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Towards a Comprehensive Framework of the Relationships between Resource Footprints, Quality of Life, and Economic Development

Stefan Cibulka and Stefan Giljum * 

Institute for Ecological Economics, Vienna University of Economics and Business (WU), 1020 Vienna, Austria; stefan.cibulka@da-vienna.at

* Correspondence: stefan.giljum@wu.ac.at

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Abstract: The relationship between economic affluence, quality of life, and environmental implications of production and consumption activities is a recurring issue in sustainability discussions. A number of studies examined selected relationships, but the general implications for future development options to achieve environmentally and socially sustainable development of countries at different levels of per capita resource footprints, quality of life, and income have not yet been investigated in detail. In this study, we use a global dataset with 173 countries to assess the overall relationship between resource footprints, quality of life, and economic development over the period of 1990–2015. We select the material footprint and carbon footprint and contrast them with the Human Development Index, the Happiness Index, and GDP per capita. Regression analyses show that the relationship between various resource footprints and quality of life generally follows a logarithmic path of development, while resource footprints and GDP per capita are linearly connected. From the empirical results, we derive a generalized path of development and cluster countries along this path. Within this comprehensive framework, we discuss options to change the path to respect planetary and social boundaries through a combination of resource efficiency increases, substitution of industries and sufficiency of consumption. We conclude that decoupling and green growth will not realize sustainable development if planetary boundaries have already been transgressed.

Keywords: decoupling; post-growth; planetary boundaries; quality of life; resource footprints; sustainable development

1. Introduction

The relationship between economic affluence, quality of life, and environmental implications of production and consumption patterns is a recurring issue in sustainability debates. A classical approach to consider sustainability aspects in economic models is adjusting the GDP via monetarized societal and environmental indicators into an alternative index, assuming that environmental pressures could be reduced via substitution of input factors and elimination of market failures through internalization of external costs [1–3]. Ecological economists have questioned these assumptions [4,5], advocating absolute instead of relative decoupling and introducing the concepts of planetary and social boundaries [6–8]. This is genuinely linked to the discussion about different economic growth narratives: degrowth versus green growth, steady-state economics, and more recently a-growth and post-growth [9–11]. Additionally, there are many conceptual solutions linked to sustainability, including resource efficiency, substitution, and circularity on the production side, as well as sufficiency and change of behavior on the consumption side [12–18].

Studies have described this relationship as the environmental intensity and the environmental efficiency of human well-being [19–21]. Mazur and Rosa [22] already found out in 1974 that the

effect of an additional unit of electricity levels off beyond a certain point. A number of studies have later investigated the relationship between well-being and energy indicators via semi-logarithmic or saturation curves, using the Human Development Index (HDI) and its components [23–25]. The indicator domestic material consumption (DMC) was regressed against HDI for countries world-wide in Dittrich et al. [26] and Giljum et al. [27], also confirming the general saturation pattern.

Instead of production-based indicators, a number of scholars [28,29] used the ecological footprint, a composite consumption-based indicator [30], and Tukker et al. [31] a set of resource footprints, including carbon, material and land footprints, to assess these against HDI and happy life years, returning similar results. Vita et al. [32] investigated the Carbon Footprint related to the satisfaction of different human needs and showed that objective indicators of well-being have a threshold with respect to related footprints, while subjective indicators do not show a clear relationship. Ambrey and Daniels [33] even found marginally lower levels of well-being with increasing carbon footprints for the average Australian case. Regarding economic development, recent studies have repeatedly reaffirmed the existence of the Easterlin paradox, indicating that life satisfaction does not increase with economic growth beyond a certain point in the long run [34–37], questioning the validity of GDP as the main measure of economic welfare.

O'Neill and colleagues [38] depart from the “safe and just space framework” by Raworth [7] and assess planetary boundaries [6,39] against social thresholds. Stoknes and Rockström [40] and Parrique and colleagues [41] have recently redefined decoupling requirements with reference to the progressing transgression of planetary boundaries, while the newest report to the Club of Rome examines how the Sustainable Development Goals (SDGs) can be achieved within the planetary boundaries [42].

Despite this large number of existing studies, the general implications for future development options to achieve an environmentally and socially sustainable development of countries at different levels of per capita resource footprints, quality of life, and income have not yet been sufficiently investigated within a single conceptual framework. This paper contributes to filling this gap, aiming at providing a basis for future research towards comprehensive sustainable development models.

We use a global dataset with 173 countries to assess the overall relationship between resource footprints, quality of life, and economic development over the period 1990–2015. We prefer footprint indicators over territorial environmental indicators, as footprints consider international supply chains and are therefore robust against burden-shifting, a key requirement in the transformation towards more sustainable production and consumption patterns [43]. We select material footprint (MF) and carbon footprint (CF) as resource use indicators and contrast them with the Human Development Index (HDI), the Happiness Index (HI), and GDP per capita. We derive timelines of individual countries and regions and identify development clusters from the empirical data. The resulting overall regression line, which—according to the existing literature (see above)—we expect to follow a concave function, is then integrated with planetary and social boundaries.

The value of our assessment is that we set variables with conceptually different characteristics in relation to each other, i.e., resource footprint indicators on the one hand and a selection of socio-economic indicators on the other hand. In contrast to existing literature, we derive a generalized framework from the empirical analysis, which allows discussing the potentials of a range of sustainability concepts, such as resource efficiency, sufficiency, and product substitution, to contribute to a transition towards an environmentally and socially sustainable development. Our approach also enables examining possible connections with conventional economic growth models. This integrated perspective is relevant, as the urgency of challenges currently faced by humanity [44,45] demands identifying systemic solutions that avoid burden shifting between environmental and social domains.

The remainder of the paper is organized as follows. Section 2 describes data sources and methodology used for the analysis. In Section 3, we present the results of the regression and timeline analyses, and cluster countries along a generalized path of development. Section 4 discusses the implications of the empirical analyses for future development options from different starting points

of resource use and quality of life. Section 5 concludes our discussion with an outlook to further refinement needs of the presented framework.

2. Materials and Methods

We applied regression analyses to examine the overall relationship between resource use, measured as consumption-based resource footprints (RF), and quality of life (QL), as approximated by the HDI, which is the only index available in an annual time series since 1990 [46]. We supplemented the HDI with the HI of the World Happiness Report [47] for comparative purposes (partially consolidated by the utilization of 3-year moving averages). We also used GDP per capita (GDP/cap) in current prices (purchasing power parity/PPP) and population data from the World Bank [48]. The data for MF, CF, and for a comparative analysis, land footprint (LF), were taken from the online tool ‘SCP-HAT’ (scp-hat.lifecycleinitiative.org) [49]. SCP-HAT provides production- as well as consumption-based indicators for a range of environmental pressures and impacts for countries worldwide. The indicators were calculated using the environmentally extended, multi-regional input-output database ‘Eora’ [50] in its 26-sector version. Material extraction data to calculate the MF were taken from the UN International Resource Panel (IRP) database [51], data on greenhouse gas emissions stem from ‘PRIMAP-hist’ by the Potsdam Institute for Climate Impact Research [52]. For comparative analysis, we also used water footprint (WF) data from the Water Footprint Network [53]. The full data set is provided in sheet 1 of the corresponding data file [54].

