenge through coordinated international efforts. The ongoing challenge is the existence of a global unequal ecological exchange, that is, low-income countries serve as net exporters of embodied natural resources (materials, energy, land) to high-income countries [68]. This means that the environmental footprints of high-income countries are larger due to their higher level of consumption, which is partly based on imports from low-income countries. This unequal distribution of environmental burdens calls into question the common but differentiated responsibilities principle. Addressing it effectively will require greater coordination at the international level involving diverse institutions and stakeholders, while recognising differentiated responsibilities: high-income countries must take the lead in reducing their resource consumption.

Global environmental sustainability is primarily challenged by the scale of total natural resources and material consumption [12,62,69,70] rather than the efficiency of natural resource use and the impacts generated. As such, the viability of the hegemonic development model relies more on the absolute decoupling of natural resources and impacts and less on relative decoupling [71].

Relative decoupling is a form of environmental efficiency promoting a more rational and efficient use of natural resources. However, this should be accompanied by a lower use of natural resources in absolute terms, given ecological limits. A just transition still demands significant progress, particularly in terms of equity and justice issues, with the responsibility falling mainly on high-HDI countries. For example, the net fossil energy exporting countries with higher HDI show a significant trend of recoupling between material footprint and HDI, and medium-HDI countries show a significant trend of coupling in CO₂ and material footprint for HDI variation [19]. With regard to climate policy, high-HDI countries must limit their emissions to ensure that the global temperature increase does not exceed 2 °C, while countries with low-HDI should be allowed to maintain their level of emissions to support their development needs [72].

As our analysis has shown, the most environmentally efficient countries are also the most sustainable, as they remain below sustainability thresholds. However, some low-HDI countries (*i.e.* Afghanistan, Burundi, Kenya, Niger, Rwanda, Togo, Uganda and Zimbabwe) are in an ‘ecological poverty trap’ [73]. This describes a situation where growing populations and decreasing biocapacity lead to resource constraints, meaning that limited resource availability in these countries could hinder progress and well-being. In our results, three of these countries (Kenya, Togo, and Zimbabwe) do not exceed any sustainability threshold, and three others are among those with the highest FEHD (Togo, 70.80; Zimbabwe, 78.26; Niger, 83.55).

In these African countries, therefore, an ambivalent situation exists. On the one hand, they are countries whose availability of resources conditions their progress. On the other, they can be considered *sustainable* countries that also perform well in terms of environmental efficiency, which clashes with the conclusions reached in other studies using DEA [33,34]. Our analysis similarly finds that several South Asian countries deviate from findings on them reported in another DEA-based study [60], and the same applies to studies focusing on urbanisation in China [61], thereby challenging the validity of the EKC in these contexts. Thus, beyond resource-use efficiency, in these countries ‘resource security’ becomes important for poverty eradication and progress [74]. Demography dynamics also play a key role, since both population and population density condition resource consumption and resource availability, which is a determining factor not only for ‘ecological

balance’ at the country level [75] but also for environmental efficiency [66].

Education and health policies are particularly crucial in low-HDI countries, as strengthening these policies results in improvement of their population’s capacities and human development. Our analysis shows that improvements in education and health do not negatively affect environmental efficiency, so interventions in these areas are particularly important. However, it is also true that in many low-HDI countries, the promotion of education and health is often dependent on foreign international cooperation, which can limit the autonomy of national development strategies.

Industrial policy also has an impact on the development of both high- and low-HDI countries. The current industrial context is characterised by financialisation and new patterns of accumulation, value creation and capture [76]. These shifts are occurring alongside major global challenges, such as the climate emergency, the energy transition, and new digital production and mobility practices. As a result, national industrial policies are being reshaped, with their success depending on changes in structural productive organisations at the micro-level. These transformations influence not only industrial and social structuring [76] but also a country’s ability to improve the natural resource efficiency and mitigate environmental impacts of productive sectors.

Our analysis has limitations. It is a static analysis using 2015 as the reference year, as this is the most recent year for which there is a wide range of consistent data. A dynamic analysis incorporating different years would complete our work by allowing an analysis of trends over time. It would inform a deeper discussion on the historical environmental burdens carried by countries and how these may have impacted their human development and well-being.