To highlight the different shape of best-fit regressions for the HDI, the HI, and GDP/cap, we performed both semi-logarithmic (1) and linear (2) regressions. In all three regressions, we used the RF indicator as an independent variable, and the HDI, the HI (generalized as QL in Equations (1)–(4) and GDP/cap as dependent variables:

$$QL_{i,t} = \text{const} + \beta \ln(RF_{i,t}) + u_{i,t} \quad (1)$$

$$QL_{i,t} = \text{const} + \beta (RF_{i,t}) + u_{i,t} \quad (2)$$

with $u_{i,t}$ being the normally distributed error term with zero mean and constant variance σ^2 . Note that by using RF as the independent variable in all regression variations ensured that the variables do not contain the same characteristics, which would be the case when regressing HDI on GDP, as the former contains GDP values as one component in the composite indicator.

To calculate the trend over time, we added an interaction variable including both RF and time (t):

$$QL_{i,t} = \text{const} + \beta_1 \ln(RF_{i,t}) + \beta_2 \ln(RF_{i,t}) t + u_{i,t} \quad (3)$$

Outputs of the overall regression analyses are the unstandardized coefficients (constant and slope), the standardized coefficients (β -values), the R^2 values, and the residuals.

Given missing data for some countries and indicators (pairwise exclusion), the number of observations is around 4000 for regressions using the whole timeframe of 1995 to 2015, and between 154 and 168 for regressions using average data over the periods 1996–2005 and 2006–2015, respectively. The approach using averaged data allowed a comparison of coefficients between the timeframes, an overall comparison between RF components and QL indicators and an easy visualization via scatter charts and timelines. In the scatter charts, we normalized HI and GDP data by putting the country with the highest number as 1, after having excluded extreme outliers above or below 3 times the interquartile range (IQR). The timeline analysis is based on scatter charts of HDI explained by MF and CF from 1990 to 2015, in five-year intervals. In order to increase readability, we partly grouped countries to regions with similar geographical and economic profiles.

To form development clusters from the dataset, the residuals from Equation (1) are used, plus the residuals of the reciprocal regression equation:

$$\ln(RF_{i,t}) = \text{const} + \beta(Q_{L_{i,t}}) + u_{i,t} \quad (4)$$

The regression is thus carried out in both directions, to calculate the residuals of both variables for all elements and years. Positive residuals of Equation (1) indicate that the HDI is higher than predicted, if they are negative, it is lower. The opposite is the case for Equation (4). Residuals of Equation (1) are usually diametrical to those of (4), meaning that data points are either above or below the curve. For details see Supplementary Material 1 and [54].

Our approach allowed an assessment of the two main parameters for sustainability, environment, and society. Its main limitation is that any model directly derived from the dataset providing more specific recommendations, e.g., to policymakers, requires a more elaborated parameterization, accounting for the variety of components on each axis. Hence, in this paper, results are discussed in an abstracted, theoretical way, leading to a descriptive framework that incorporates concepts linked to sustainability only in an aggregated manner.

3. Results

3.1. Regression Analysis

In Table 1, we present regression results between HDI, HI, and GDP/cap and the MF and CF.

Table 1. Logarithmic and linear regressions of Human Development Index (HDI), Happiness Index (HI), GDP/cap and Material Footprint (MF)/Carbon Footprint (CF).

		Logarithmic Coefficients				Linear Coefficients				N
		const	B var	β	R ²	const	B var	β	R ²	N
1	HDI vs. MF (1990–2015)	0.383 **	0.138 **	0.836 **	0.698	0.514 **	0.012 **	0.736 **	0.542	4000
2	HDI vs. MF	0.420 **	0.130 **	0.853 **	0.727	0.545 **	0.012 **	0.759 **	0.577	166
3	HI vs. MF 06–15 avg (Figure 1)	0.512 **	0.092 **	0.724 **	0.524	0.586 **	0.009 **	0.711 **	0.505	154
4	GDP/cap vs. MF	−0.126 **	0.226 **	0.727 **	0.529	0.003	0.028 **	0.833 **	0.694	164
5	HDI vs. CF (1990–2015)	0.401 **	0.130 **	0.768 **	0.590	0.569 **	0.008 **	0.532 **	0.283	4002
6	HDI vs. CF	0.457 **	0.124 **	0.800 **	0.640	0.579 **	0.011 **	0.635 **	0.403	166
7	HI vs. CF 06–15 avg (Figure 1)	0.527 **	0.094 **	0.701 **	0.492	0.612 **	0.009 **	0.608 **	0.369	154
8	GDP/cap vs. CF	−0.116 **	0.246 **	0.753 **	0.567	0.001	0.035 **	0.860 **	0.738	164

* significance <0.05; ** significance <0.01; **bold**: best fit comparison.

As Table 1 shows in lines 1 and 5, both MF and CF for the full period of 1996 to 2015 can be well estimated via a logarithmic regression, with R²-values between 0.698 (MF) and 0.590 (CF). However, this relationship changes when analyzing RFs against the GDP/cap values. For linear regressions, the R² values and slopes of the GDP PPP/cap are higher than those of the HDI, while R² values of logarithmic regressions are higher for the HDI than for GDP PPP/cap (see lines 2–4 and 6–8, respectively). Comparing this with the HI, we can observe that the R² values are slightly below the explanatory values of the HDI, but still higher for the logarithmic than for the linear regression; the intercepts are slightly higher, while the variable coefficients are clearly lower. This shows that the logarithmic nature does also apply for the HI, though with a lower explanatory value and a flatter curve. Figure 1 provides a visual presentation of the main results illustrated in Table 1 using the 2006–2015 average numbers for each country considered in the regression.

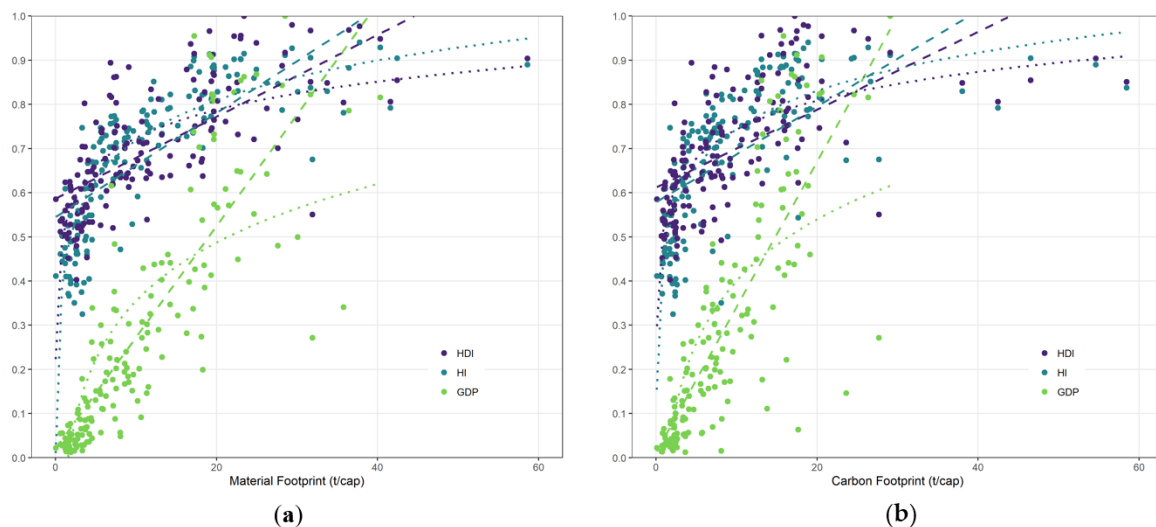


Figure 1. Material Footprint (a) and Carbon Footprint (b) plotted against Human Development Index (HDI), Happiness Index (HI) and GDP/cap (GDP), 2006–2015 averages. Dashed lines: linear regression curve. Dotted lines: logarithmic regression curve.

It visualizes that the logarithmic regression fits better for HDI and HI, while the linear regression for GDP PPP/cap. These results are in line with previous studies, suggesting a linear relationship between RFs and GDP/cap [24,55]. This difference does not only exist because of the methodological fact that the HDI contains the logarithm of GDP/cap as one out of three variables. First, this composition of the HDI was based on the cognition that marginal utility of consumption decreases at higher levels. Second, education and life expectancy also level off at higher development levels. Moreover, existing studies indicate that there is also a logarithmic relationship between GDP/cap and average life satisfaction, which is a subjective measure of well-being [56]. Finally, although it contains many more factors than the HDI, the logarithmic regression explaining the HI by RFs also reaches high explanatory values (see Table 1).

The addition of an interaction variable, resource footprint multiplied with time [see 54], shows that for both RFs, the factor time has a significant, positive effect on the slope. The interaction variable $CF \cdot t$ shows a beta of 0.285** and an adjusted R^2 of 0.639 (from 0.590 without time factor), while the beta of $MF \cdot t$ is 0.170**, and the adjusted R^2 rises from 0.698 to 0.713. This analysis reveals an increasing slope over time, pointing towards a slightly increasing resource efficiency, particularly regarding the CF. This effect can also be shown by comparing the averaged values of the timeframes 1996–2005 and 2006–2015 for MF and CF (see the corresponding data file [54]).

To sum up, the regression analysis reveals that (1) there is a strong relationship between quality of life and natural resource use, that (2) this relationship can be described by a concave (logarithmic) function, that (3) this function increases in slope over time [compare with 23], and that (4) GDP/cap, in contrast, shows a linear relationship to QL. This difference implies that a resource-efficient increase in QL could at the same time lead to a decrease of GDP/cap, depending on its resource elasticity (see in detail Section 4).

According to the results, both HDI and HI are applicable for a generalized framework based on the logarithmic regression line, which shows interesting developments regarding its slope and position, while GDP/cap more closely follows a linear curve. Generally, multi-factor indices for QL contain education and health, and further factors such as freedom to make choices, perspectives in life, democratic rights, and safety. GDP/cap, or similar indicators, is usually a part of such an index (e.g., HDI, inequality-adjusted HDI [57], Happiness Index of the World Happiness Report [47], or the OECD Better Life Index [58]). This is important, as it allows the assessment of rebound effects of QL on GDP/cap and vice versa (see Section 4). Therefore, for the purpose of the generalized framework

discussed in Section 4, QL is defined as an abstracted multi-factor index, and GDP/cap is assumed as one of its constituents.

In order to analyze, which categories of natural resources fit into the overall regression model, we performed an assessment on the level of the main components of the Material and Carbon Footprint (see Supplementary Material 2). The MF consists of biomass, metal ores, minerals and fossils; the CF of carbon dioxide, methane, nitrous oxide and other GHGs. For comparative purposes, we also included the Land Footprint of pasture, crops and forest as well as the Water Footprint disaggregated into green, blue and grey water. The details of the analysis can be found in the corresponding data file [54]. Following this analysis, RF components suitable to be added to a framework based on the concave path of development are all raw materials, all greenhouse gases, to a certain extent cropland, and grey water. For the purpose of the generalized framework presented in Section 4, all suitable environmental pressures will therefore be addressed as resource footprints per capita (RF/cap).

3.2. Timeline Analysis

For a closer examination of development patterns and properties of the development path, we drew timelines and derive development clusters (Section 3.3). Figure 2 illustrates the timelines of 42 countries and country groups between 1990 and 2015, for all see all timeline data and details, see [54]. We show the MF on the left and the CF on the right, plotted against HDI (a,b) and GDP/cap (c,d).