It is also important to remember that the DEA results reflect relative efficiency within the 120 countries analysed. Finally, our study does not consider, for example, different industrial structures among regions worldwide. Treating regions as homogeneous DMUs may not be accurate – a limitation also identified by Zhou et al. [35]. Therefore, future research should categorise countries according to common socio-economical and/or environmental characteristics and integrate these groupings into analyses.

6. Conclusions

This paper contributes to filling a gap in human development studies, which have historically lacked in the integration of sustainability, and shows the context in which a just and sustainable transition can take place. It draws on the established field of social metabolism, and in particular the use of environmental footprints, serving as a nexus between the ecological economics and the realm of progress and social justice in which human development is framed. Within this framework, a novel efficiency indicator, FEHD, is proposed.

With respect to the initial hypotheses, hypothesis 1 is not fulfilled, given that FEHD decreases as countries obtain higher human development. The same trend is observed when comparing efficiency with each component of human development individually (Figs. 3–5). However, multivariate analysis, which captured the effects jointly, led us to reject only sub-hypothesis 1.3, related to income. Consistent with the overall test of hypothesis 1, the higher (lower) the FEHD of countries, the lower (higher) their income index. The education and health variables, on the other hand, are not significant, so we can neither affirm nor dismiss the fulfilment of sub-hypotheses 1.1 and 1.2, respectively. Finally, hypothesis 2 is also not fulfilled; the analysis concludes that the opposite is true in that efficiency in the use of natural resources decreases as countries exceed sustainability thresholds.

The difficulties of combining high levels of development and environmental sustainability are widely known, and countries with higher levels of human development maintain unsustainable resource consumption. However, there is no agreement on the efficiency of natural resource use. Thus, approaches such as the EKC suggest that

technological advances associated with economic development can lead to improvements in efficiency and environmental impacts. Other studies question the efficiency of resource use in generating well-being in low-income African and Asian countries.

In contrast to these approaches, this paper supports the view that countries with lower levels of human development are more efficient in the use of natural resources. The analysis concludes that the countries with the highest (lowest) FEHD are those with the lowest (highest) human development. Moreover, these relatively more environmentally efficient countries are the most sustainable, as they exceed fewer sustainability thresholds. Among the dimensions of human development, income is the one that presents the greatest problems in maintaining high levels of efficiency. Advances in education and health do not conflict with environmental efficiency.

Finally, the paper shows that it is possible to combine high human development with environmental efficiency (i.e. Sri Lanka and Moldova). According to the analysis, there is scope for further research to find the best initiatives and policies for improving the environmental efficiency of high human development countries in their use of natural resources and, in turn, on achieving higher levels of human development in low human development countries. The study offers insights into the typology of countries, based on FEHD, which can be further explored in order to better address their economic, social, environmental and territorial characteristics. This will help clarify countries' responsibilities and guide the steps needed for a more just and sustainable transition.

Appendix

Table A1, Table A2

Table A1
Descriptive statistics and correlation matrix (DEA inputs-outputs).

Variable	Mean (SD)	(Min, Max)	Material footprint	Total primary energy footprint	Ecological footprint	Human Dev. Index	CO ₂ emissions
Material footprint	15.652 (12.615)	(0.560, 59.760)	1.000				
Total primary energy footprint	27.998 (26.984)	(0.120, 147.15)	0.864**	1.000			
Ecological footprint	3.304 (2.140)	(0.695, 12.710)	0.859**	0.922**	1.000		
Human Dev. Index	0.750 (0.138)	(0.376, 0.954)	0.732**	0.713**	0.762**	1.000	
CO ₂ emissions	4.908 (4.937)	(0.042, 27.301)	0.795**	0.884**	0.855**	0.640**	1.000

Table A2
Descriptive statistics and correlation matrix (truncated regressions).

Variable	Mean	SD	FEHD	Life expectancy index	Education index	GNI index
FEHD	44.570	23.330	1.000			
Life expectancy index	0.822	0.111	- 0.714**	1.000		
Education index	0.698	0.161	- 0.774**	0.790**	1.000	
GNI index	0.743	0.153	- 0.872**	0.845**	0.878**	1.000

Note: ** Correlation is significant at the 0.01 level (2-tailed).