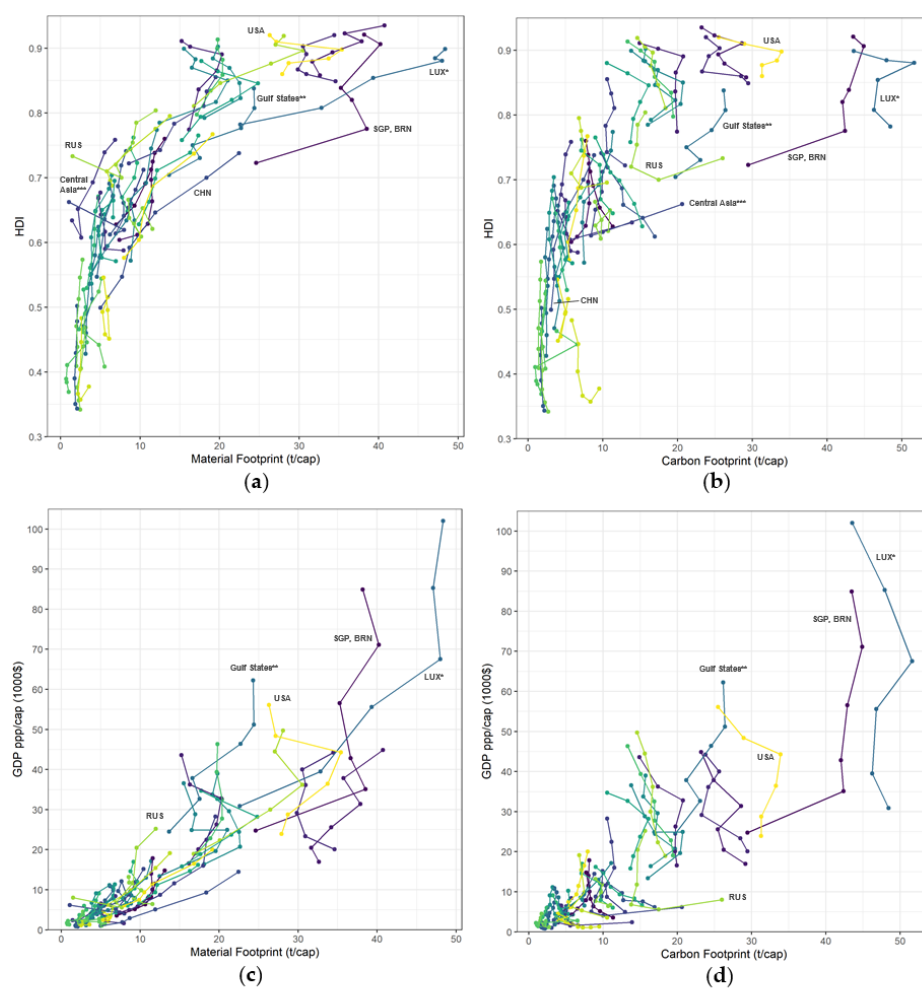


Figure 2. Timelines of material footprint plotted against HDI (a), carbon footprint plotted against HDI (b), material footprint plotted against GDP/cap (c) and carbon footprint plotted against GDP/cap (d), 1995–2015, 5-year intervals.

As one could expect from the regression analysis, the overall shape of timelines including HDI explained by RFs follows a logarithmic curve (Figure 1, above). Interestingly, the timelines are not constantly moving along the line, but rather in steps of acceleration and deceleration. The highest RFs, together with high development, can be found in small European states, such as Luxembourg and Monaco, Asian City-States (Singapore, Brunei), and in the Anglo-Saxon New World, driven by urbanization and consumption patterns. China can be found at the lower right of the curve as well, having caught up with many of the European countries in recent years when it comes to the footprint, but not with regard to HDI. In former USSR countries, RFs dropped significantly around 1990; since then, both HDI and RFs are rising, with wide differences between the sub-regions: Caucasus remains left of the overall curve; Central Asia, in contrast, has crossed the overall scatter and has now comparably high RFs. The MENA region shows two different patterns [29]; while the Gulf States are clearly at the lower right of the curve (higher MF, comparatively lower HDI), most other parts of the region are very close to the overall pattern. Many Asian and Latin American sub-regions with medium HDI show a trend towards higher development with lower RF, starting from a position at the lower right of the curve, slowly catching up with QL and resource efficiency, and possible examples for the resource-dependent countries currently stagnating at the lower right, such as Southern African and Central Asian countries.

Regarding the timelines of GDP/cap, the linear structure is very well visible for the MF, again tending to get slightly steeper at higher development levels, which could be interpreted as relative decoupling. However, this development was particularly strong between 2005 and 2010, when the financial crisis occurred; thereafter, the original development more or less continued, indicating that no absolute decoupling has taken place. Regarding CF, the tendency towards a higher slope (relative decoupling) is clearly visible. In cases with negative slopes, even absolute decoupling can be observed. These developments are also visible for HDI and HI, but in a different form. Around 2005, some timelines (e.g., European regions, Japan) changed direction, and maintained an increasing HDI and declining RFs; most of the MF timelines, however, stagnate since, while points of turnaround are more distinct regarding CFs. Possible reasons for these movements will be assessed in Section 4.1.

3.3. Deriving Development Clusters

Development clusters allow a closer assessment, which countries can be found above or below the path of development, provide further information about its properties, and could be used for a differentiated approach in the context of international regulations, allocation of development aid, as well as SDG prioritization [59]. To derive development clusters, we used standardized residuals of the overall regression analysis carried out in Section 3.1. and its reciprocal form, showing the position of a country in relation to the overall regression curve. In addition to the statement of whether a country is above or below the curve, or has transgressed it in either direction [54], the coordinate system can be further subdivided into development levels. As the limits between low, medium, and high development are only indicative and shift over time, we refrain from using specific numbers and explain the clusters in an abstract model.

The cluster system can be explained as follows (see Figure 3). Cluster A contains developed countries, Cluster B consists of countries in transition, while Cluster C consists of developing countries; least developed countries (LDCs) can be found in Cluster D (compare Fritz and Koch [60] and Cahen-Fourot [61] with slightly different clusters). Clusters B and C are subdivided into B1, B2, C1, C2, with the (1) to the upper left, and the (2) to the lower right of the curve. The tails of the curve are different: A is subdivided into A1 (above the line, lower resource use), A2 (above the line, higher resource use), and A3 (below the line). Cluster D cannot be subdivided using the data at hand, as the resource footprints of LDCs are very low, and QL seems to be mostly dependent on factors linked to political instability (war, crisis, lack of institutions).

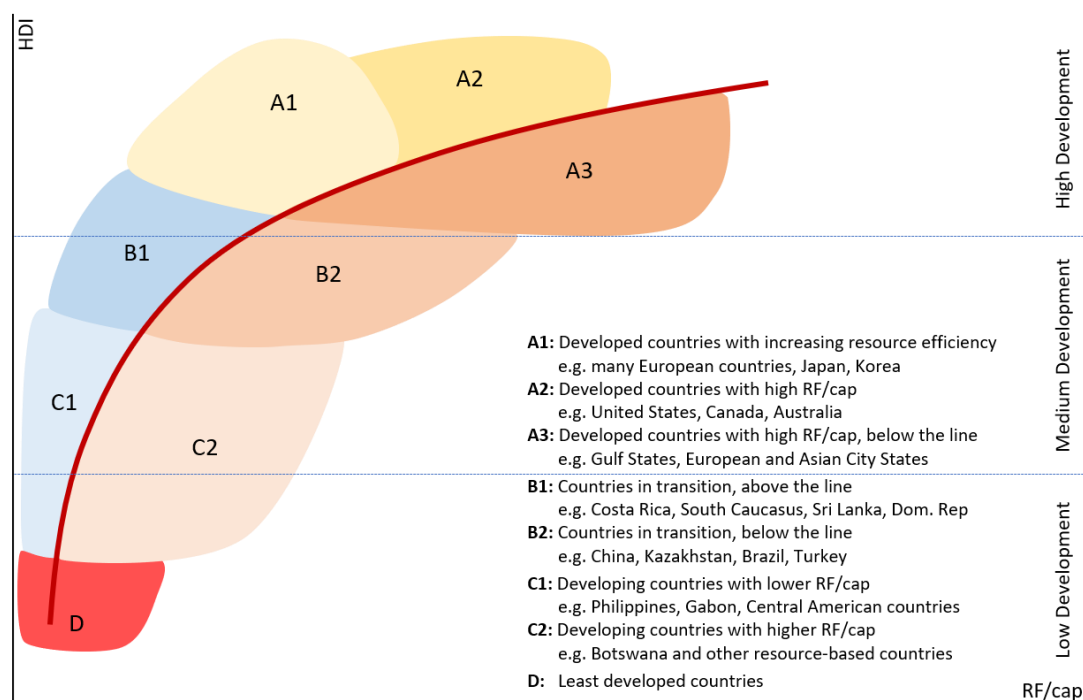


Figure 3. Derived development clusters based on the analysis of per-capita resource footprints (RF/cap) and the relation to the Human Development Index (HDI).