References

[1] A. Sen, in: A. Alfred (Ed.), *Development as Freedom*, Oxford University Press, 1999.
 [2] J. Hickel, The sustainable development index: measuring the ecological efficiency of human development in the anthropocene, *Ecol. Econ.* 167 (2020) 106331, <https://doi.org/10.1016/J.ECOLECON.2019.05.011>.

CRediT authorship contribution statement

Jorge Gutiérrez-Goiria: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Iker Etzano:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Andrés-Fernando Herrera:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **José Domingo García-Merino:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

University of the Basque Country. Research grant number GIU21/011. 'Policy Coherence for Development and International Cooperation' Research Group and Research grant number US25/12. Basque Government. Research grant number IT1567-22. Ekopol: 'Transition pathways' Research Group. We would like to thank Iñaki Sasia for his help in preparing Fig. 1.

- [6] T.O. Wiedmann, H. Schandl, M. Lenzen, D. Moran, S. Suh, J. West, K. Kanemoto, The material footprint of nations, in: *Proceedings of the National Academy of Sciences of the United States of America* 112, 2015, pp. 6271–6276, <https://doi.org/10.1073/pnas.1220362110>.
- [7] O. Akizu-Gardoki, T. Wakiyama, T. Wiedmann, G. Bueno, I. Arto, M. Lenzen, J. M. Lopez-Guede, Hidden energy flow indicator to reflect the outsourced energy requirements of countries, *J. Clean Prod.* 278 (2021) 123827, <https://doi.org/10.1016/j.jclepro.2020.123827>.
- [8] A.Y. Hoekstra, A.K. Chapagain, Water footprints of nations: water use by people as a function of their consumption pattern, *Water Resour. Manage* 21 (2007) 35–48, <https://doi.org/10.1007/s11269-006-9039-x>.
- [9] L. Chancel, Global carbon inequality over 1990–2019, *Nat. Sustain.* 5 (2022) 931–938, <https://doi.org/10.1038/s41893-022-00955-z>.
- [10] K. Fang, R. Heijungs, G.R. De Snoo, Theoretical exploration for the combination of the ecological, energy, carbon, and water footprints: overview of a footprint family, *Ecol. Indic.* 36 (2014) 508–518, <https://doi.org/10.1016/j.ecolind.2013.08.017>.
- [11] A. Galli, T. Wiedmann, E. Erwin, D. Knoblauch, B. Ewing, S. Giljum, Integrating ecological, carbon and water footprint into a “footprint Family” of indicators: definition and role in tracking human pressure on the planet, *Ecol. Indic.* 16 (2012) 100–112, <https://doi.org/10.1016/j.ecolind.2011.06.017>.
- [12] A.Y. Hoekstra, T.O. Wiedmann, Humanity’s unsustainable environmental footprint, *Science* 344 (6188) (2014) 1114–1117, <https://www.science.org/doi/10.1126/science.1248365>.
- [13] S. Zhang, D. Zhu, Q. Shi, M. Cheng, Which countries are more ecologically efficient in improving human well-being? An application of the Index of Ecological Well-being Performance, *Resour. Conserv. Recycl.* 129 (2018) 112–119, <https://doi.org/10.1016/j.resconrec.2017.10.015>.
- [14] S. Zhang, D. Zhu, Incorporating “relative” ecological impacts into human development evaluation: planetary boundaries-adjusted HDI, *Ecol. Indic.* 137 (2022) 108786, <https://doi.org/10.1016/j.ecolind.2022.108786>.