The position of a country in a certain cluster is not arbitrary but depends on various factors. As the RFs are based on consumption instead of production, the economic sector composition of a country should not play an important role; however, analyses have shown that resource-based developing countries can typically be found in the lower right. Which factors influence the position of a specific country above the path of development needs to be analyzed in future research. The finding that countries with less resource dependence, islands, and countries with a socialist history seem more likely to be above the path of development (in Clusters B and C) may be a point of departure.

4. Discussion

In the discussion section, we aim at setting the results of the analysis presented in Section 3 in the context of current sustainability debates. First, we assess the properties of the path of development and illustrate the principal options to change its shape. Then, concepts such as decoupling, planetary and social boundaries are added, establishing an indicative goal area of sustainable development (SD). We then outline the potential of different strategies, such as efficiency, substitution, and sufficiency, to reach the SD area. Finally, based on the different statistical relationships, effects of SD on economic growth and the interplay with economic growth models will be examined.

4.1. Properties of the Path of Development

The path of development (PoD) is the overall regression line of quality of life (QL) as a function of consumption-triggered environmental pressures per capita (expressed as RF/cap). Figure 4 shows four possible changes of the PoD: movements along the path (upper left), changes in efficiency (upper right), shifts due to changed needs (bottom left), and shifts due to other QL factors (bottom right). The shifts in the lower part of Figure 4 are mathematically identical but will be distinguished due to their very different nature. In this section, the four adjustments are mostly reviewed in isolation; combinations will be assessed in Section 4.3. For each case, examples for developing countries (A) and industrialized countries (B) are visualized.

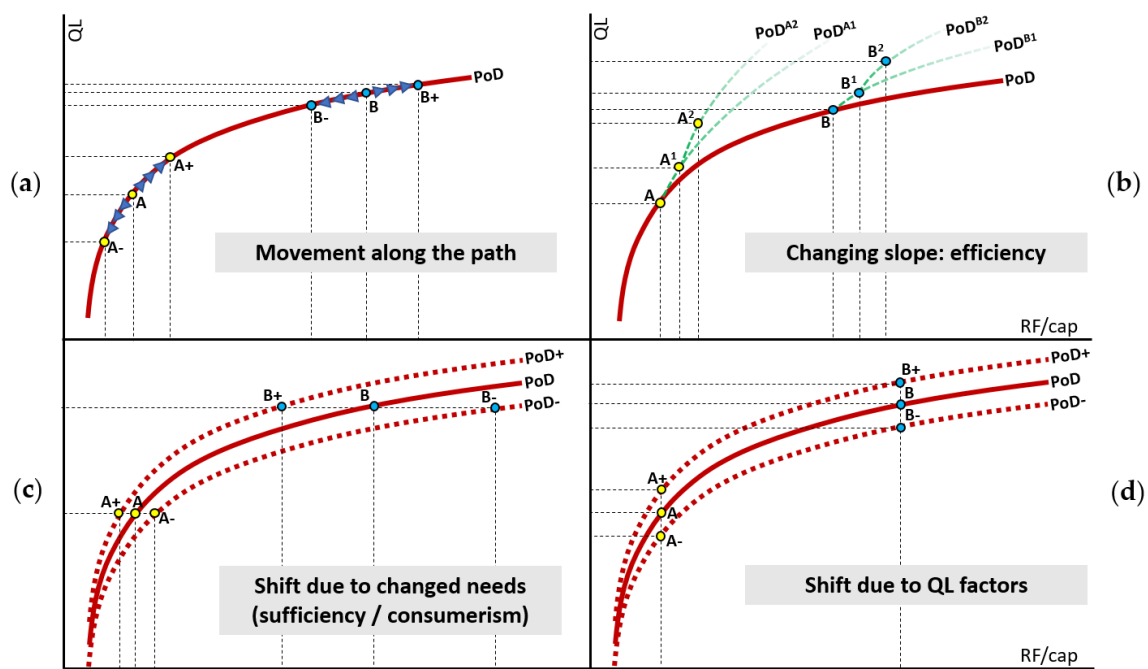


Figure 4. Options to change the generalized Path of Development (PoD): movement along the PoD (a), changing the slope of the PoD (b), shifts of the PoD due to changed needs (c), and shifts of the PoD due to other Quality of Life (QL) factors (d).

Starting with movements along the path from point B, a decline to B- or an increase to B+ has a rather small effect on QL, while a movement from point A to A- or A+ implies a huge change in QL (Figure 4a). Such a movement occurs if, *ceteris paribus*, RF/cap increases or decreases. RF/cap will, for example, increase with total economic output and decrease with regulatory measures that aim at reducing levels of resource consumption or emissions. Interesting factors to be discussed at this point are consumer preferences, substitution of industries (e.g., through a higher circularity or more efficient industries) and obsolescence since they are closely linked to other changes (see below).

The chart in Figure 4b shows changes in the slope of the PoD, which can be described as the marginal effect of RF/cap on QL; thus, the strength of the effect depends on the elasticity at the point of change. Accordingly, factors influencing the slope are connected to resource efficiency measures, such as technological progress and higher levels of circularity. Increasing resource efficiency leads to a movement from A to A1, B to B1, and further to A2 and B2, if resource efficiency keeps on increasing; in the maximum case, the PoD could thereby get vertical, but never turn to the left, if only the marginal resource use gets more efficient. In contrast, if resource efficiency improves by the substitution of existing industries and production methods, which could be explained by an initial downward movement along the curve, followed by an upward movement along a more efficient path, an overall movement to the upper left could be possible (see also Section 4.3).

The chart in Figure 4c shows a shift due to changed needs of consumers; this refers to the debate of different approaches of well-being, i.e., ‘hedonistic’ versus ‘eudaimonic’ well-being [13]. The former requires ever-increasing pleasure-seeking (consumerism, or even decadency), while the latter refers to a good life of self-realization (flourishing). If such a shift occurs, RF/cap declines with lower consumption needs, but QL remains, *ceteris paribus*, at the same level. This can be illustrated via a higher PoD (A to A+, B to B+), and implies that an initial downward movement due to consumer preferences is per definition (QL remains the same) covered by the resulting upshift. The opposite movement due to increased consumption needs results in a downshift of the PoD (A to A-, B to B-). The sensitivity for this change is particularly high at higher development levels.

Figure 4d shows the shift of the PoD, from A to A+ or A-, B to B+ or B-, induced by changes of other QL factors. Such a shift can have a constant effect at all development stages and is triggered by

the change of a variable on the y -axis, involving issues such as equality, societal recognition, personal freedom, democratic participation, health status, life satisfaction, safety, security or other factors directly influencing QL. As mentioned in Section 3.1, GDP/cap is also an endogenous variable on the y -axis, an increase due to technological progress would thus also lead to an upshift of the PoD.

To sum up, there are four possible mechanisms how a countries' position at its development path can be influenced: (1) movement along the curve; (2) change of the slope; (3) shift due to changed needs and consumer behavior; and (4) shift due to factors affecting the y -axis. The question of which underlying economic, social, and cultural factors determine which of these movements, cannot be conclusively assessed with the data used in this paper. However, our propositions can be used as hypotheses for future analyses of specific clusters and timelines.

4.2. Planetary and Social Boundaries and Their Implications for Decoupling

In this chapter, the PoD will be set into the context of different growth and decoupling concepts. Planetary and social boundaries will be added to create an indicative goal of SD, leading to a normative condition, how the PoD needs to change. This condition will then be applied in the subsequent chapters.

Figure 5 illustrates the development path viewed from the perspective of economic growth (a) and QL (b). We introduce the environmental and social boundaries and indicate variations in decoupling. Departing from a random point along the development path in the GDP-oriented perspective, four areas need to be defined to explain different decoupling and growth concepts. Any further development to the right of the starting point, along and to the right of the line, reflects no decoupling between GDP/cap and RF/cap (orange). A development with increasing GDP/cap, but less strongly growing RF/cap, indicates the area of relative decoupling (yellow). Absolute decoupling is any development to the left of the point of departure (declining RF/cap, green and blue). To separate the concepts of green growth and degrowth, the former is any development above the point of departure, which stays left of the curve (green and yellow), while the latter is any development below this point (blue area). Accordingly, the green area is the intersection of absolute decoupling and green growth.

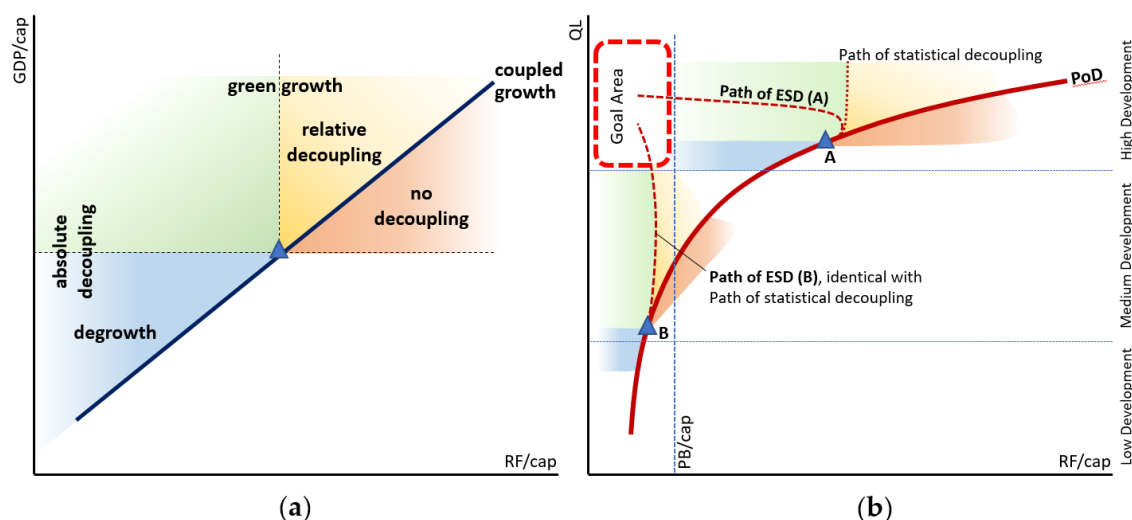


Figure 5. Development paths, decoupling and boundaries in the context of the linear relationship between per-capita Resource Footprints (RF/cap) and GDP/cap (a) and the logarithmic relationship between RF/cap and QL, considering per-capita Planetary Boundaries (PB/cap) (b).

This framework is now applied to the PoD, indicating the relations between QL and RF/cap at two possible stages of development (compare colors from points A and B). The main difference is that now, the areas need to be reframed. The blue area, in particular, is no longer degrowth in terms of GDP/cap, but decreasing QL. Although GDP/cap is a constituent of QL, this difference is important, even more so due to the different shapes of the curves, which results from the declining marginal utility of higher

income, and in particular from the non-GDP factors of QL. From that perspective, not degrowth in economic terms must be avoided, but decreasing QL [34,35].

Figure 5b additionally introduces an abstracted planetary boundary per capita (PB/cap), assuming that a transformation into consumption-triggered per capita numbers is possible [62]. Since GHGs clearly follow the PoD, “climate change” fits into the suggested framework. For the “biochemical flows” of nitrogen and phosphorus, a similar pattern was found by O’Neill and colleagues [38]. “Ozone depletion” is strongly linked to “other GHGs” (halogenated hydrocarbons), while “ocean acidification” is strongly linked to CO₂. Pollutants with immediate effects are more likely to follow the EKC [63], such as SO₂ or VOCs; among the PBs, only “aerosol loading” could probably be considered an EKC-pollutant. In contrast, “biosphere integrity” [64] and “novel chemical species” are no typical EKC-pollutants and are assumed to also follow the PoD. “Land-system change” cannot be conclusively assessed from the data used; according to our data analysis, “freshwater use” does not follow the PoD [54].

From previous studies [31,38] and from the fact that a number of planetary boundaries have already been transgressed [6,39], it can be assumed that the threshold introduced as a vertical line is located relatively close to the *y*-axis, when compared to the current position of high-consuming, industrialized countries. Together with the (indicative) social boundary, above which QL is considered to be high (development levels on the right side), PB/cap forms a sustainable goal area, within which both societal and environmental demands are fulfilled (compare “Goldemberg’s corner” in the field of energy, introduced in the mid-1980s [65]).