- [15] O. Akizu-Gardoki, G. Bueno, T. Wiedmann, J.M. Lopez-Guede, I. Arto, P. Hernandez, D. Moran, Decoupling between human development and energy consumption within footprint accounts, *J. Clean Prod.* 202 (2018) 1145–1157, <https://doi.org/10.1016/j.jclepro.2018.08.235>.
- [16] I. Arto, I. Capellán-Pérez, R. Lago, G. Bueno, R. Bermejo, The energy requirements of a developed world, *Energy Sustain. Dev.* 33 (2016) 1–13, <https://doi.org/10.1016/j.esd.2016.04.001>.
- [17] M. Jiang, P. Behrens, Y. Yang, Z. Tang, D. Chen, Y. Yu, L. Liu, P. Gong, S. Zhu, W. Zhou, B. Zhu, A. Tukker, Different material footprint trends between China and the world in 2007–2012 explained by construction- and manufacturing-associated investment, *One Earth* 5 (1) (2022) 109–119, <https://doi.org/10.1016/j.oneear.2021.12.011>.
- [18] M. Papięz, S. Śmiech, K. Frodyma, J. Borowiec, Decoupling is not enough - evidence from fossil fuel use in over 130 countries, *J. Clean Prod.* 379 (2022) 134856, <https://doi.org/10.1016/j.jclepro.2022.134856>.
- [19] H. Xu, Y. Gao, C. Wang, Z. Guo, W. Liu, D. Zhang, Exploring the nexuses between carbon dioxide emissions, material footprints and human development: an empirical study of 151 countries, *Ecol. Indic.* 166 (2024) 112229, <https://doi.org/10.1016/j.ecolind.2024.112229>.
- [20] D.D. Moran, M. Wackernagel, J.A. Kitzes, S.H. Goldfinger, A. Boutaud, Measuring sustainable development-nation by nation, *Ecol. Econ.* 64 (2008) 470–474, <https://doi.org/10.1016/j.ecolecon.2007.08.017>.
- [21] M. Salman, G. Wang, D. Zha, Modeling the convergence analysis of sustainable production and consumption in terms of ecological footprints and human development index in Belt and Road Initiative countries, *Sustain. Prod. Consum.* 30 (2022) 233–254.
- [22] H. Bian, J. Gao, Y. Liu, D. Yang, J. Wu, China’s safe and just space during 40 years of rapid urbanization and changing policies, *Landscape Ecol.* 39 (4) (2024) 1–15, <https://doi.org/10.1007/s10980-024-01868-2/FIGURES/6>.
- [23] D.W. O’Neill, A.L. Fanning, W.F. Lamb, J.K. Steinberger, A good life for all within planetary boundaries, *Nat. Sustain.* 1 (2) (2018) 88–95, <https://doi.org/10.1038/s41893-018-0021-4>.
- [24] K. Raworth, A doughnut for the Anthropocene: humanity’s compass in the 21st century, *Lancet Planet. Health* 1 (2) (2017) e48–e49, [https://doi.org/10.1016/s2542-5196\(17\)30028-1](https://doi.org/10.1016/s2542-5196(17)30028-1).
- [25] A. Roy, T. Dutta, Y. Li, X. Dong, Human development at the cost of the environment?—an application of planetary pressures-adjusted human development index in the lens of planetary boundaries, *Environ. Sci. Pollut. Res.* 30 (12) (2023) 32383–32405, <https://doi.org/10.1007/s11356-022-24399-2/METRICS>.
- [26] H. Schlesier, M. Schäfer, H. Desing, Measuring the doughnut: a good life for all is possible within planetary boundaries, *J. Clean Prod.* 448 (2024) 141447, <https://doi.org/10.1016/j.jclepro.2024.141447>.
- [27] W. Steffen, K. Richardson, J. Rockström, S.E. Cornell, I. Fetzer, E.M. Bennett, R. Biggs, S.R. Carpenter, W. De Vries, C.A. De Wit, C. Folke, D. Gerten, J. Heinke, G. M. Mace, L.M. Persson, V. Ramanathan, B. Reyers, S. Sörlin, Planetary boundaries: guiding human development on a changing planet, *Science* 347 (6223) (2015) 1259855, <https://doi.org/10.1126/science.1259855>.