In order to reach this area, a “path of sustainable development (SD)” must be introduced. We can see from Figure 5b that, if the PBs are already transgressed (e.g., at point B, illustrating an industrialized country), the goal area can only be achieved through permanent (continued) and sufficiently strong decoupling. The limit of absolute decoupling (the path from a given development state, which has no correlation with RF/cap) is only identical with the path of SD, if planetary boundaries are not yet transgressed (e.g., from point A, illustrating a developing country). Stoknes and Rockstroem [40] also differentiate between green growth, requiring absolute decoupling (the green area), and “genuine green growth”, requiring “sufficient decoupling” (the “goal area”). Parrique et al. [41] also characterize the decoupling requirements as absolute, global, permanent, and sufficient.

That green growth and even absolute decoupling might not be sufficient to reach the SD goal area is indeed concerning, particularly as several PBs have already been transgressed on a global scale, and even more in industrialized countries [38]. Although the shape of the path of SD can be observed in the data (see Section 3.2), the development towards the goal area is questionable, since the turning points in many of the regional timelines took place during the economic crisis, and are rather stagnating since. Other studies have found decelerations and yet again accelerations of environmental pressures in relation to QL indicators [66] and in particular no permanent and sufficient decoupling [41]. Therefore, it will be even more important to develop policies to support a continued improvement on the path towards SD, instead of a stagnation far beyond the PBs.

4.3. Options to Reach the Goal Area

So how can the elements, as developed in Section 4.1., be utilized to remodel the PoD in a way that it converges towards a path of SD? Four possible combinations of PoD adjustments are shown in Figure 6. In each case, we depart from point A, which would under business-as-usual-circumstances (striving for economic growth, slightly increasing resource efficiency) become point B. In all cases, three possible scenarios of increasing efficiency are assumed, and illustrated via green dashed lines, showing a range of possible developments, i.e., A to B1, B2 or B3 instead of A to B. Neither of the four options contains an upshift via exogenous factors, which would constitute an additional movement in all cases, depending on socio-economic policies (see Figure 4 above).

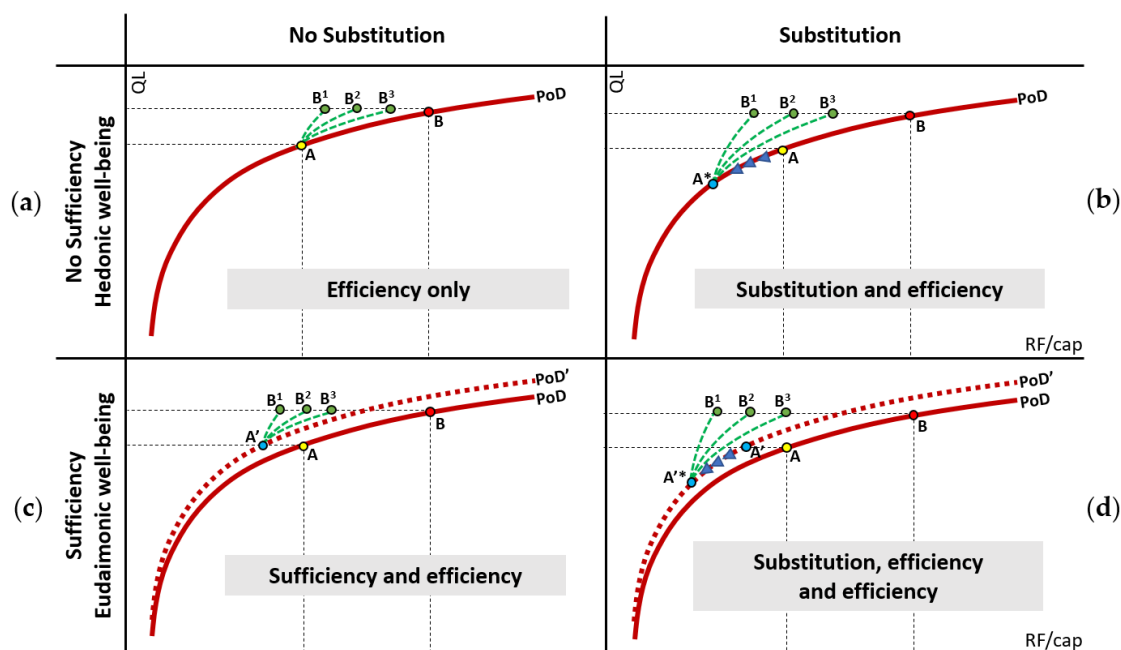


Figure 6. Options to move towards the goal area: efficiency measures only (a), substitution and efficiency (b), sufficiency and efficiency (c), and a combination of substitution, sufficiency and efficiency (d).

Figure 6a shows an increasing slope, i.e., increasing efficiency of additional units only. Obviously, regardless of the strength of this effect, the result is better than B, but RF/cap would still increase. This option falls within the concept of relative decoupling, and would not be sufficient if PBs are already transgressed. In Figure 6b, the combined effects of substitution and efficiency increase are illustrated. Substitution is, in this framework, illustrated as a downward movement along the PoD from A to A*, and the subsequent upward movement along the green dashed lines to the same QL level as A. From there, further pursuing the more efficient paths leads to B1, B2 or B3. Depending on the strength of this effect (e.g., due to technological progress or the implementation of circular economy practices), relative or to a certain extent absolute decoupling could be possible.

A similar result could be achieved via a combination of sufficiency and efficiency increase (Figure 6c). Per definition of sufficiency (see Section 4.1), A turns to A', since RF/cap increases, while QL remains the same. The net effect could again be relative or absolute decoupling, depending on the strength of the effect and the assumed increase in efficiency. In the case illustrated in Figure 6d, substitution, sufficiency, and efficiency increase are combined. Sufficiency leads to A', substitution to A* and up to the QL level of A; continued more efficient development would lead to B1, B2, or B3. These endpoints would now more likely constitute absolute decoupling, and possibly even “sufficient decoupling”, which is needed to decrease RF/cap below the PB. Comparing these options, we conclude that the further PBs are already transgressed, the higher is the importance of “double decoupling,” [13] particularly also including sufficiency. This is also in line with the call for a systemic approach to reaching sustainable production and consumption patterns through addressing—in addition to efficiency—also overall volumes of consumption, distributional aspects, and required social and institutional changes [67].

4.4. The Relationship to Economic Growth Models

In this last part of the discussion, based on the examination of the PoD and the path of SD, a conceptual overview of the relationship to GDP/cap is derived, thereby also touching the question of green growth versus degrowth. Since even absolute decoupling may not be sufficient after transgressing PBs, it seems interesting to discuss how turning to a path of SD beyond this point would affect GDP/cap, and how this interacts with economic growth models.

Figure 7 shows the PoD and a path of SD (c), while (a) depicts GDP/cap as a function of RF/cap, in its linear shape as described in Section 3.1. The colored areas are chosen in accordance with the decoupling sketch presented in Section 4.2. We assume a path of SD from point A to point B, due to a combination of substitution and sufficiency, as indicated in Section 4.3. Marking off points A and B in the upper chart shows that following the path of SD would, *prima facie*, lead to a lower GDP/cap. This could be a consequence of substitution leading to declining returns of existing industries (e.g., production, mining), and sufficiency leading to lower consumption and production.

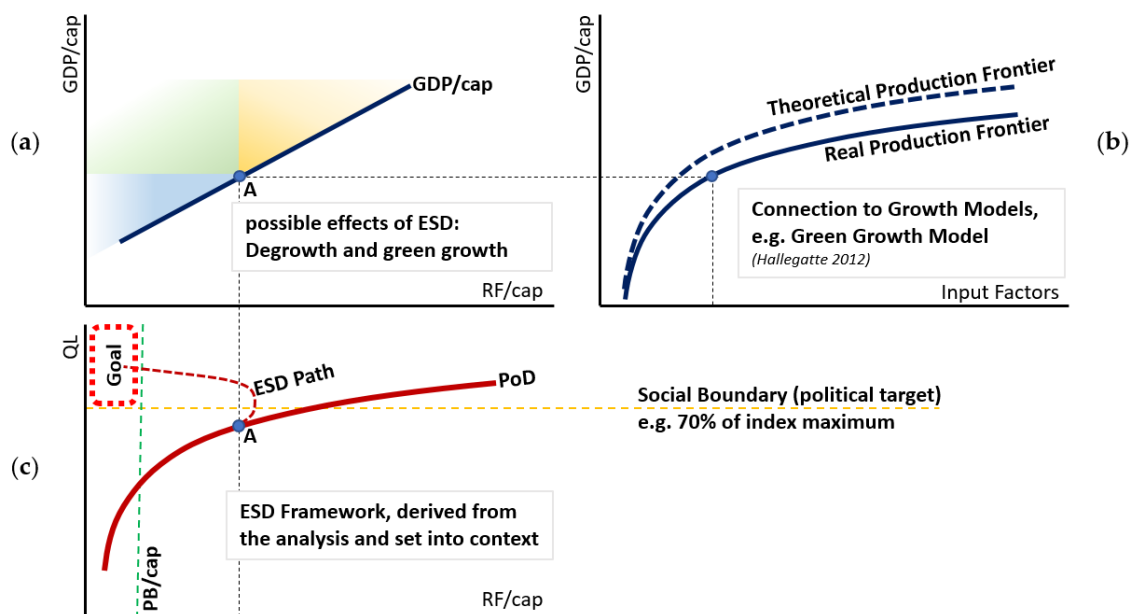


Figure 7. Links between the Path of Development and economic growth models: SD framework for GDP/cap, linear shape (a), Green Growth Model [68] (b), and SD framework for QL, log-shape (c).

However, rebound effects on GDP/cap must be considered [69], which can be expected in two ways: (1) Increasing the slope by reducing the resource elasticity; (2) shifting the GDP/cap line upward. The slope of the linear curve increases through increased resource efficiency and can thus be applied for the substitution case. The initial downward movement is at least partially made up by replacing new sectors, such as circular economy businesses (e.g., recycling instead of mining, product services instead of mass production) and renewable energies instead of fossils. Regulatory measures would also most likely lead to a downward movement due to increased costs of mitigation measures, but would not automatically trigger the same extent of positive rebound. Thus, stricter pollution control or regulations without direct rebound effects would require complementary measures, e.g., increasing QL via GDP-related (technological progress, subsidies for substituting industries) or non-GDP QL-factors.

The overall effect of rebounds on GDP/cap depends on their strictly economic strength. For example, sufficiency through promoting eudaimonic well-being does not result in a positive rebound on the GDP/cap, since consumption is reduced without replacement, while QL remains the same. These rebounds can be positive (compare point B'' in the green area) or negative (point B' in the blue area). The rebound strength may also depend on the stage of development – the initial loss of the replaced sector might be more difficult to substitute at lower development levels – and the availability of more efficient technologies. As the net development could be either green growth or degrowth, GDP/cap might have risen or fallen, even though QL has increased at the same time. This result strongly supports the argument of economists advocating a-growth and post-growth approaches. It does not primarily matter whether GDP/cap grows (net development) since QL can increase due to non-GDP factors as well as through GDP-related rebound effects, particularly beyond a certain level of development (wellbeing-consumption paradox [34,35]).

To assess possible interdependencies with classical growth theories, we suggest connecting the framework presented in Figure 7 with classical economic growth models, through horizontally transposing the y -axis with GDP/cap to another chart. In Figure 7b, classical growth models could be applied, for example, the Green Growth Model by Hallegatte et al. [68], using the classical growth predictors human and physical capital, labor, but also environmental capital. Applying Hallegatte's propositions about production frontier and ineffective production on our framework seems to indicate that the slope of the GDP/cap curve could also be increased by internalizing external costs. An upshift could also be achieved through a shift to input factors other than natural resources (substitution in the neoclassical sense, compare Hartwick's rule [70]) and improved technologies (more output with the same input). These propositions could be used as a starting point for future studies about the connection between frameworks developed in the fields of classical environmental economics on the one hand, and ecological economics on the other hand.

5. Conclusions

In our study, we provided an assessment of the relationships between natural resource use, quality of life, and economic affluence for countries worldwide in the time period of 1990 to 2015. Regression analyses showed that the relationship between resource footprints and quality of life can be generally described by a logarithmic curve; this path of development can be applied for all greenhouse gases, raw materials, and other resource footprints. At the same time, resource footprints and GDP per capita are linearly connected. Departing from this empirical analysis, an assessment of the paths' properties showed how slope and position of the curve can be influenced. Through the addition of the concepts of decoupling, planetary, and social boundaries, we established a goal area of SD. We illustrated that decoupling and green growth might not be sufficient in a situation, where planetary boundaries have already been transgressed, and that a combination of efficiency increase, substitution of industries, and sufficient consumption will be necessary. Although still increasing well-being and considering rebound effects, these measures may result in a rising, stagnating or declining GDP/cap (a-growth).

The SD framework developed in this paper allows a joint assessment of different economic, social, and environmental concepts, thus facilitating the communication of sustainability challenges, as well as highlighting opportunities through combining different strategies. Points of departure for future research towards a new, comprehensive framework may focus on the question on how the proposed SD framework could be parameterized (in either aggregated form or disaggregated into several QL and RF indicators) and further refined. Aspects that need attention are how to use smaller geographical, demographic, and economic entities, how factors such as inequality and population development could be included, which factors influence the properties of specific development clusters and path, and how our propositions regarding economic development proof in empirical terms.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2071-1050/12/11/4734/s1>, S1: Utilization of residuals to form development clusters; S2: Analysis of Resource Footprint components.

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