- [28] J. Vogel, J.K. Steinberger, D.W. O’Neill, W.F. Lamb, J. Krishnakumar, Socio-economic conditions for satisfying human needs at low energy use: an international analysis of social provisioning, *Glob. Environ. Change* 69 (2021) 102287, <https://doi.org/10.1016/j.gloenvcha.2021.102287>.
- [29] W.F. Lamb, J.K. Steinberger, A. Bows-Larkin, G.P. Peters, J.T. Roberts, F.R. Wood, Transitions in pathways of human development and carbon emissions, *Environ. Res. Lett.* 9 (1) (2014) 014011.
- [30] J.K. Steinberger, J.T. Roberts, From constraint to sufficiency: the decoupling of energy and carbon from human needs, 1975–2005, *Ecol. Econ.* 70 (2) (2010) 425–433, <https://doi.org/10.1016/j.ecolecon.2010.09.014>.
- [31] UNEP. Global Material Flows and Resource Productivity Assessment Report for the UNEP International Resource Panel, 2016. <https://wedocs.unep.org/handle/20.500.11822/21557>.
- [32] S. Chen, A. Li, L. Hu, M.G.R. N’Drin, Understanding the efficiency in generating human development in sub-Saharan Africa: a two-stage network DEA approach, *Soc. Indic. Res.* 171 (1) (2024) 295–324.
- [33] N. Amowine, H. Li, K.B. Boamah, Z. Zhou, Towards ecological sustainability: assessing dynamic total-factor ecology efficiency in Africa, *Int. J. Environ. Res. Public Health* 18 (17) (2021) 9323, <https://doi.org/10.3390/ijerph18179323>.
- [34] T. Dietz, E.A. Rosa, R. York, Environmentally efficient well-being: rethinking sustainability as the relationship between human well-being and environmental impacts, *Human Ecology Review* 1 (16) (2009) 114–123.
- [35] H. Zhou, Y. Yang, Y. Chen, J. Zhu, Data envelopment analysis application in sustainability: the origins, development and future directions, *Eur. J. Oper. Res.* 264 (1) (2018) 1–16, <https://doi.org/10.1016/j.ejor.2017.06.023>.
- [36] E.B. Mariano, V.A. Sobreiro, D.A. do N. Rebelatto, Human development and data envelopment analysis: a structured literature review, in: *Omega* (United Kingdom), 54, Elsevier Ltd, 2015, pp. 33–49, <https://doi.org/10.1016/j.omega.2015.01.002>.
- [37] A. Charnes, W.W. Cooper, E. Rhodes, Measuring the efficiency of decision making units, *Eur. J. Oper. Res.* 2 (6) (1978) 429–444, [https://doi.org/10.1016/0377-2217\(78\)90138-8](https://doi.org/10.1016/0377-2217(78)90138-8).
- [38] W.W. Cooper, L.M. Seiford, J. Zhu, in: W.W. Cooper, L.M. Seiford, J. Zhu (Eds.), *Handbook On Data Envelopment Analysis, Handbook On Data Envelopment Analysis*, 164, Springer US, 2011, <https://doi.org/10.1007/978-1-4419-6151-8>.
- [39] D. Ferraz, E.B. Mariano, D. Rebelatto, D. Hartmann, Linking Human development and the financial responsibility of regions: combined index proposals using methods from data envelopment analysis, *Soc. Indic. Res.* 150 (2) (2020) 439–478, <https://doi.org/10.1007/s11205-020-02338-3>.
- [40] D.K. Despotis, Measuring human development via data envelopment analysis: the case of Asia and the Pacific, *Omega* (Westport) 33 (5) (2005) 385–390, <https://doi.org/10.1016/j.omega.2004.07.002>.
- [41] V. Vierstraete, Efficiency in human development: a data envelopment analysis, *Eur. J. Comp. Econ.* 9 (3) (2012) 425–443, <http://eaces.liuc.it>.
- [42] D. Ferraz, H.F. Morales, J.S. Campoli, F.C.R. De Oliveira, D.A.D.N. Rebelatto, Economic complexity and human development: DEA performance measurement in Asia and Latin America, *Gest. Prod.* 25 (4) (2018) 839–853, <https://doi.org/10.1590/0104-530X3925-18>.
- [43] B.P. Singh, K. Yadava, Technical efficiency of financial inclusion and human development: insights from the Indian states, *Econ. Notes* 51 (2) (2022) 1–19, <https://doi.org/10.1111/ecn.12199>.
- [44] E.B. Mariano, D. Ferraz, S.C. de Oliveira Gobbo, The human development index with multiple data envelopment analysis approaches: a comparative evaluation using social network analysis, *Soc. Indic. Res.* 157 (2) (2021) 443–500, <https://doi.org/10.1007/s11205-021-02660-4>.
- [45] S. Blancard, J.F. Hoarau, A new sustainable human development indicator for small island developing states: a reappraisal from data envelopment analysis, *Econ. Modell.* 30 (1) (2013) 623–635, <https://doi.org/10.1016/j.econmod.2012.10.016>.
- [46] L.M. Seiford, J. Zhu, Modeling undesirable factors in efficiency evaluation, *Eur. J. Oper. Res.* 142 (1) (2002) 16–20, [https://doi.org/10.1016/S0377-2217\(01\)00293-4](https://doi.org/10.1016/S0377-2217(01)00293-4).
- [47] H. Scheel, Undesirable outputs in efficiency valuations, *Eur. J. Oper. Res.* 132 (2) (2001) 400–410, [https://doi.org/10.1016/S0377-2217\(00\)00160-0](https://doi.org/10.1016/S0377-2217(00)00160-0).
- [48] G. Wang, M. Salman, K. Zhang, The impact of urbanisation on green total factor productivity: exploring threshold and mediating effects of human capital, *Int. J. Health Plann Manage* 39 (5) (2024) 1482–1502, <https://doi.org/10.1002/hpm.3820>.
- [49] A. Emrouznejad, Ł. Brzezicki, C. Lu, Development and evolution of slacks based measure models in data envelopment analysis: a comprehensive review of the literature, *J. Econ. Surv.* 39 (2025) 2106–2133, <https://doi.org/10.1111/joes.12682>.
- [50] V.J. Bolós, R. Benítez, V. Coll-Serrano, Continuous models combining slacks-based measures of efficiency and super-efficiency, *Cent. Eur. J. Oper. Res.* 31 (2) (2023) 363–391, <https://doi.org/10.1007/s10100-022-00813-5>.
- [51] A. Licerán-Gutiérrez, M.P. Horno-Bueno, A. Gómez-Ortega, N. Mirza, Key factors of European banking efficiency: an application of DEA methodology, *J. Fin. Report. Account.* (2025), <https://doi.org/10.1108/JFRA-09-2024-0668>.
- [52] M.R. Ghasemi, J. Ignatius, B. Rezaee, Improving discriminating power in data envelopment models based on deviation variables framework, *Eur. J. Oper. Res.* 278 (2) (2019) 442–447.
- [53] V.V. Podinovski, E. Thanassoulis, Improving discrimination in data envelopment analysis: some practical suggestions, *J. Product. Anal.* 28 (2007) 117–126, <https://doi.org/10.1007/s11123-007-0042-x>.
- [54] J. Cámara-Aceituno, M.J. Hermoso-Orzáez, J. Terrados-Cepeda, et al., Application of the data envelopment analysis technique to measure the environmental efficiency of the 27 countries of the European Union during the period 2012–2020, *Clean Techn. Environ. Policy* 26 (2024) 1477–1505, <https://doi.org/10.1007/s10098-023-02553-9>.
- [55] A. Masternak-Janus, M. Rybczewska-Błażejowska, Comprehensive regional eco-efficiency analysis based on data envelopment analysis: the case of Polish regions, *J. Ind. Ecol.* 21 (1) (2017) 180–190, <https://doi.org/10.1111/jiec.12393>.
- [56] E. Villamor, O. Akizu-Gardoki, J.T. Heinonen, G. Bueno, Global multi-regional input-output methodology reveals lower energy footprint in an alternative

- community project, *Sustain. Prod. Consum.* 34 (2022) 65–77, <https://doi.org/10.1016/j.spc.2022.09.003>.
- [57] L. Simar, P.W. Wilson, Estimation and inference in two-stage, semi-parametric models of production processes, *J. Econ.* 136 (1) (2007) 31–64, <https://doi.org/10.1016/j.jeconom.2005.07.009>.
- [58] G.M. Grossman, A.B. Krueger, Economic growth and the environment, *Q. J. Econ.* 110 (2) (1995) 353–377.
- [59] T. Dietz, E.A. Rosa, R. York, Driving the human ecological footprint, *Front. Ecol. Environ.* 5 (1) (2007) 13–18. <https://esajournals.onlinelibrary.wiley.com/doi/full/10.1890/1540-9295%282007%295%5B13%3ADTHEF%5D2.0.CO%3B2>.
- [60] F.A. Twum, X. Long, M. Salman, C.N. Mensah, W.A. Kankam, A. Kwamena Tachie, The influence of technological innovation and human capital on environmental efficiency among different regions in Asia-Pacific, *Environ. Sci. Pollut. Res.* 28 (2021) 17119–17131, <https://doi.org/10.1007/s11356-020-12130-y/Published>.
- [61] G. Wang, M. Salman, K. Zhang, Exploring the dynamic spatial spillover and nonlinear threshold effect of urbanization on urban green development efficiency in China, *Ecol. Indic.* 175 (2025) 113570, 2025.
- [62] S. Bringezu, Possible target corridor for sustainable use of global material resources, *Resources* 4 (1) (2015) 25–54, <https://doi.org/10.3390/RESOURCES4010025>.
- [63] IPCC, Summary for Policymakers - Special Report: Global Warming of 1.5 °C, 2018, <https://doi.org/10.1017/9781009157940.001>.
- [64] D.M. Martínez, B.W. Ebenhack, Understanding the role of energy consumption in human development through the use of saturation phenomena, *Energy Policy* 36 (4) (2008) 1430–1435.
- [65] A. Pasternak, (2020). Global energy futures and human development: a framework for analysis, Oak Ridge: U.S. Department of Energy, UCRL-ID-140773. <https://geni.org/globalenergy/issues/global/qualityoflife/HDI-and-electricity-consumption.pdf>.
- [66] L. Tamburino, G. Bravo, Ecological efficiency: the ability to achieve human well-being while limiting environmental impact, *Environ. Sustain. Indic.* 21 (2024) 100322, <https://doi.org/10.1016/J.INDIC.2023.100322>.
- [67] K.W. Knight, E.A. Rosa, The environmental efficiency of well-being: a cross-national analysis, *Soc. Sci. Res.* 40 (3) (2011) 931–949, <https://doi.org/10.1016/j.sres.2010.11.002>.
- [68] C. Dorninger, A. Hornborg, D.J. Abson, H. Von Wehrden, A. Schaffartzik, S. Giljum, J.-O. Engler, R.L. Feller, K. Hubacek, H. Wieland, Global Patterns of Ecologically Unequal Exchange: Implications for Sustainability in the 21st Century, 2020, <https://doi.org/10.1016/j.ecolecon.2020.106824>.
- [69] F. Krausmann, C. Lauk, W. Haas, D. Wiedenhofer, From resource extraction to outflows of wastes and emissions: the socioeconomic metabolism of the global economy, 1900–2015, *Global Env. Change* 52 (2018) 131–140, <https://doi.org/10.1016/j.gloenvcha.2018.07.003>.
- [70] H. Haberl, D. Wiedenhofer, D. Virág, G. Kalt, B. Plank, P. Brockway, T. Fishman, D. Hausknost, F. Krausmann, B. Leon-Gruchalski, A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights, *Env. Res. Lett.* 15 (2020) 065003, <https://doi.org/10.1088/1748-9326/ab842a>.
- [71] T. Parrique, J. Barth, F. Briens, C. Kerschner, A. Kraus-Polk, A. Kuokkanen, J. H. Spangenberg, Decoupling Debunked. Evidence and Arguments Against Green Growth as a Sole Strategy for Sustainability, The European Environment Bureau, 2019.
- [72] J.C.J.M. van den Bergh, W.J.W. Botzen, Global impact of a climate treaty if the human development index replaces GDP as a welfare proxy, *Clim. Policy* 18 (1) (2018) 76–85, <https://doi.org/10.1080/14693062.2016.1227954>.
- [73] M. Wackernagel, D. Lin, M. Evans, L. Hanscom, P. Raven, Defying the footprint Oracle: implications of country resource trends, *Sustainability* 11 (7) (2019) 2164, <https://doi.org/10.3390/su11072164>.
- [74] M. Wackernagel, L. Hanscom, P. Jayasinghe, D. Lin, A. Murthy, E. Neill, P. Raven, The importance of resource security for poverty eradication, *Nat. Sustain.* 4 (8) (2021) 731–738, <https://doi.org/10.1038/S41893-021-00708-4>.
- [75] L. Tamburino, G. Bravo, Reconciling a positive ecological balance with human development: a quantitative assessment, *Ecol Indic* 129 (2021) 107973, <https://doi.org/10.1016/J.ECOLIND.2021.107973>.
- [76] H.J. Chang, A. Andreoni, Industrial policy in the 21st century, *Dev. Change* 51 (2) (2020) 324–351, <https://doi.org/10.1111/DECH.12570>.